DEVELOPMENT OF A CUSTOMIZABLE PRODUCTION LINE LAYOUT PLANNING SYSTEM FOR SRI LANKAN FAST FASHION APPAREL INDUSTRY

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DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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ABSTRACT

Fast fashion apparel industry is having a significant growth in international markets. Frequent fluctuation of customer demand with smaller batch quantities and, short lead-times, are the key characteristics of fast fashion apparel products. Main target markets of Sri Lankan ready-made apparel industry are rapidly adapting the fast fashion strategy. In order to retain and attract the customers of Sri Lankan ready-made apparel industry, it is essential to address the frequent problems related with fast fashion apparels. This research addresses the increased changeover cost related with production line layouts, which is the major problem in terms of fast fashion apparels.

The developed production layout planning system uses dynamic cellular manufacturing concept as the basis. A comprehensive literature review, case study on a selected factory, and questionnaires were used to determine the essential features included in the developed system. The developed system consists of two mathematical models, an algorithm and a computer program to determine the optimum layout solutions that minimize the costs of machine set-ups, machine relocations, material handling, and workload balancing. The developed system is validated using case studies conducted in five apparel manufacturing factories that are currently producing fast fashion apparels. According to the validation results, the developed system is capable of achieving significant cost saving percentages compared to current state in the selected factories.

Key words: fast fashion, layout planning, dynamic cellular manufacturing system

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LIST OF ABBREVIATIONS

Abbreviation	Description
CFP	Cell Formation Problem
CMS	Cellular Manufacturing System
DCFP	Dynamic Cell Formation Problem
DCMS	Dynamic Cellular Manufacturing System
EDB	Export Development Board
GL	Group Layout
GS	Group Scheduling
GT	Group Technology
KWC	Kilbridge and Wester Column
LCR	Largest Candidate Rule
MGI	Machine Group Identification
MMD	Multi/Mixed Model Deterministic
MMS	Multi/ Mixed Model Stochastic
MPS	Master Production Schedule
MTM	Method Time Measurement
PF/MG	Product Families/Machine Grouping
PFI	Product Family Identification
PMTS	Predetermined Motion Time System
RPW	Ranked Positional Weight
SCMS	Static Cellular Manufacturing System
SMD	Single Model Deterministic
SMS	Single Model Stochastic
SMV	Standard Minute Value

TMU	Time Measurement Unit
UALBP	U-shaped Assembly Line Balancing Problem
UK	United Kingdom
US	United States
WIP	Work In Progress

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CHAPTER 1: INTRODUCTION

1.1 Introduction to fast fashion apparel products

Fast fashion apparels are characterized as highly fashionable products with affordable prices in the mid-to-low range, which demands for quick response and frequent assortment changes (Vecchi, & Buckley, 2016; Elavia, 2014; Caro, & Martinez-de-Albeniz, 2014; Cachon, & Swinney, 2011). Fast fashion apparel products can be either completely new styles and/or recurrence of variations of previous styles with minor changes in trims, accessories, color, pleats, etc (Joy, Sherry, Venkatesh, Wang, & Chan, 2012; Memic, & Minhas, 2011; Cachon, & Swinney, 2010). As mentioned by Bhardwaj, & Fairhurst (2010), Jovanovic, Mann, Katsioloudis, & Dickerson (2014), Memic, & Minhas (2011) and Cachon, & Swinney (2011), frequent fluctuation of customer demand with smaller batch quantities and, short production and distribution lead-times, are the key characteristics of fast fashion apparel products.

Because of the increasing consumer demand, fast fashion segment in apparel industry has shown a rapid growth internationally during past few years (Mo, 2015; Jovanovic et al., 2014; Tartaglione, & Antonucci, 2013; Aus, 2011). More importantly, Caro, & Martinez-de-Albeniz (2014) stated it as a high growth potential area of international apparel business. Based on the findings of the research conducted by ShopperTrak (2015), international consumer demand growth rate of fast fashion apparels is 21.8% whereas basic products and luxury products stands for 13.2% and 7.1% consecutively.

As stated by Mo (2015), Memic, & Minhas (2011) and Bhardwaj, & Fairhurst (2010), the modern apparel retailers consider fast fashion as the key to success and best survival strategy in dynamic apparel business. Due to immense growth in fast fashion apparel business, majority of the retailers in European region and United States have shifted to fast fashion apparel products (Caro, & Martinez-de-Albeniz, 2014; Joy et al., 2012; Cachon, & Swinney, 2011). In addition to that, there is a markedly growth in demand for fast fashion apparels in Asian countries, rising about 10% per year (PwC HK, 2015).

1.2 Impact of fast fashion apparel industry on Sri Lankan ready-made apparel manufacturers

Ready-made apparel industry is the key export revenue maker in Sri Lankan economy. According to the Sri Lanka Export Development Board (EDB) statistics of year 2016, textile and apparel sector accounts for about 45% of the Sri Lankan total gross export revenue. Out of this, the ready-made apparel exports accounts for nearly 90.3%. It emphasizes the impact of apparel exports on Sri Lankan economy.

The United States (US) and United Kingdom (UK) are the two main target markets of Sri Lankan ready-made apparel industry (EDB, 2016). As stated by Lieber (2017), Smithers (2017), Gilliland (2017) and Caro, & Martinez-de-Albeniz (2014), majority of the retailers in Sri Lankan ready-made apparel target markets have shifted to fast fashion strategy. Increasing demand for fast fashion apparel products in main target markets have forced Sri Lankan apparel manufacturers to become flexible to dynamic demand conditions (Chandrasekera, 2016; JAAF, 2016; So, 2013). Due to inherent characteristics of fast fashion apparel products, the ability to achieve greater manufacturing flexibility to cope with characteristics of fast fashion apparels has become a key competitive advantage of ready-made apparel manufacturers (Caro, & Martinez-de-Albeniz, 2014; Jovanovic et al., 2014; Gugnani, 2012).

According to Caro, & Martinez-de-Albeniz (2014) and Kentli, Dal, & Alkaya (2013), some of the fast fashion apparel retailers have started to near-shore the ready-made apparel manufacturing phase to European and North American countries rather than outsourcing to Asian countries. It is to achieve expected shorter lead-times of fast fashion apparel products. Mo (2015) and Cachon, & Swinney (2011) stated that, although the near-shoring is the most effective way of achieving shorter lead-times, it resulted in comparatively high production costs than that of Asian countries. Wage rates are comparatively lower in countries such as Vietnam, Bangladesh, Sri Lanka and China than that of the in-house manufacturing in fast fashion retailing countries and near-shored countries (Mo, 2015). Consequently, many of the retailers outsource the apparel production stage to comparatively low wage countries to compensate the increased transportation costs with low production cost (Bhardwaj, & Fairhurst, 2010). However, outsourcing to low cost countries resulted in considerably longer lead-times and therefore fast fashion retailers look forward to the countries that are capable of achieving shorter manufacturing lead-times with low production cost (Caro, & Martinez-de-Albeniz, 2014; Doeringer, & Crean, 2006).

According to Hirano (2016) and Arnold (2011) manufacturing lead-time is the total time taken between order placement at the manufacturing plant and shipment of finished goods to the customer. It is the summation of queue time before production, production lead-time, waiting time after completing production, and transportation time (Schmenner, 2012; Hofstede, Benatallah, & Paik, 2008). Queue time before production, waiting time after completing production and transportation time are highly influenced by logistics and supply chain management decisions (Caro, & Martinez-de-Albeniz, 2014). Study carried out by UNCTAD (2014) shows that Sri Lankan ready-made apparel manufacturers import around 70% - 80% of the required raw materials from other countries such as China, Pakistan, India, etc. As a result, the effect on manufacturing lead-time due to delays in raw material supplier processes and inbound/outbound logistics are rather uncontrollable to Sri Lankan read-made apparel manufacturers. Issues related to logistics and supply chain management can be reduced to a certain extent in light of multiple researches available on fast fashion apparel industry. Out of them, Sabet, Yazdani, & De Leeuw (2016), Orcao, & Perez (2014), Shen (2014), Zhelyazkov (2011), Zhenxiang, & Lijie (2011), Alim, & Hasan (2010), Mihm (2010) and Nagurney, & Yu (2010) have taken noticeable efforts on reducing lead-time by logistics and supply chain management.

Reduction of production lead-time is essential to achieve the demanded shorter manufacturing lead-time of fast fashion apparels (Caro, & Martinez-de-Albeniz, 2014; So, 2013). As mentioned by Schmenner (2012), production lead-time is the summation of changeover time and processing time. Lago, Martinez-de-Albeniz, Moscoso, & Vall (2013) and Johnson (2003) stated that production lead-time can be drastically reduced by minimizing the changeover time.

Fast fashion apparels are characterized with high frequency of changes in product demand and product mix. Due to that, manufacturing processes have to undergo frequent changes to match with the characteristics of fast fashion apparels. Number of fashion seasons within a year has been increased due to fast fashion strategy

(Bhardwaj, & Fairhurst, 2010). Some seasons end less than one week or can be extended depending on the customer demand (Choi, 2013). Due to that, for a defined planning horizon, the number of changeovers required for fast fashion orders is higher than that of traditional mass production. This results in increased changeover cost in fast fashion apparel production when compared with mass production.

Changeover costs are increased in production or assembly department than that of other departments in a ready-made apparel manufacturing factory (Michelini, & Razzoli, 2013; Ahmad, Bagum, Rashed, Khalil, & Iqbal, 2012; Zhao, & Yang, 2011). It is due to the use of semi-automatic machines with high labor involvement in apparel production/assembly stage (Zhao, & Yang, 2011). JAAF (2016) and So (2013) mentioned that increased changeover costs related with production lines of fast fashion apparels is the major issue faced by Sri Lankan fast fashion apparel manufacturers. Reason for that is the frequent rearrangement of machine layouts in production department to match with dynamic demand of fast fashion apparels (JAAF, 2016; So, 2013). Excessive rearrangement of layouts may significantly increase the cost of machine movement, lost production time and disruptions on operators' learning curve (Kia, Shirazi, Javadian, & Tavakkoli-Moghaddam, 2013)

As mentioned by Forghani, Mohammadi, & Ghezavati (2013), Nicholas (2011) and Benjafaar, Heragu, & Irani (2000), introduction of an appropriate production layout planning system drastically reduces the changeover costs. Several authors have proposed systems to reduce changeover time in machine-intensive industries (Cakmakci 2009; Johnson, 2003). Since the fast fashion apparel production department is considered as highly labor-intensive (Zhao, & Yang, 2011), complete adaptability of such systems is infeasible. As the fast fashion apparel segment is introduced recently, there exists a significant gap in available literature on production layout planning systems applicable for fast fashion orders (Kentli et al., 2013; Kincade, & Kanakadurga, 2013). Furthermore, initial discussions with industry resource personnel showed that the increased changeover cost due to the use of inappropriate production layout systems for fast fashion orders in production department is the major issue faced by Sri Lankan ready-made apparel manufacturers. Therefore, this research aims to develop an appropriate production layout planning system for fast fashion orders in order to address the prevailing issue faced by Sri Lankan ready-made apparel manufacturers.

1.3 Research problem statement

Increased changeover cost due to inappropriate production layout planning systems used for fast fashion apparels in production department is the major problem faced by Sri Lankan ready-made apparel manufacturers.

1.4 Research objectives

1. To study the layout related problems that affect the changeover cost of production department regarding fast fashion apparels
2. To identify the constraints related with layouts used in production department
3. To develop a production layout planning system for production department of Sri Lankan fast fashion apparel manufacturers
4. To validate the developed production layout planning system for fast fashion apparels

1.5 Significance of the research

Ready-made apparel exports industry plays a significant role in Sri Lankan economy. Main target markets of Sri Lankan ready-made apparel export industry are swiftly adapting the fast fashion strategy. Due to rapid growth of fast fashion apparel industry, retailers seek to outsource apparel manufacturing phase to countries that are capable of achieving expected shorter lead-times of fast fashion apparel products with low production cost. As a result, countries with comparatively low wage rates are under immense pressure to reduce lead-time of manufacturing processes. In that situation, achieving shorter lead-time in manufacturing processes by Sri Lankan ready-made apparel manufacturers will be a key competitive advantage over regional countries. Several researchers have addressed the issues related with supply chain management and retailing decisions of fast fashion apparel products in order to achieve the demanded shorter lead-times (Choi, 2017; Caro, & Martínez-de-Albeniz, 2015; Fernie, & Grant, 2015). Literature review and initial discussions had with industry resource personnel of Sri Lankan ready-made apparel manufacturing factories show that there is a significant deficiency of production layout planning systems designed to minimize changeover cost of fast fashion apparel products. This research addresses the prevailing gap in literature and the lack of production layout planning system for fast fashion orders in Sri Lankan ready-made apparel manufacturing factories.

One of the key benefits of developed production layout planning system is the ability to determine optimal layout configurations with minimum changeover costs at the beginning of each planning horizon. Focusing only on changeover cost minimization may reduce the layout performance after changeover process. In order to avoid that, the developed layout system incorporates several aspects such as material handling minimization, workload balancing, and capacity considerations.

Unlike the traditional trial-and-error methods of forming machine layouts, the developed system determines optimal layout configurations with maximum cost saving percentages before implementing it in actual production environment. This facilitates the users of the developed system to alter the design features to match with different demand scenarios. Ability to alter the input parameters of production layout plan beforehand minimizes the possible disruptions to production processes. In addition, the developed system considers the maximum utilization of available space. Outputs of the developed system consist of defined locations for dynamic cells and machines in plant floor. It minimizes the excessive re-arrangement of machine locations during and after layout changeovers.

Although this research focuses on production department, it can be used as the basis for further researches on layout planning in other departments and relevant processes. Collective minimization of changeover times in total manufacturing process will facilitate the ready-made apparel manufacturers to obtain required shorter lead-times of fast fashion apparels.

1.6 Scope and limitations

Group technology (GT) principles and dynamic cellular manufacturing system (DCMS) concepts are used as the basis for developed production layout planning system for fast fashion apparel orders. The developed system addresses the research problem using three major segments. They are;

1. Dynamic cell formation for considered planning horizon/s
2. Determination of the cells locations in plant floor (inter-cell layout)
3. Design of intra-cell layout, which includes determination of machine arrangement within the dynamic cells and operator assignment to respective operations

Optimal layout plan is generated by the minimizing costs of machine relocations, machine set-ups, material handling, and workload balancing whilst considering multiple constraints related with machine layouts in production department such as space constraints, capacity constraints, and cell formation constraints, etc. It is possible to customize the input data and alter the constraints of the developed system based on user requirements.

Main inputs for the developed production layout planning system are the production related data provided by planning departments of ready-made apparel manufacturing factories. These data depends on the decisions made by planning department in collaboration with internal departments (merchandising, product development, cutting, production, technical, etc) and external partners such as raw material suppliers and end-customers. Production planning decisions directly influence the number of machine layouts changeovers in production department. As mentioned by Forghani et al. (2013), Suresh, & Kay (2012) and Irizarry, Wilson, & Trevino (2001), a complete reduction of changeover time can be achieved by simultaneously addressing the problems such as order scheduling, supply chain management, internal supporting department management and production layout planning. According to the initial discussions had with industry resource personnel and So (2013), increased changeover costs due to inappropriate layout planning systems used in production department is the major issue related with fast fashion apparels.

Hence the changeover cost minimization in this research is focused only on production layout planning.

The developed system consists of two mathematical models, an algorithm, and a computer program. Manual computation of the developed mathematical models and algorithm will produce erroneous results due to complexity. Hence, a program code is developed by using an existing software package, LINGO 15.0. Generated program code is capable of computing optimal solutions for the defined set of inputs, variables, constraints and objective functions of developed production layout planning system. It is possible to modify the program code based on user requirements. In order to do that, respective users must be familiar with the used programming language.

The developed system is validated based on the case studies carried out on intimate apparel manufacturing factories. It can be used for production environments with similar set-ups of manufacturing process.

1.7 Outline of the Thesis

The thesis is structured as follows;

- Introduction to the research problem and current state of related researches are briefly discussed in Chapter 1.
- Chapter 2 presents the literature reviewed throughout this research.
- Methodology followed in this research is briefly discussed in Chapter 3.
- Chapter 4 discusses the results of the questionnaire developed to justify the research problem and to identify an appropriate layout type for the development of production layout planning system for fast fashion apparels
- Chapter 5 describes the case study carried out in a ready-made apparel manufacturing factory, selection of DCMS design approach and identification of the design attributes to include in the development of mathematical models for DCMS design.
- Chapter 6 presents the developed production layout planning system for fast fashion apparels based on DCMS.

- Chapter 7 discusses the results and validation of the developed system by using data from selected case studies.
- Conclusions of the research and possible future research directions are discussed in Chapter 8.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter presents the comprehensive literature review carried out during the research. Key aspects discussed in this chapter can be summarized as follows.

1. Introduction to fast fashion apparels and its key characteristics
2. Frequently faced problems related with fast fashion apparel trend with respect to ready-made apparel manufacturers' perspective
3. Influence of fast fashion apparel industry on Sri Lankan ready-made apparel manufacturers and main problem faced by Sri Lankan apparel manufacturers in fast fashion context
4. Role of layout flexibility in achieving expected manufacturing flexibility of fast fashion apparels and parameters to evaluate layout flexibility
5. Characteristics of existing layout types used in different industries
6. Introduction to DCMS design, DCMS design approaches, and descriptions on DCMS designing stages
7. Modeling of DCMS design problems
8. Validation of layout system designs for labor-intensive industries and the use of software packages for solving and validating mathematical models

2.2 Introduction to fast fashion apparels and its key characteristics

Apparel products can be classified into six major segments as; basic commodity products, fashion-basic products, better fashion, bridge fashions, designer collections and custom-made haute couture products (Doeringer, & Crean, 2006). The latter four products are often denoted by the term fashion/luxury fashion products. According to Joy et.al (2012) and Bhardwaj, & Fairhurst (2010), fashion apparel products generate higher profit margin when compared to basic and fashion-basic products. Variations in basic products are insignificant and the design features remain same for a long period. Some of the examples for these products are basic plain t-shirts, underwear vests and socks. Apparel products with high production volume and longer lead-time are categorized under basic products (Caro, & Martinez-de-Albeniz, 2014; Doeringer, & Crean, 2006). Fashion basic products vary from basic products due to added trims, & accessories (Caro, & Martinez-de-Albeniz, 2014).

Fast fashion apparels are known as mimics of luxury apparel products (Vecchi, & Buckley, 2016; Elavia, 2014; Joy et al., 2012; Memic, & Minhas, 2011). As mentioned by Bhardwaj, & Fairhurst (2010), Jovanovic et al. (2014), Memic, & Minhas (2011) and Cachon, & Swinney (2011), frequent fluctuation of customer demand with smaller batch quantities and, short production and distribution lead-times, are the key characteristics of fast fashion trend. In addition to that, fast fashion apparels are characterized as highly fashionable products with affordable prices in the mid-to-low range, which demands for quick response and frequent assortment changes (Caro, & Martinez-de-Albeniz, 2014; Cachon, & Swinney, 2011). Fast fashion apparel products can be either completely new styles and/or recurrence of variations of previous styles with minor changes in trims, & accessories, color, pleats, etc (Joy et al., 2012; Cachon, & Swinney, 2010). Number of fashion seasons within a year has been increased due to fast fashion strategy (Bhardwaj, & Fairhurst, 2010). Some seasons end less than one week or can be extended depending on the customer demand (Choi, 2013).

2.3 Problems related with fast fashion apparel trend in ready-made apparel manufacturers' perspective

In contrast to the traditional mass production, fast fashion apparel retailers force the manufacturers to achieve shorter lead times with smaller batch sizes (Caro, & Martinez-de-Albeniz, 2014; Memic, & Minhas, 2011). Therefore, other than the four main seasons, additional seasons are added to the fashion calendar of a year (Memic, & Minhas, 2011; Bhardwaj, & Fairhurst, 2010). Furthermore, an intense pressure is on manufacturers to reduce their production costs in order to maintain lower price at the retailing stage (Gugnani, 2012; Bhardwaj, & Fairhurst, 2010). Hence, fast fashion apparel retailers' focus on ready-made apparel manufacturers with reduced labour, material, and shipping costs (Abernathy et al., 2006).

Multiple authors have developed systems to improve the agility of fast fashion supply chain, demand forecasting and marketing strategies (Fontana, & Miranda, 2016; Du, Leung, & Kwong, 2015; Mehrjoo, & Pasek, 2014; Turker, & Altuntas, 2014; Ciarniene, & Vienazindiene, 2014). According to Fontana, & Miranda (2016) and Caro, & Martinez-de-Albeniz (2014), general assumption made for these models is static and precise lead-time in manufacturing processes, which is the essential factor in planning the retailing process. In order to achieve the expected lead-times, apparel manufacturers have to implement possible approaches that are applicable to individual production capabilities.

As stated by FEI (2016), Brooks (2015), ILO (2014) and So (2013) fast fashion apparel manufacturers seeks to achieve expected shorter lead-times of fast fashion apparels by increasing overtime. However, Roger & Ruwanpura (2016), Chan (2013) and Bernhardt et al. (2007) stated that the end-customers' awareness on ethical manufacturing processes demands to reduce the employee overtime. As a result, apparel manufacturers must find an appropriate method to achieve demanded shorter lead-times of fast fashion apparels while minimizing these problems (Chan, 2013).

Mo (2015) stated that the internal manufacturing process has to undergo frequent changes due to the inherent characteristics of fast fashion apparel products. The effect of dynamic demands is severe in assembly/production department due to high labour-intensive nature (Zhao, & Yang, 2011). Increased number of changeovers in assembly department is identified as the main problem faced by ready-made apparel manufacturers in terms of fast fashion apparels (Cachon, & Swinney, 2011). According to Kentli et al. (2013), Kincade, & Kanakadurga (2013), De Carlo, Arleo, Borgia, & Tucci (2013), and Doeringer & Crean (2006) frequent changes in machine layouts in apparel production department is the major issue related with increased changeover costs of fast fashion apparel assembly stage.

2.4 Influence of fast fashion apparel industry on Sri Lankan ready-made apparel manufacturers

As per the industrial personnel, number of fast fashion orders received by Sri Lankan apparel manufacturers is steadily increasing during past few years (Chandrasekera, 2016; So, 2013). According to Chandrasekera (2016), So (2013) and Islam, & Liang (2012), shifting of consumer behaviour from mass production to fast fashion has forced Sri Lankan apparel manufacturers to become more responsive to the market dynamics.

As stated by Kelegama (2006), competitive strengths of Sri Lankan apparel industry are low labour cost, high labour standards, educated workforce and investment friendly government policies. On the other hand, main competitive disadvantage is longer production lead-time when compared to regional apparel manufacturers (Kelegama, 2006). Production lead-time in Sri Lankan apparel industry is about 90-150 days where the international benchmark lead-time is around 60 days (Ethical Fashion Forum, 2016; So, 2013; Islam, & Liang, 2012; Rajapaksha, 2009).

In terms of fast fashion apparels, the main problem faced by Sri Lankan ready-made apparel manufacturers is the increased changeover costs due to frequent rearrangement of machine layouts in production department (Ethical Fashion Forum, 2016; JAAF, 2016; So, 2013). As mentioned by JAAF (2016) and So (2013), key reason for that is the use of inappropriate machine layouts in sewing department for fast fashion orders.

2.5 Layout flexibility and its relationship with manufacturing flexibility

De Carlo et al. (2013), Benjaafar, & Sheikhzadeh (2000) and Yang, & Peters (1998) emphasized that improving layout flexibility is vital to achieve reduced changeover time under volatile demand scenarios. According to Egilmez, Suer, & Huang (2012) and Raman, Nagalingam, & Lin (2009), layout flexibility is defined as the *"ability of a layout to effectively withstand various changes that arise from unceasing transformations in customers' requirements and the enterprises' internal disturbances in terms of cost and time*". Layout flexibility has direct negative relationship with changeover time (Neumann, & Fogliatto, 2013; Egilmez et al., 2012; Raman et al., 2009). In other words, high layout flexibility results in reduced changeover costs and vice versa.

As mentioned by Harashima, & Ohno (2010) and Wadhwa, & Rao (2003) manufacturing flexibility is identified as the ability of a system to react or absorb the variations in factors such as; customer demand, machine, & operator conditions, process, product design. Improving the manufacturing flexibility is key competitive factor in fast fashion apparel industry (Caro, & Martinez-de-Albeniz, 2014; So, 2013). Several authors have emphasized the need of improving layout flexibility in order to increase the manufacturing flexibility (Neumann, & Fogliatto, 2013; Raman et al., 2009; Nomden, & Slomp, 2003; Leondes, 2001; Chang, 1999).

De Carlo et al. (2013) argued that selection of flexible layout is vital to achieve a high level of manufacturing flexibility to face the today's volatile demand in fast fashion market.

2.5.1 Parameters to evaluate layout flexibility

According to Shafigh, Defersha, & Moussa (2017), Kumar, & Raj (2016), Ulutas, & Islier (2015), Zhao, & Wallace (2014), Joseph, & Sridharan (2011), Neumann, & Fogliatto, (2013), Oke (2013), Stephens, & Meyers, (2013), Li, C., Tang, Li, C., & Li, L., (2013), Kulturel-Konak (2007), Gupta, & Lambert (2007), Leondes (2001) and Tempelmeier, & Kuhn (1993), layout flexibility can be increased by improving following parameters.

1. **Routing flexibility**: Ability of a layout to possess multiple alternative processing routes for a single product and ease of re-routing products with minimum layout re-configuration
2. **Material handling flexibility**: Capability of a layout to complete a product with minimum material movement between required processing steps
3. **Robustness**: Ability of a layout to continuously perform close to optimum performance level under multiple different demand scenarios without changing physical layout configuration.
4. **Ease of re-configuration**: Facilitates low cost easy rearrangement of layout in response to variable demand
5. **Level of distribution of machine duplicates throughout the plant floor**: Increased number of machine duplicates throughout the plant floor results in improved ability to re-route the products in case of production disruptions in previously assigned route. This factor highly depends on the routing flexibility.

Flexibility of available layout types can be evaluated by using these five parameters (Ulutas, & Islier, 2015).

2.6 Characteristics of existing layout types

As mentioned by Niakan (2015), Shih, & Goncalves Filho (2014), Ghosh et al. (2014), Ang, Khadanga, & Ho (2014), Modrak (2011), Silva (2010), and Jacobs, Chase, & Aquilano (2004) available layout types can be listed as follows.

- Process/ Job shop/ Functional layout
- Product/ Assembly line layout
- GT layout/ Cellular layout
    - Static cellular layout
    - Dynamic cell layout
    - Virtual cells on distributed layout
- Fractal layout

2.6.1 Process layout/ Job shop/ Functional layout

Key characteristics of process layout are as follows.

1. Machines with similar functionality are grouped in to different specific locations and the products are moved from one production station to another until all the processing requirements are completed (Ang et al., 2014; Malakooti, 2014; Modrak, & Pandian, 2011)
2. Multiple processing routes are available for a single product layout (Silva, 2010) and hence the increased routing flexibility as one of the major advantages (Modrak, & Pandian, 2011)
3. It is robust for multiple demand scenarios. Number of set-ups will be reduced in process layout but with an increase of material handling (Kumar, & Suresh, 2006; Hachicha, Masmoudi, & Haddar, 2008).
4. Main disadvantages of process layouts

i) High material handling complexity for products with higher number of processing steps (Malakooti, 2014; Kumar, & Suresh, 2006)

ii) Longer throughput times (Nomden, 2011)

iii) It is ideal for manufacturing high volume-low variety products (Malakooti, 2014; Dwijayanti, Dawal, & Aoyama, 2010; Kumar, & Suresh, 2006; Sly, 1997), which require machines that are difficult to move and/or require special environment.

2.6.2 Product layout/ assembly line layout

Key characteristics of product layout

1. Machines are arranged according to the operational sequence of a particular product (Malakooti, 2014).
2. It is suitable for products with high volume and low product variety (Malakooti, 2014; Ang et al., 2014).
3. Relatively low throughput times compared to process layout.
4. Main advantages of product layout are; simplified coordination of subsequent operational routings, reduced set-up times and reduced waiting times (Silva, 2010; Dwijayanti et al., 2010; Sirovetnukul, & Chutima, 2010) and improved worker efficiency due to repetitive operations of similar products (Nomden, 2011).
5. Major disadvantages of product layout: Lack of flexibility, dependency of throughput time on bottleneck operation, high cost of layout re-configuration, absence of multiple processing routes to handle breakdowns or bottleneck operations, and disruption of total line output due to breakdown of a single machine (Kumar, & Suresh, 2006; Nunkaew, & Phruksaphanrat, 2013; Silva, 2010).

2.6.3 GT layout /Cellular layout

GT is a manufacturing philosophy that exploits the similarities within a manufacturing system (Suresh, & Kay, 2012; Benhabib, 2003; Arn, 1975). Nomden (2011) and Bellgran, & Safsten (2009) stated that the basic principle of GT is similar products are most likely to have similar solutions. In GT, products with similar design and manufacturing characteristics are grouped in to product families (Rajput, 2007; Benhabib, 2003). Machines that are required to process the product families are grouped in to GT cells (Suresh, & Kay, 2012).

Malakooti (2014) and Nomden (2011) discussed about two similarity types considered in GT philosophy as; Routing similarities and Processing similarities. Routing similarities exists when multiple products in manufacturing system are having similar process routes and operational sequences to complete the product. Processing similarities exist when multiple products are having similar processing requirements with similar operations. Cellular manufacturing systems are formulated based on routing similarities whilst the processing similarities are used in process-oriented systems (Nomden, 2011).

Some of the benefits of GT based cellular layout are listed below (Nunkaew, & Phruksaphanrat, 2013; Modrak, & Pandian, 2011; Hachicha et al., 2008; Rajput, 2007; Priest, & Sanchez, 2001).

- Reduced set-up time,
- Simplified material flows and Reduced material handling,
- Material flows are less complicated than that of functional layout.
- Reduced work-in-progress inventory,
- Reduced throughput time,
- Improved sequencing and scheduling on the shop floor
- Employee related benefits
- Product quality is higher due to specialized workforce and operations with poor quality are easily traceable.
- Machine cells facilitate close supervision of the workers.

GT provides the basis for three main categories of cellular layouts. They are static, dynamic, and virtual cellular layout (Nomden, 2011).

2.6.3.1 Static cellular layout

Key characteristics of static cellular layout

1. Main purpose is to retain benefits of high productivity in product layout and flexibility of process-oriented layouts (Hachicha et al., 2008; Rajput, 2007; Priest, & Sanchez, 2001).
2. Similar products are grouped in to product families so that a particular single cell is capable of processing one or more products (Hachicha et al., 2008).
3. Static cell formation is done by considering constant product demand for an entire planning horizon. Therefore, the optimal layout for one product may not be the optimal solution for a different product (Niakan, 2015; Nomden, 2011; Mukerjee, 2006).

4. Due to low routing flexibility (Neumann, & Fogliatto, 2013; Marsh et al., 1997), introduction of new products to the static cellular layout result in deterioration of the cell performance and eventually cause a major layout rearrangement (Balakrishnan, & Hung Cheng, 2005; Chowdary, Slomp, & Suresh, 2005).

2.6.3.2 Dynamic cellular layout

Key characteristics of dynamic cellular layouts

1. It is formed by considering multiple periods and the product mix and demand requirements vary in each period in dynamic environment (Deep, & Singh, 2016; Niakan, 2015; Mahdavi, Aalaei, Paydar, & Solimanpur, 2010).
2. Formed cells for a particular period may not be the optimal solution for subsequent periods. This requires layout reconfiguration in uncertain demand conditions.
3. Designing process of dynamic cellular layout aims to obtain most suitable layouts by balancing two conflicting costs, i.e. changeover costs and material handling costs, by minimizing the summation of these for a considered planning horizon (Niakan, 2015; Balakrishnan, & Hung Cheng, 2005; Mungwattana, 2000).

2.6.3.3 Virtual cells on distributed layout

Key characteristics of virtual cells on distributed layout

1. Virtual cell formation deals with logical approach whereas the static and dynamic cellular layouts are designed based on physical approach (Xambre, & Vilarinho, 2007; Chowdary, & Praveen, 2005)
2. In general, virtual cells are formed on distributed layouts. Distributed layouts facilitate increased material handling flexibility under fluctuations in product mix and product volume (Benjaafar et al., 2002; Lahmar, & Benjaafar, 2002)
3. Resource grouping in virtual cells is not physically reflected in the system. Once the production of product family is completed, the cell is disbanded and free to form another cell without physical rearrangement of resources (Nomden, 2011, Benjaafar et al., 2002).
4. It is most suitable to manufacture low volume high variety products (Hamedi, Ismail, Esmaeilian, & Ariffin, 2012; Benjaafar et al., 2002; Xambre, & Vilarinho, 2007)

5. Negligence of human factors is the major drawback, which limits the practical use of this layout. Due to frequent disbanding of teams, team building, learning and problem solving are absent in virtual cells (Hamedi et al., 2012).

2.6.4 Fractal layout

Key characteristics of fractal layout

1. Each fractal cell is capable of producing almost every product type manufactured within the company (Modrak, & Pandian, 2011; Jaramillo, & McKendall, 2010) but with different material handling efficiencies (Goldengorin, Krushinsky, Pardalos, & Panos, 2013)
2. It is robust for multiple demand scenarios (Information resources management association, 2013)
3. Limitations of fractal layout

i) It is rather unsuitable for manufacturing processes with hazardous machines that require separate floor area (Goldengorin et al., 2013).

ii) Requirement of excessive number of identical machines (Jaramillo, & McKendall, 2010)

iii) Increased scheduling complexity (Nomden, & Slomp, 2003)

iv) Difficulty in visual management due to absence of standard layout within fractal cells, and the requirement of highly skilled workforce (Silva, 2010)

Nomden, & Slomp (2003) analyzed the four layout types, process, distributed, fractal and dynamic cellular, based on four performance characteristics. They are;

i) Scheduling simplicity: Ease of scheduling products over various machines in manufacturing layout

ii) Pooling simplicity: Ease of assigning operations of products to alternative resources or process routes

iii) GT orientation: Ability of a layout to gain benefits of similarities present in different product types

iv) Team orientation: Ability of the layout to support autonomous teams to complete manufacturing of a product

Qualitative results of their study are presented in Table 4.5. In their study, the relative score of each layout type with respect to each performance measure is indicated from 1 to 4, where 1 is for best and 4 for least.

Table 4.5 – Qualitative analysis of the layout performance characteristics of process, distributed, fractal and dynamic cellular layouts (Source: Nomden, & Slomp, 2003)

Layout type	Scheduling simplicity	Pooling simplicity	GT orientation	Team orientation
Process	3	1	4	4
Distributed	4	3	3	3
Fractal	2	2	2	2
Dynamic cellular	1	4	1	1

As given in Table 4.5, dynamic cellular layout type accounts for highest relative score for three performance measures except the pooling simplicity. The effect of low pooling simplicity can be diminished by improving material handling flexibility at dynamic cell design stage (Aljuneidi, 2013; Nomden, & Slomp, 2003).

In a dynamic cell layout, product families are dedicated to machine cells and thereby the scheduling of new product to the layout can be easily done by selecting the appropriate family. Cellular layouts are generated through exploiting similarities as in GT principles. In dynamic cell layouts, the inherent characteristics of GT concept are improved to suit volatile demand scenarios. The scheduling simplicity and GT orientation facilitates operator learning. Reason for that is the increase of task repetitions due to product families (Nomden, & Slomp, 2003). Higher the number of repetitions of a particular operation, higher will be the operator learning and vice versa (De Carlo et al., 2013). Since the dynamic cells are responsible for complete manufacturing of assigned products, it is possible to form autonomous operator groups for each cell (Nomden, & Slomp, 2003). Furthermore, it facilitates the team-based incentive schemes (Rafiei, & Ghodsi, 2013).

2.7 Introduction to DCMS design

As stated by Mungwattana (2000), four basic types of production requirement are considered in GT based cellular layout designs as; static, dynamic, stochastic, and deterministic. Production requirement in any industry can be represented by using one or more of these types.

Static production requirement assumes a constant product mix and demand for entire planning horizon. There can be either static-deterministic production requirement or static-stochastic production requirement. In first case, the product mix and demand for entire planning horizon are precisely known at the cell formation stage. For the second one, possible product mix and demand for the period are known with certain probabilities.

Dynamic production requirement implies multiple demand fluctuations within a planning horizon. The entire planning horizon is divided in to periods based on the product mix and/or demand in each period. Similar to static production requirement, there are two possible scenarios in dynamic production requirement as; dynamic-deterministic, and dynamic-stochastic. The definitions for deterministic and stochastic production requirements are same as abovementioned whilst the consideration is on multiple periods.

Based on the production requirement, several authors have developed production layout systems for different industries other than fast fashion apparels (Ulutas, & Islier, 2015; De Carlo et al., 2013; Khaewsukkho, 2008; Nomden, & Slomp, 2003). As mentioned by Hamedi et al. (2012), Nomden (2011) and Benjafaar et al. (2000), existing layout types such as product layout, process layout and cellular layout provide the basis for these systems. Out of these, DCMS showed promising results in minimizing changeover times of industries with volatile demand conditions similar to fast fashion apparels (Bayram, & Sahin, 2016; Ulutas, & Islier, 2015; Dalfard, 2013; Ahkioon, Bulgak, & Bektas, 2009; Balakrishnan, & Hung Cheng, 2005; Asgharpour, & Javadian; 2002). Niakan, Baboli, Moyaux, & Botta-Genoulaz (2016) stated that systematically designed DCMS are capable of withstanding multiple different demand scenarios with minimum changeover cost and material handling cost.

2.7.1 DCMS design approaches

As stated by Niakan et al. (2016), Renna, & Ambrico (2015), Rafiei, & Ghodsi (2013), Rezazadeha, Mahini, & Zarei (2011), Pillai, Hunagund, & Krishnan (2011), Suer, Huang, & Maddisetty (2010), Balakrishnan, & Hung Cheng (2005) and Benjaafar et al. (2002), DCMS design has shown significantly better results than Static Cellular Manufacturing Systems (SCMS) when the product mix and demands varies over production periods. In DCMS design, configuration of cells can be changed from one period to another to match with the demand of each period (Niakan et al., 2016; Rafiei, & Ghodsi, 2013). These changes are minimized by considering all the possible demands in corresponding planning horizon and optimizing the cost terms under each demand as a whole and period wise. Although DCMS result in relatively high rearrangement cost than the SCMS, the effect is mitigated by improved material handling efficiency in dynamic cells (Rafiei, & Ghodsi, 2013).

Zarea Fazlelahi, Pournader, Gharakhani, & Sadjadi (2016) and Pillai et al. (2011) stated that DCMS design approaches can be broadly divided into two main categories as;

- Adaptive/flexible approach
- Robust approach

In first approach, machines are periodically rearranged with demand variations. Main assumptions for flexible DCMS design are low machine reconfiguration and relocation costs. Flexible dynamic cell layout approach is most suitable for production environments with fully automated machines that can be easily reconfigured through software modification in a central computer (Zarea Fazlelahi et al., 2016). Furthermore, as stated by Pillai et al. (2011), it is often used for industries with lightweight machineries with relatively low machine relocation costs than that of heavy machinery industries.

Zarea Fazlelahi et al. (2016) stated that robust layouts are most suited when rearrangement of layout cause significant disruption to production processes. Robust approach aims to develop a single layout that can withstand multiple product scenarios for multiple periods. The robust approach is often confused with SCMS design (Deep, & Singh, 2015). SCMS are designed to be stable over an entire planning horizon, whereas robust approach of DCMS focuses on multiple periods within a planning horizon (Deep, & Singh, 2015). Similar to robust approach of DCMS, physical configuration of SCMS layout remains steady for the designed planning horizon. However, SCMS accounts for variable performances that may significantly deviate from optimal value under different product scenarios. As mentioned by Paydar, Saidi-Mehrabad, & Teimoury (2014), main difference of robust approach when compared to SCMS is that robust layouts of DCMS are designed to remain near-optimal performance throughout predetermined periods. Higher the robustness of layout for multiple product scenarios during multiple periods, lower will be the number of changeovers and vice versa (Patel, J., & Patel, S., 2014).

Zarea Fazlelahi et al. (2016) and Deep, & Singh (2015) argued that optimal benefits of DCMS design can obtained by balancing the robust and flexible approaches.

2.7.2 Stages of designing a DCMS

Mahdhavi et al. (2013), Rafiei, & Ghodsi (2013), Kia et al. (2012), Mutingi, & Onwubolu (2012) and Hachicha et al. (2008) discussed about four generic stages of designing a DCMS. They are;

1. Dynamic cell formation problem (DCFP): involves grouping of parts with similar processing requirements and corresponding machines into part families.
2. Group layout problem (GL): includes layout of machines within each cell (intra-cell layout problem/ machine layout problem) and layout of cells with respect to one another (inter-cell layout)
3. Group scheduling (GS): involves scheduling of parts for production
4. Resource allocation: assignment of tools, manpower, materials, and other resources

Ebrahimi, Kia, & Komijan (2016) and Mutingi, & Onwubolu (2012) mentioned that there are three possible approaches available to generate solutions for these stages as; simultaneous, sequential and independent. In the ideal case, these stages should be addressed simultaneously to obtain the best possible solutions for DCMS design (Parashar, 2008). As mentioned by Ebrahimi et al. (2016) DCMS design using simultaneous approach is rare in the available literature. Due to complex nature of the decision problem, most of the studies on DCMS design have focused on generating solutions for four stages independently or sequentially (Rafiei, & Ghodsi, 2013). Sequential approach addresses these stages in a disjointed fashion, and hence the accuracy of final solution is often reduced (Onwubolu, 2011; Selim, Askin, & Vakharia, 1998). Parashar (2008) stated that due to direct inter-connection between these four stages, solutions obtained through independent approach may not accurately reflect the expected benefits of DCMS design.

According to Modrak (2014) selection of simultaneous, sequential or individual solution generating approach depends on nature of data available and requirements of particular industry. In addition, dynamic cell formation techniques greatly affect the ability of selecting a suitable approach.

Four stages of DCMS design (i.e., Dynamic cell formation problem (DCFP), Group layout problem (GL), Group scheduling (GS), and Resource allocation) are briefly discussed in subsequent sections.

2.8 Dynamic Cell Formation Problem (DCFP)

DCFP involves in grouping machines and products into families based on their similarities (Giri, & Moulick, 2016; Rajput, 2007).

Three main approaches are used to address the DCFP (Arora, Haleem, & Singh, 2013; Kahraman, 2012; Modrak, & Pandian, 2011; Curry, & Feldman, 2010; Mungwattana, 2000).

They are;

- Product family identification (PFI)
- Machine group identification (MGI)
- Product families/machine grouping (PF/MG)

As stated by Arora et al. (2013) in PFI approach, initially the product families are identified by using an appropriate technique. Thereafter the machines are allocated to the respective product families. MGI approach groups the machines in to cells based on routing similarities followed by assignment of product families to the formed cells (Prabu, & Kalaamani, 2012). In the third approach, product family formation and machine grouping are done simultaneously. Out of these, the third approach is highlighted as optimum cell formation (CF) method (Mungwattana, 2000; Selim et al., 1998).

2.9 Group layout (GL)

According to Mahdhavi et al. (2013) and Rafiei, & Ghodsi (2013) GL determines the arrangement of machines in cells (intra-cell layout/ machine layout) and layout of cells with respect to one another in plant floor (inter-cell layout).

2.9.1 Inter-cell layout types

As stated by Niroomand (2013), Jain, Khare, & Mishra (2013) and Drira, Pierreval, & Hajri-Gabouj (2007) the candidate locations for cell placement of inter-cell layout decision can be represented as discrete or continuous formulation. In discrete formulation, the plant floor is divided into rectangular blocks with the same area and shape, and each block is assigned to a cell. Wang, Hu, & Ku (2005) stated that if the cells have unequal areas, they can occupy different blocks as shown in the Figure 2.4 (a). In continuous formulation, All the cells are placed anywhere within the planar site and must not overlap each other as given in Figure 2.4 (b) (Niroomand, 2013; Jain et al., 2013; Drira et al., 2007; Fruggiero, Lambiase, & Negri, 2006).

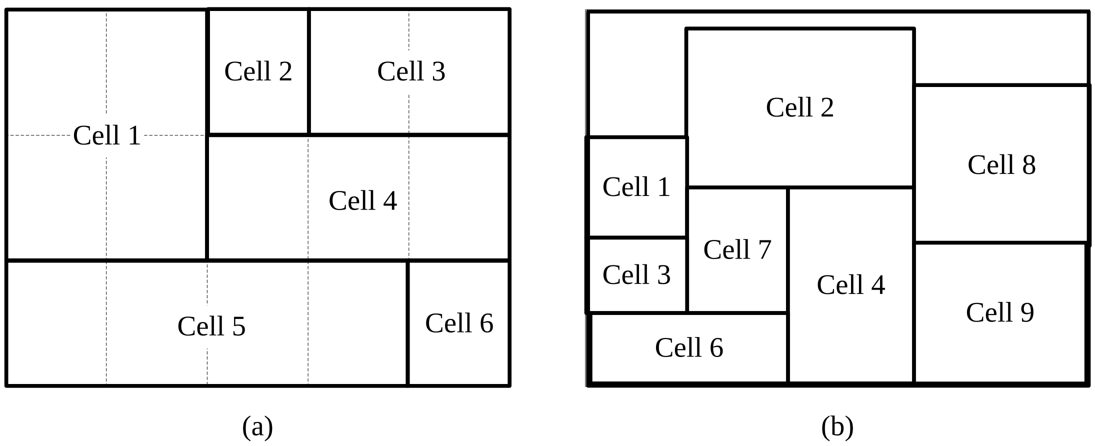

Figure 2.4 – Discrete and continuous formation (Source: Drira et al., 2007)

Several authors have stated that the discrete representation of the layout is commonly used for group layout problems (Drira et al., 2007; Dunker, Radons, & Westkamper, 2005; Meller, Narayanan, & Vance, 1999; Das, 1993). As mentioned by Drira et al.

(2007), continuous formulation results in complexities in supervision and material handling when it comes to the cell level.

2.9.2 Existing intra-cell layout types

Intra-cell layout configurations can be broadly categorized into three segments as; multi-row layouts, loop layout, and single-row layouts (Malakooti, 2014; Anbumalar, Mayandy, & Prasath, 2014; Leonides, 2012). Categorization of intra-cell layout types represents its material flow pattern (Heragu, 2008). Out of these the single-row layouts are further divided into ten sub-categories based on differences in material flow pattern (Pai, Yap, Dawal, Ramesh, & Phoon, 2016; Lv, Liu, Wang, & Cai, 2013; Scholz, Jaehn, & Junker, 2010; Dwijayanti et al., 2010).

1. L-shaped layout
2. T-shaped layout
3. W-shaped layout
4. Comb layout
5. Spine layout
6. Straight through layout
7. Straight single-line double-row layout (with/without center table)
8. S-shaped/ Z-shaped layout
9. Semi-circular layout
10. U-shaped layout

Characteristics of the intra-cell layout types are given in Table 4.6.

Table 4.6 - Characteristics of the intra-cell layout types

Type	Characteristics
Multi-row	Designed for industries with low labor involvement (Malakooti, 2014; Leonides 2012). Simultaneously process multiple products on same machine. Need computerized material handling methods (Tubaileh, & Siam, 2017; Soimart, & Pongcharoen, 2011; Morad, 2000)
Loop	Used in highly automated industries (Anbumalar et al., 2014). Robotic devices or closed-loop conveyers are used to transport materials (Solimanpur, Vrat, & Shankar, 2005; Morad, 2000).
L-shaped	Used for machines with increased safety hazards and/or machines with high relocation cost and/or machines fixed to the plant floor (Mehrotra, Syal, & Hastak, 2005; Rao, 2004).
T-shaped	Multiple products with similar sub-assembly requirements are simultaneously manufactured in vertical segments (Dwijayanti et al., 2010; Ho, & Moodie, 1998)
W-shaped	Used to arrange large number of operations into compact area. Commonly used in machine-intensive cells (Prasath, & Johnson, 2015)
Comb and Spine	Products with similar operation requirements are simultaneously processed (Siti Farah Nadiah, 2007; Muther, 2002). Creates isolated islands in case of unidirectional machines (Meng, Heragu, & Zijm, 2004)
Straight through layout	Straight and parallel production lines where input materials enter one end and output products are received from the other end (Clark, 2009). Material handling is done by using conveyor belts, Automated Guided Vehicles (AGVs), and tables (Rao, 2004). Low level of layout flexibility, and poor operator and machine utilization. Space utilization is fluctuated for products with different machine requirements (Muther, 2002)
Straight single-line double-row layout	Generated by combining two straight through layouts to form a single layout (Wu, 1999).
S or Z-shaped	Used for products with large number of operations in machine intensive industries. Facilitates extensive operator sharing. (Lv et al., 2013)
Semi-circular	Used with highly automated machineries and usually a robotic device placed at the center of semi-circle operates the machines (Morad, 2000).
U-shaped	Improved operator movements with minimum walking distances and interruptions. Higher machine and operator utilization, and communication between workers. Increased ease of supervision due to lesser number of operators within a compact area. (Pan, 2014; Modrak, & Pandian,2011;Lahmar, & Benjaafar,2002; Scheller, 1995)

Configuration of these intra-cell layout types are illustrated in Figure 2.5-2.15.

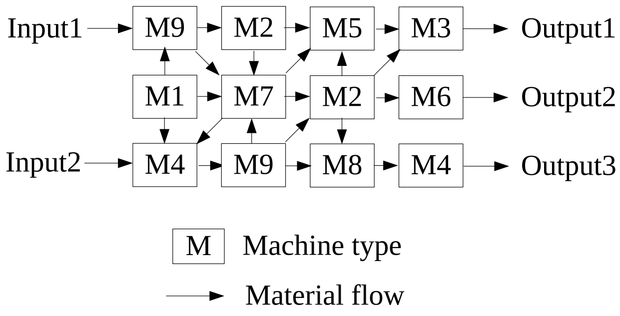

Figure 2.5 – Multi-row layout (Source: Suo, 2012; Morad, 2000)

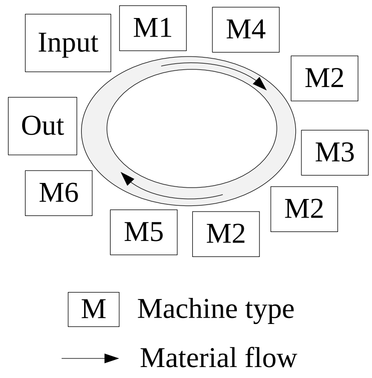

Figure 2.6 – Loop layout (Source: Solimanpur et al., 2005)

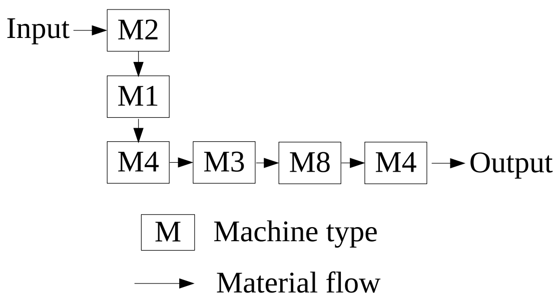

Figure 2.7 – L-Shaped layout

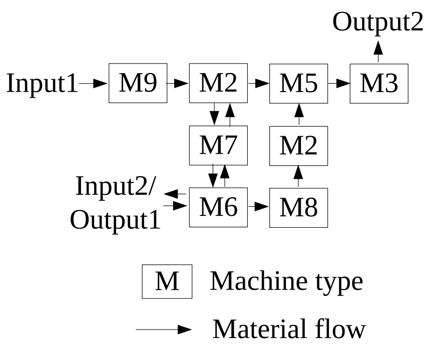

Figure 2.8 – T-Shaped layout

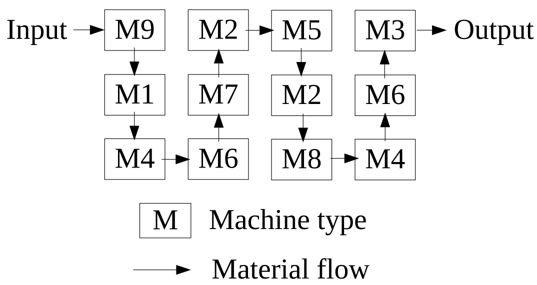

Figure 2.9 – W-Shaped layout

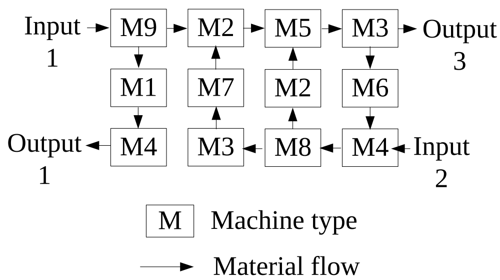

Figure 2.10 – Comb layout

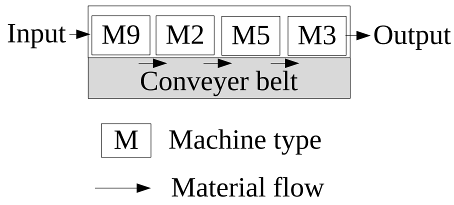

Figure 2.11 – Straight through layout

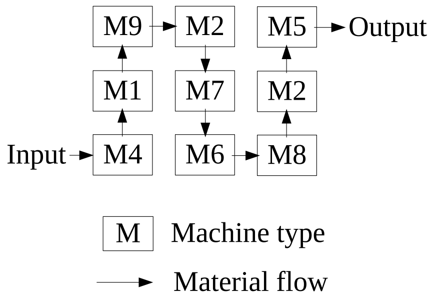

Figure 2.12 – S/Z-shaped layout

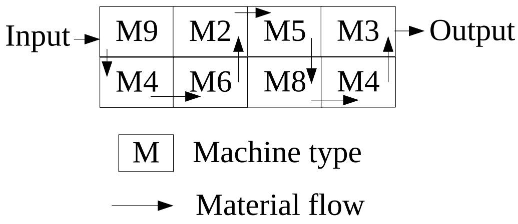

Figure 2.13 – Straight single-line double-row layout

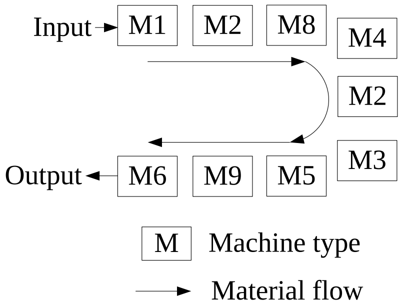

Figure 2.14 – U-shaped layout

2.9.3 Intra-cell layout types used in sewing department

As stated by Lanarolle, & Ratnayake (2014), Oksuz, & Satoglu (2014), Sudarshan, & Rao (2014), Pan (2014), Paneru (2011) and Shumon, Arif-Uz-Zaman, Rahman, & Khulna (2010) straight through layout, straight single-line double-row layout with and without center table, and U-shaped layouts are most commonly used layout types in sewing department. U-shaped layout can balance the workload on different machines with minimum physical interruptions due to layout configuration (Sarkar, 2015; Chase, Jacobs, Aquilano, & Agarwal, 2008). Protzman et al. (2010) stated that operators in U-shaped layout are more productive with less physical fatigue due to reduced walking distances. As a result, both machine and operator utilization in U-shaped layout is higher than that of straight through and straight single-line double-row layout without center table (Malakooti, 2014; Suo 2012). Furthermore, Protzman et al. (2010) and Bukchin, Meller, & Liu (2006) mentioned that many labor-intensive industries replace the straight through and straight single-line double-row layout without center table, with U-shaped layouts since it accounts for increased communication between workers. Having less number of operators within compact area in U-shaped layouts facilitates the ease of supervision (Stevenson, & Sum, 2002). Glock, & Kunz (2005) stated that U-shaped layout with stand up operators is the best approach to improve both operator flexibility and layout flexibility of labor-intensive industries under volatile demand scenarios.

2.10 Group Scheduling (GS)

As stated by Gan, & Gromiha (2010), GS determines the optimal sequence of different and related machine tasks, and the sequence of the cells. Majority of the studies on GS problems are solved in two levels as;

i) Cell loading problem: Determination of sequence of part families and second step identifies the sequence of parts within the families
ii) Cell scheduling problem: Aims to complete all the considered jobs on time while ensuring best utilization of man power and machines.

2.11 Resource allocation

According to Liu et al. (2016), Mejia, & Velasco (2012), Kahraman (2012), Irizarry et al. (2001) and Liu (2006) dynamic cell formation for labor-intensive industries should consider worker flexibility, & assignment/reassignment/cross-training.

Worker flexibility is defined as the ability of a worker to process operations on different machines within the cells or outside the cells (Liu et al., 2016). As mentioned by Hamedi et al. (2012), from the worker flexibility point of view, workers are different from each other in terms of following factors.

"(1) Number of skills

– Single-level flexibility: Workers assigned to cells are assumed to have the same degree of cross-training or multi-functionality. In these systems, every worker is trained to operate a machine in a similar number of departments.

– Multi-level flexibility: Each worker can operate a different number of tasks.

(2) Task proficiencies

– Homogeneous worker flexibility: Workers assigned to a cell or a shop has the same level of proficiency at performing the assigned task.

– Heterogeneous worker flexibility: Workers have a different level of proficiency at performing their assigned tasks."

Mahdavi, Aalaei, et al. (2010) stated that the majority of the researches on dynamic cell formation for labor-intensive industries assume workers are with multi-level and heterogeneous flexibility. Chen, J. C., Chen, C. C., Su, Wu, & Sun (2012) and Bidanda, Ariyawongrat, Needy, Norman, & Tharmmaphornphilas (2005) have analyzed the human related issues in manufacturing cell designs. According to their studies, operator assignment to cells is done based on managers' and supervisors' intuition and the seniority of respective operators. However, these decisions depend on operator skill level and proper skill identification must be considered when assigning operators (Chen et al., 2012).

Since the dynamic cell formation consider multiple periods, the worker skill level may improve or deteriorate due to learning and forgetting effect (Mir, & Rezaeian, 2016). Therefore, the bottleneck operations may shift between periods. As a result, Mir, & Rezaeian (2016) stated that worker reassignment to cells and cross training should be done during different periods.

As stated by Mir, & Rezaeian (2016), Islam (2014), Chang (2013) and Holland (2013), nature of material flows, operator assignment approaches, and assembly line balancing approaches are key essential factors to consider when allocating resources in DCMS design.

2.11.1 Possible material flows in an intra-cell layout

Minimization of intra-cell material handling cost is the main consideration of intra-cell layout design (Mahdavi, Teymourian, Baher, & Kayvanfar, 2013; Chang, 2013). Intra-cell material handling distances depends on the possible machine locations within the U-shaped layout. In addition, operator assignment approach directly influences the intra-cell material handling distances.

Having complicated material flows within the U-shaped layout extends intra-cell material handling distances and may result in reduced overall performance of the layout (Hailemariam, 2010). According to Chang (2013), Hailemariam (2010) and Praveen, Chowdary, & Deshmukh (2006) there are four types of material movement as; forward flows, backtracking, bypassing and cross-flows. An illustration of these four material movements is given in Figure 2.16.

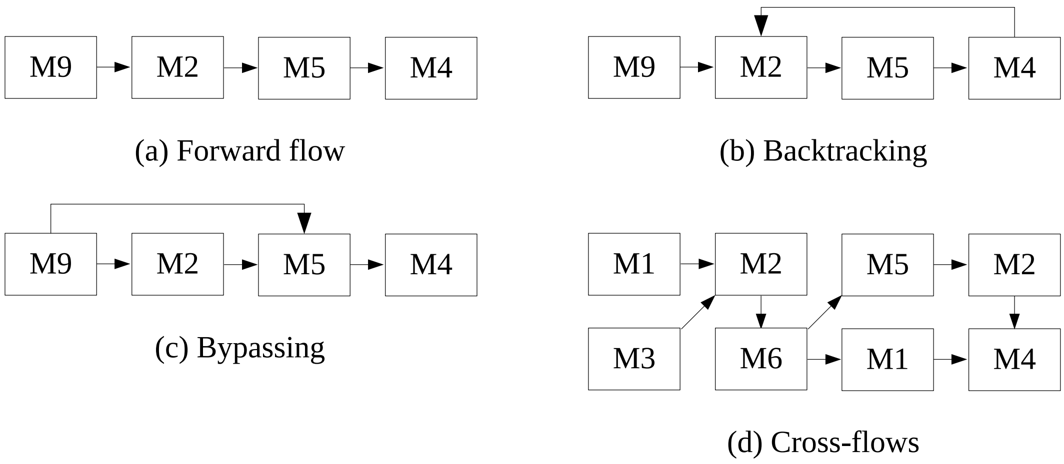

Figure 2.16 – Four types of material movement in intra-cell layout (Source: Hailemariam, 2010; Wu, 1999)

As stated by Chang (2013), Hailemariam (2010), Praveen et al. (2006) and Wu (1999) possible machine arrangement conditions causing these four types of material movement are as follows.

Forward flows: Machines are placed exactly same as the operation sequence. Multiple identical machines are available throughout the material path based on the production requirement.

Backtracking movement: Product re-visits one or more preceding operations. Reason for backtracking is the differences between operation sequence required for particular product and sequence of machine arrangement in single-row type layouts.

Bypassing: Product requires visiting one or more succeeding machines.

Cross-flows: Generally, cross flows occur when table or conveyor belt is used for material handling. In case of U-shaped layouts, the inter-cell part movement is considered as a cross-flow.

Both backtracking and bypassing movements result in longer material movement paths thus increasing material handling cost (Hailemariam, 2010). Tanchoco (1994) stated that the backtracking as least desirable movement when developing an intra-cell layout. Reason for that is the complexity of material handling and increased Work-In-Progress (WIP). Bypassing results in underutilization of the machines and often causes backtracking movements. Mahdavi, Teymourian, et al. (2013), Chang (2013), Chang, Wu, T., & Wu, C. (2013) and Morad (2002) emphasized that primary objective of any intra-cell layout design must be the minimization of backtracking and bypassing movements of the parts within the cells.

2.11.2 Operator assignment approaches in U-shaped cells

Pan (2014), De Carlo, Borgia, & Tucci (2013), De Garmo, Black, & Kohser (2011), Baudin (2007) and Silva, & Alves (2006) suggested three main operating modes for the operator assignment problem in U-shaped cells. They are caravan or rabbit-chase, bucket-brigade and baton-touch.

2.11.2.1 Caravan or rabbit-chase

Figure 2.15 shows an example of caravan or rabbit-chase method.

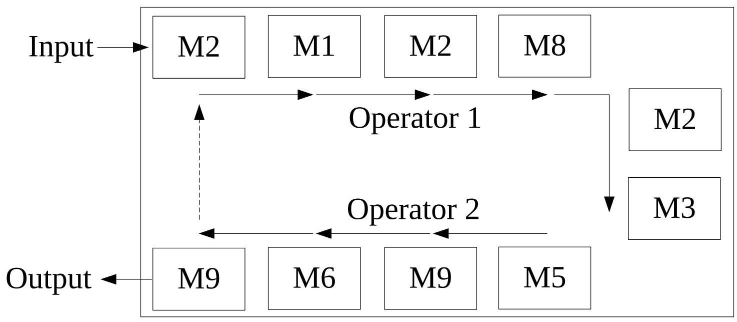

Figure 2.15 – Caravan/ Rabbit-chase method (Source: Baudin, 2007)

Key characteristics of caravan or rabbit-chase method

1. At most two operators are assigned to operate all the machines assigned to U-shaped cell (Ozgurler et al., 2010; Oliveira, & Alves, 2009; Silva, & Alves, 2006)
2. After completing each operation, operator proceeds to next machine in the sequence to perform succeeding operation (Baudin, 2007) and the operators follow each other through entire operation sequence in the cell.
3. Operators must be able to perform all the operations of the cell. If three or more operators are assigned, queue is generated within the cell behind the slowest operator (Ozgurler et al., 2010).

4. Application of rabbit-chase in U-shaped cell must satisfy assignment of highly skilled operators with same work rhythm (Pan, 2014).

2.11.2.2 Bucket-brigade

Key characteristics of bucket-brigade method

1. Operators follow operation sequence in entire cell (Baudin, 2007).
2. Once the last operator finished a unit, he/she takes the next unit from preceding operator and continues processing it (Bartholdi, & Eisenstein, 2005). This is repeated in entire cell until the first operator starts a new unit.
3. A mixture of slow and faster operators can be used. Faster operators are always downstream from the slower ones (Bratcu & Dolgui, 2005). The operators are assigned from slowest to fastest operator along the cell.
4. As stated by De Carlo, Borgia, & Tucci (2013) and De Garmo et al. (2011) this is a self-balancing approach and operators must be able to perform multiple operations.

General design of bucket-brigade method is given in Figure 2.16.

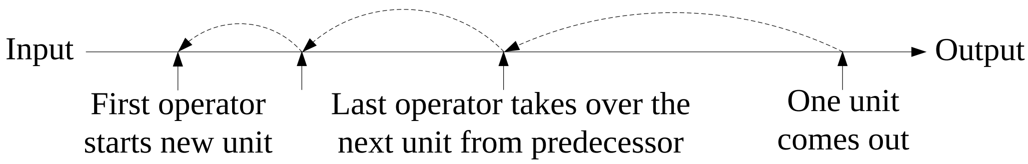

Figure 2.16 – Bucket brigade method (Source: Pan, 2014, Baudin, 2007)

2.11.2.3 Baton-touch

Figure 2.17 shows an example of baton-touch method.

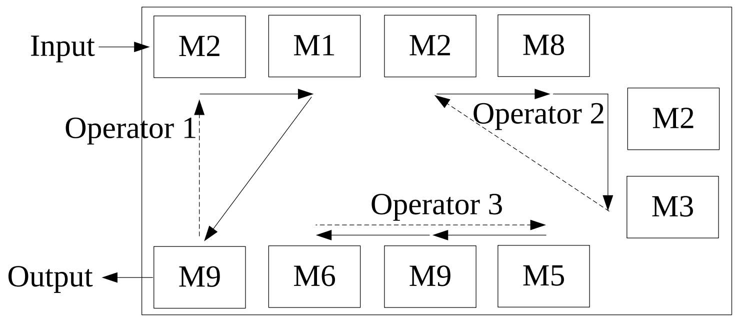

Figure 2.17 – Baton-touch method

Key characteristics of baton-touch method

1. Each operator is assigned to specific number of operations while ensuring minimum walking distances (Black, 2007)
2. Assignment of machines to the operator is done by forming virtual sub-cells on the same side of the cell or across the other side (Palominos, Valdivia, & Quezada, 2015). After completing the operations in assigned sub-cells, operator hand over the pieces to the next operator (Black, & Schroer, 1993).
3. Minimized forgetting effect due to fewer operations/ machine assignment. Furthermore, baton-touch method simplifies the supervision.(Hellman, Lindahl, & Malmberg, 2011; Baudin, 2007)
4. Main advantages: Simplified design steps, ease of operator supervision, requirement of limited skill sets to operate the assigned machines and balanced workload between operators (Hirano, 2009).

Selection of appropriate U-shaped cell operating method depends on skill level of the operators in actual environment. Hellman et al. (2011) mentioned that it is vital to examine operators' skill based data before selecting an operating method.

According to the study on popular U-shaped cell operating modes in apparel assembly stage, Pan (2014) concluded that baton-touch/ sub-cells and bucket-brigade are most suitable to obtain higher output. These results vary with the desired WIP level in cells and number of operators (Pan, 2014). An appropriate method must be used to decide the optimum number of operators per each U-shaped cell (Baudin, 2007). De Garmo et al. (2011) stated that the U-shaped line balancing techniques can determine the operator assignment to machine cells.

2.11.3 U-shaped assembly line balancing problem (UALBP)

As mentioned by Avikal, Jain, Mishra, & Yadav (2013), Chen et al. (2012), Kara, Ozguven, Yalcin, & Atasagun (2011) and Sirovetnukul, & Chutima (2010), UALBP involves in organizing operations into workstations such that each workstation has near to equal workload/time for processing a unit. Operation assignment to workstation should incorporate the precedence diagrams in balancing process. Precedence diagram is generated by using operations sequence of particular product. Each single workstation may contain one or more operations (N. Kriengkorakot, & P.

Kriengkorakot, 2014; Avikal et al.,2013). Unlike the straight-line layouts, the line balancing in U-shaped cells is more complex because operation assignment to workstations can be done in forward, backward or both directions in precedence diagram. It can be formulated as a modification of straight-line balancing problem (Chen et al., 2012; Sirovetnukul, & Chutima, 2010; Kursun, & Kalaoglu, 2009).

According to N. Kriengkorakot, & P. Kriengkorakot (2014), Pachghare, & Dalu (2012) and Sirovetnukul, & Chutima (2010), U-shaped assembly line balancing problems can be classified into four categories as;

UALBP-1: Assigning operations to stations such that the number of stations are minimized for a given fixed cycle time

UALBP-2: Minimize the cycle time for a given number of stations

UALBP-E: Maximize the line efficiency by simultaneously minimizing cycle time and number of stations based on their interrelationship. In UALBP-E, cycle time and number of stations are variables unlike in UALBP-1 and UALBP-2.

UALBP-F: This is to assess the feasibility of the problem to establish whether a feasible line balancing solution is available for a given combination of cycle time and number of stations.

As stated by Guo (2016), Reginato, Anzanello, & Kahmann (2016) and Sharma, Thakar, & Gupta (2014), both straight-line and U-shaped assembly line balancing problems can be further classified into four categories as;

(i) SMD –Single Model Deterministic: This model considers a single product assigned to assembly line with deterministic operation processing times. Minor fluctuations in processing times are allowed due to slight variations in operator skill level.

(ii) SMS – Single Model Stochastic: Major processing time variations due to changes in human behavior, lack of motivation, low equipment reliability, environmental factors are considered in this model. Probability of processing time variations is known.

(iii) MMD - Multi/Mixed Model Deterministic: Deterministic processing times are considered with multiple products being manufactured simultaneously in same assembly line.

(iv) MMS - Multi/ Mixed Model Stochastic: Probabilistic processing times and multiple products in same assembly line are considered in this model. The learning-forgetting effects and associated processing time variations are included in model formulation.

Traditional line balancing approaches used for straight-line layouts such as Largest Candidate Rule (LCR) Method, Kilbridge and Wester Column (KWC) Method and Ranked Positional Weight (RPW) Method are incapable to accommodate multiple inputs that are needed to model U-shaped layouts (Sirovetnukul, & Chutima, 2010). Therefore, UALBP is often solved by using mathematical programming and heuristic algorithms (Oksuz, & Satoglu, 2014; Sudarshan, & Rao, 2014; Sirovetnukul, & Chutima, 2010).

2.12 Modeling of DCMS design problems

2.12.1 Techniques used for DCMS designs

Selection of a suitable DCMS design technique depends on the nature of the industry (Suo, 2012). As mentioned by Roy, & Komma (2014), Arora et al. (2013) and Aljuneidi (2013), most prominently used techniques for DCMS design are as follows.

1. Classification and coding systems
2. Clustering methods: Array-based/ Hierarchical/ Non-hierarchical
3. Graph theoretic approaches
4. Knowledge based and pattern recognition methods
5. Fuzzy clustering and modeling approaches
6. Neural network approaches
7. Mathematical programming approaches
8. Meta-heuristic algorithms

Each of the abovementioned techniques is discussed briefly hereafter.

Characteristics of these methods are given in Table 4.7.

Table 4.7-Characteristics of techniques used for DCMS design

Technique	Characteristics
Classification and coding	Analyzes the design features of products using prototype. Each design feature is coded and product family formation is done manually after analyzing the codes. (Aljuneidi, 2013)
Clustering methods	Done based on Product Flow Analysis (PFA). Main limitations: absence of analytical methodology and great dependability on judgment of the analyst. (Singh, & Rajamani, 2012; Kamrani, Parsaei, & Liles, 1995)
Graph theoretic approaches	Represent machines as vertices of the graphs and the similarity coefficient between machines or products are analyzed by weights of arcs. Drawback: negligence of practical data such as production volumes, alternative production routes, material handling (Suresh, & Kay, 2012)
Knowledge based and pattern recognition methods	Uses artificial intelligence and pattern recognition techniques to generate product families and cell layouts (Suresh, & Kay, 2012; Singh, & Rajamani, 2012)
Fuzzy clustering and modeling approaches	Considers uncertainty of product related data such as processing times, production volume, and machine availability and functionalities (Suresh, & Kay, 2012; Kamrani, Parsaei, & Liles, 1995)
Neural network approaches	Forms the part families based on machine requirements (rows of PMIM are taken as the input) or forming machine cells based on processing capabilities (use columns of PMIM as input) (El-Kebbe, & Danne, 2009)
Mathematical programming approaches	Flexible to incorporate multiple objective functions and constraints to precisely represent the characteristics and requirements of actual production environment.
Meta-heuristic algorithms	Stochastic search algorithms that inspired from mechanisms in natural science (Nourie et al., 2013; Syberfeldt, & Lidberg, 2012). Optimize a problem by iteratively improving candidate solutions of a given objective function.

2.12.2 Solution representation of DCMS designs

According to Mohammadi, & Forghani (2017), Sakhaii et al. (2016), Shafigh, et al. (2017), Deep, & Singh (2015), Zuo, Murray, & Smith (2014) and Rafiee, Rabbani, Rafiei, & Rahimi-Vahed (2011), basic cellular layout formation is done by using 0-1 incidence matrix. 0-1 matrix is generated by using product data and associated machine data. This simplifies the design and computational process of cellular layout formation (Mahdavi, & Mahadevan, 2008). 0-1 entry is used to denote if the product type is required to assemble using particular machine type or not (Deep, & Singh, 2015).

As stated by Mohammadi, & Forghani (2017) and Deep, & Singh (2015), perfect grouping of product families and machines to cells is impossible in practical situations and hence for the real world problems the goal of CFP is to obtain near to ideal solutions. In such situations, two main objectives are considered in cell formation.

They are;

1. To minimize number of zeros inside the block diagonal boxes (Voids)
2. To minimize number of one's outside of the block diagonal boxes (Exceptional elements)

Sakhaii et al. (2016), Kia et al. (2014), Zuo et al. (2014) and Rafiee et al. (2011), have stated that the primary objective of cell formation problem is minimizing total material handling cost and therefore, solution matrix with minimum number of voids and exceptional elements is often selected as the optimal solution for CFP.

2.12.3 Design attributes of CMS

When designing a cell layout, it is essential to identify the resource constraints that determine the capacity and overall performance of the layout (Sakhaii et al., 2016; Hamedi et al., 2012; Egilmez et al., 2012).

As mentioned by Egilmez et al. (2012), manufacturing cells can be either machine-intensive or labour-intensive. Limited involvement of operator on operational output is the key characteristic of machine-intensive cells. Operators load the raw material or half-assembled product to the machine, control quality and unload the output from machine. Conversely, labour-intensive cells require full time attendance of the operators to complete the tasks on machines.

Sewing/assembly department is known as high labor-intensive (Islam, Rahman, & LeHew, 2015; Guo, Ngai, Yang, & Liang, 2015). Semi-automatic sewing machines are used in majority of the apparel manufacturing plants for past few decades (Zhao,

& Yang, 2011). Therefore, operator should continually attend to control the machine to process a particular operation. Level of automation in sewing department is comparatively low due to several reasons as; variable customer demand in product designs, inconsistent fabric properties, complexity of production lines, high investment cost of automated machines, etc (Dissanayaka, Ranasinghe, & Senanayake, 2016; Mittlehauser, 1997). Thus, attention must be paid to the operator related factors when developing a DCMS for labor-intensive industries. There is a significant gap in available literature on DCMS design for labor-intensive industries. Mungwattana (2000) argued that analyzing the design attributes (i.e., assumptions, input data, objective function/s, and constraints) of both static and virtual CMS is beneficial to develop a well-designed DCMS. Therefore, literature review is carried out to identify the design attributes used for mathematical programming models in CMS design problems in general for both labour-intensive, and machine-intensive industries. Summary of the literature review on CMS design attributes are given in Appendix A.

Design attributes used for development of mathematical programming model for particular industry determine its applicability on other industries with similar settings (Williams, 2013). Fulfillment of data quality dimensions is a crucial fact that determines the validity of a developed model (Rudolph, Gottlob, Ian, & Van Harmelen, 2013; Barzdins, & Caplinskas, 2013; Jaakkola, 2008; Weinberg, 2007). If the data sets used for model development do not suffice the quality dimensions, their use may lead to wrong decisions and erroneous conclusions (Barzdins, & Caplinskas, 2013; Weinberg, 2007).

Barzdins, & Caplinskas (2013), Weinberg (2007), Zbicinski (2006) and Roberts (1994) emphasized that the good record of input data is essential to develop and evaluate a layout design for a practical situation.

2.13 Issues related with implementation of DCMS

In case of labor-intensive industries, implementation of a newly introduced layout system on actual production environment does not guarantee accurate depiction on its effectiveness to address the identified problem (Protzman et al., 2016; Johnson, & Wemmerlov, 2004). According to the study carried out by Johnson, & Wemmerlov

(2004), implementation of a new cellular layout system causes five change management issues as; "*lack of champion, lack of operator skills, work force resistance to change, management unwillingness to take risk, and lack of positive experiences with previous cell designs"*. Using trial and error methods to validate the developed layout system after practical implementation results in disruptions to production processes (Sundar, Balaji, & Kumar, 2014; Fraser et al., 2007; Hobbs, 2003). As stated by Protzman et al. (2016), Sundar et al. (2014), and Bryson (2006), operators' resistance to change and disruptions to production processes during implementation are the most prominent issues, which decide the acceptance or rejection of a newly implemented cellular layout system for labor-intensive industries. The extent of these problems is severe if the current layout system used in particular industry is different from new cellular layout system (Johnson, &Wemmerlov, 2004).

2.13.1 Operators' resistance to change

Hyer, & Wemmerlov (2001) discussed the issues faced when a process layout is converted U-shaped cells in actual production environment. According to their study after the initial implementation phase, operators have shifted back to their previous way of workload balancing and walking patterns even though a sophisticated U-shaped cell design is introduced. Due to that reason, Hyer, &Wemmerlov (2001) concluded that implementation of well-designed layout systems for a particular industry might not guarantee noticeable reduction of the addressed problem. Significant level of re-education to the operators and supervisors is needed to witness an improvement in U-shaped cells (Protzman et al., 2010). This situation is severe in departments with high labor involvement (Sundar et al., 2014; Kovacheva, 2010). Reason for that is employee's resistance to change into new systems.

Shifting from one layout type to another makes the affected operators to go through stages of psychological change (Protzman et al., 2016). This is known as change cycle and it consists of four generic stages; resistance, denial, acceptance and commitment (Palmer, 2004). The change cycle is often referred as "The four phase model of change" and it can be represented as given in Figure 2.21.

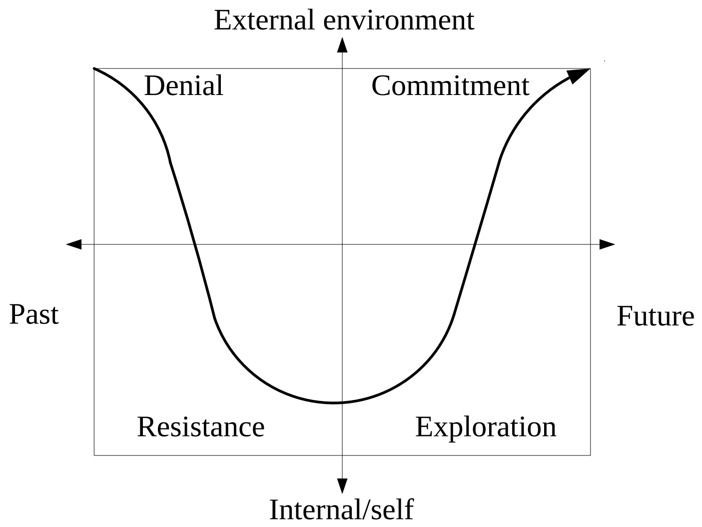

Figure 2.21 – The four Phase model of change (Source: Protzman et al., 2016; Bryson, 2006; Palmer, 2004)

As mentioned by Bryson (2006), it is unlikely that the operators will progress through these stages simultaneously. Operators may go back and forth of these four phases before stabilizing and adopting the change (Protzman et al., 2016).

Chakravorty, & Hales (2008) stated that due to operators' resistance to change and technical problems, newly implemented manufacturing cells go through three evolutionary stages before they begin to perform at optimal level. Technical problems arise due to inappropriate managerial decisions regarding resources required for layouts and level of cooperation of supporting departments. These evolutionary stages should be properly managed in order to achieve the true benefits of cell implementation efforts (Chakravorty, & Hales, 2008).

- First stage – both human and technical problems exist; Human problems dominate at this stage and require conflict management skills to resolve them.
- Second stage – human problems improve, and technical problems persist; requiring formal problem-solving methods to resolve.
- Third stage – both human and technical problems improve, and cells begin to perform at the optimal level.

As stated by Sundar et al. (2014) and Bovey, & Hede (2001), these three stages greatly depend on state of the relationship between operators and management, level of re-education, intervention of supportive departments and fluctuations of operator pool, etc.

2.13.2 Disruptions to the production processes

If the existing layout system is different from a new cellular layout design, physical implementation of new cellular layout may disrupt the current production processes due to initial arrangement of cells (Sundar et al., 2014; Johnson, & Wemmerlov, 2004). In addition, certain amount of period is needed to train and educate the operators, supervisors, mechanics, and managers of the production department (Bovey, & Hede, 2001). As mentioned by Sundar et al. (2014), and Bovey, & Hede (2001), this phase can be extended depending on the change cycle. Fraser et al. (2007) conducted a study on physical implementation of new cell layouts. According to their study, a number of trials and adjustments must be done to fine-tune the overall operations of cells before completely adapt to new cellular layout system. Fraser et al. (2007) and Hobbs (2003) stated that disruptions to the production flow could be minimized by changing the layout during low-demand periods and when the plant is temporarily closed. As a result, the physical implementation of their new cells needed considerable amount of time ranging from six to eight months. This is the time taken to coordinate material handlers, production planning, employee training and series of meetings with involved employees. Time for four phases of psychological change is not considered in their study.

Bayram, & Sahin (2016), Sundar et al. (2014) and Sharma, Phanden, & Singhal (2013) emphasized that most suitable way to validate a newly introduced layout system for labor-intensive industries is by virtually modeling the developed layouts and comparing results with current state.

2.14 Use of software packages for solving and validating mathematical models

As stated by Bayram, & Sahin (2016), Elbenani, & Ferland (2012), Leon et al. (2013), Tunnukij, & Hicks (2009), and Goncalves, & Resende (2004) manual computation to obtain solutions in CFP may produce erroneous results due to solution complexity. Hence, the use of computer software packages for validation of the layout models before physical implementation is the most popular approach in recent studies on DCMS (Bayram, & Sahin, 2016; Masmoudi, & Hachicha, 2013).

Sharma, Phanden, & Singhal (2013) emphasized that it is advantageous to use software for effective evaluation of cell formation models for highly volatile demand scenarios. Main benefit of using software packages is reduced redesign costs by verifying layout feasibility and desired improvements of selected performance measures early in the design process (Bangsow, 2010). In addition, the possible errors can be identified and modifications to the cell formation model can be done before installing it on production floor (Bayram, & Sahin, 2016; Heilala, 1999).

The actual improvements resulted from newly implemented cellular layout systems may become unnoticeable due to various issues discussed in Section 2.13. True benefits of a cellular layout system when compared to current layout system are visible only if both layout systems are evaluated while operating in a common state without such unpredictable issues (Bayram, & Sahin, 2016). Using software packages for evaluating layouts is advantageous in this situation.

As mentioned by Hosseinpour, & Hajihosseini (2009), majority of the firms prefer commercially available software packages that are specifically designed for particular purposes rather than developing a program using general-purpose programming languages such as C++, Java, etc. Reason for that is it reduces the time taken for developing a program code for specific purpose. According to Agrawal, Bhardwaj, Kumar, & Sharma (2015) software packages for cellular layout problems can be divided in to two categories as; software for simulation and mathematical programming model based problems.

Brenner (2012) argued that using simulation tools might give misleading results to mathematical programming models with two or more objective functions. Even the smallest objective functions for cell formation problem generate large number of possible alternative solutions. Simulation models do not guarantee near-optimal or optimal solutions whilst the simulation model development for such systems is time consuming and complex (Vallabhaneni, 2013; Brenner, 2012).

2.14.1 Existing software packages to solve and validate mathematical programming model based problems

LINGO, CPLEX and GAMS are the most commonly used software packages for mathematical programming based problems (Agrawal et al., 2015; Esmailnezhad, Fattahi, & Kheirkhah, 2015; Anbumalar, & Raja-Chandra-Sekar, 2015; Azadeh, Moghaddam, Nazari–Doust, & Jalalvand, 2015; Kasimbeyli, Dincer, & Ozpeynirci, 2010). These software packages generate optimal solutions with reasonable time with high level of accuracy for mathematical programming based problems.

According to Agrawal et al. (2015), Esmailnezhad et al. (2015) and Depince, Chablat, &Woelk (2007), LINGO software is most frequently used for solving mathematical programming model based problems in cellular layouts. It allows the users to program their developed mathematical models and algorithms by using multiple software features to obtain optimal solutions. User friendliness is the key advantage of using LINGO software. In addition, Agrawal et al. (2015) stated that ability to solve mathematical programming based models with two or more objective functions with minimum run time is one of the main reasons for using it for cellular layout designs. Unlike the generalized programming languages, modeling language used in LINGO software is specifically designed for optimization of mathematical programming models. It is possible to either use the in-built functions provided in software or generate a program by using the programming language of LINGO software (Yan, Jiang, & Eynard, 2008; Cunningham, & Schrage, 2004).

CHAPTER 3: METHODOLOGY

3.1 Introduction

Methodology followed in the development of production layout planning system for fast fashion apparels is discussed in this chapter. Findings from literature review, questionnaires, and case studies were used to develop, evaluate and validate the developed system.

3.2 Literature review

Comprehensive analysis of available literature was done throughout the research. Key areas covered in the literature review are listed below.

- Introduction to fast fashion apparels and its key characteristics
- Frequent problems faced by ready-made apparel manufacturers in terms of fast fashion apparels
- Influence of fast fashion apparel industry on Sri Lankan ready-made apparel manufacturers
- Layout flexibility and its relationship with manufacturing flexibility
- Characteristics of existing layout types
- Introduction to DCMS design, stages of designing a DCMS, and modeling of DCMS design problems
- Validation of layout system designs for labor-intensive industries
- Use of software packages for solving and validating mathematical models

3.3 Questionnaire 1 (QE 1)

Questionnaire 1 was developed based on the findings from literature review and the discussions had with industry resource personnel. Results were used to justify the research problem, to select an appropriate layout type for fast fashion apparel assembly stage, and to select the product category with highest demand for fast fashion orders.

3.4 Case study on a factory

An intimate apparel manufacturing factory was selected to carry out an in-depth analysis of the factors related with layouts used for fast fashion apparel production stage. It is referred as Factory 1. Changeover procedure, and features of the existing layout design were observed through the case study on Factory 1.

Based on case study and literature review, mathematical programming approach was selected for the development of production layout planning system. Furthermore, observations of Factory 1 and literature review were used to select an appropriate intra-cell layout type and operator assignment approach.

Case study on Factory 1 was used for the initial identification of design attributes to include in mathematical models and algorithm of the developed system. A questionnaire (referred as QE 2) was conducted to generalize and prioritize the design attributes to include in the developed system.

3.5 Development of production layout planning system for fast fashion apparels

Two phases were considered for the mathematical model development of production layout planning system. They are; Phase 1: Dynamic cell formation (Generates part families, machine groups simultaneously), and Phase 2: Intra-cell layout and operator assignment to operations (Determines the physical arrangement of machines within the dynamic cells whilst ensuring balanced workload between operators).

Thereafter, an algorithm was developed to combine these two phases with the purpose of obtaining simultaneous solution approach with enhanced solution accuracy.

Manual computation of the solutions for DCMS may not guarantee accurate results due to problem complexity. Therefore, the developed system was coded using a computer software package, LINGO 15.0, to generate optimal layout solutions.

3.6 Validation of the developed production layout planning system

Validation of the developed algorithm was done based on the data collected on fast fashion orders from five different intimate apparel manufacturing factories. Costs saving percentages of optimal solutions were calculated with respect to the current layout systems used in selected factories. Validity of the developed system was statistically tested.

CHAPTER 4: JUSTIFICATION OF THE RESEARCH PROBLEM AND SELECTION OF AN APPROPRIATE LAYOUT TYPE FOR FAST FASHION APPARELS

4.1 Introduction to the QE 1 and result analysis

As stated by Mo (2015), Caro, & Martinez-de-Albeniz (2014) and Cachon, & Swinney (2011), outsourced order quantities of fast fashion apparels typically varies from 50 to 4000 pieces per order. In addition, the initial discussions with industry personnel showed that the typical production lead time of fast fashion orders is varying from one day to two weeks depending on customer requirements. Preliminary questionnaire survey was carried out to identify the companies that are currently manufacturing export apparel orders in these ranges of order quantity and production lead-time. According to EDB, Sri Lanka (2014), there are about 250 ready-made apparel manufacturing companies in Sri Lankan apparel export industry. Preliminary questionnaire was conducted among 223 companies. Out of this, 91 companies have stated that it is impossible to response due to non-disclosure agreements made with retailers. Results of preliminary questionnaire showed that out of the responded 132 companies, 124 companies are currently manufacturing fast fashion apparels. QE 1 was distributed among these 124 companies. Number of received responses for the QE 1 was 118 with response rate of 95.16%.

QE 1 was developed based on the findings from literature review and discussions had with industry personnel. It is given in Appendix B.

QE 1 consisted of five-point Likert-type questions and close-end questions. These questions are referred as QE 1.1, QE 1.2, etc. It was advised to select the options of QE 1 based on only the fast fashion orders.

Objectives of the questions given in QE 1 are as follows.

QE 1.1: To identify the machine types being used for majority of the operations in production department. Given options are; Fully automatic machines, Semi-automatic machines

QE 1.2: To identify the problems that are contributing to increased changeover costs of fast fashion orders in production department based on their frequency of occurrence. Given options are; Increased machine movement between different locations, Increased machine setting and adjustment, Increased operator training time, Increased defect rate.

QE 1.3: To identify the factors to include in layout design for fast fashion orders based on their importance. Given options are; Reduce total machine set-up time, Minimize machine movements, Reduce material handling cost, Reduce WIP, Reduce material handling complexity, Increase the ease of supervision.

QE 1.4: To select the product category/categories with highest demand for fast fashion orders. Given options are; Intimate apparels, Casual wear, Sports wear, Swim wear, Bridal wear, Children's wear, Work wear.

QE 1.2, and QE 1.3 are Likert-type questions to rate the frequency and importance of the given options, respectively. Rating scales used for these two questions are as follows.

Rating scale of QE 1.2: 5 - Highly frequent, 1 - Least frequent

Rating scale of QE 1.3: 5 - Highly important, 1 - Least important

Procedure for result analysis of the Likert-type questions is given in Section 4.1.1. Close-end questions are analyzed based on the percentage of responses.

4.1.1 Hypothesis testing of Likert-type questions in QE 1

Hypothesis testing of Likert-type questions can perform by using either z-test or t-test (Quirk, & Palmer-Schuyler, 2016; Singh, 2007; Cummins, 1997). As stated by Babin, & Zikmund (2015) and Fellows, & Liu (2015), z-test is more accurate if the sample size for the tested questions is greater than 30 with a known standard deviation for population. According to Section 4.1, number of responses received for QE 1 is 118 and thus it is the sample size for hypothesis testing. Standard deviation of population is unknown for the Likert-type questions in QE 1. Therefore, one-sample t-test is used for hypothesis testing of Likert-type questions in QE 1.

Hypothesis for QE 1.2 is given below.

Null hypothesis $H_o: \mu < 4;\ i.e., problem\ is\ not\ highly\ frequent$

Alternative hypothesis $H_a: \mu \geq 4;\ i.e., problem\ is\ highly\ frequent$

Similarly, hypothesis for QE 1.3 is as follows.

Null hypothesis $H_o: \mu < 4;\ i.e., factor\ is\ not\ important$

Alternative hypothesis $H_a: \mu \geq 4;\ i.e., factor\ is\ important$

Degree of freedom for QE 1.2 and QE 1.3 is 117, hypothesis mean is 4 and significance level is 95%. Null hypothesis is rejected if the resultant p-value is less than 0.05.

4.2 Results analysis of QE 1

4.2.1 Justification of the research problem

According to the initial discussions had with industry personnel and studies done by Kincade, & Kanakadurga (2013), So (2013), Kentli et al. (2013) and Doeringer & Crean (2006), increased changeover costs due to the use of inappropriate production layout planning systems in production department is the main problem related with fast fashion orders. It is identified as the research problem (Section 1.4). However, there exists a possibility that the intensity of this problem may vary between different factories. Hence, QE 1.1 and QE 1.2 were used to justify the identified research problem. Results of QE 1.1 and QE 1.2 are analyzed in Section 4.2.1.1 and 4.2.1.2, respectively. Summary of the results and research problem justification is given in Section 4.2.1.3.

4.2.1.1 Level of operator involvement in production department

According to Zhao, & Yang (2011) and Mittlehauser (1997), machines used in apparel production department can be categorized in to two types based on the level of operator intervention to complete an operation. They are fully automatic, and semi-automatic machines.

In fully automatic machines, the operators load the raw material or half-assembled product to the machine, monitor the quality and unload output from machine. Machines can be pre-programmed to operate automatically with little intervention of the operator. Examples for such machines are button-hole, and welt pocket sewing machines (Zhao, & Yang, 2011). Operator should continually attend to control the machine to process a particular operation on semi-automatic machines. Other than these two machine types, there are manual operations that require minimum tools to complete an operation or can be done without any tool. Examples for such operations are; marking required points, trimming excess fabric edges and removing the excessive threads.

Results of QE 1.1 showed that 97.62% of the Sri Lankan fast fashion apparel manufacturing factories use semi-automatic machines in the production department. Hence, it is possible to conclude that there exists a high labor involvement in production department of Sri Lankan apparel manufacturing factories and thereby it is labor-intensive.

4.2.1.2 Frequent problems related with increased changeover costs of fast fashion orders

Kentli et al. (2013), Kincade, & Kanakadurga (2013), Karim (2013) and De Carlo et al. (2013) identified two main problems contributing to comparatively higher changeover cost of fast fashion apparels than that of mass production in the production department. They are; increased machine movement between different locations, and increased machine setting and adjustment. In addition, Kentli et al. (2013) stated that increased operator training time, and increased defect rate are problems related with changeover costs in fast fashion apparel production stage.

QE 1.2 was used to analyze whether these problems are highly frequent or not in production department when manufacturing fast fashion apparels. In addition to the options given in QE 1.2, some of the respondents have stated that raw material delays, poor coordination with supporting departments, insufficient number of operators, and machine breakdowns are some problems that affect the changeover costs in production department.

Table 4.1 shows summary of the hypothesis test results using t-test for each of the problems given in QE 1.2.

Table 4.1 – Summary of the t-test results of the QE 1.2

Problems	Mean	Standard deviation	t-value	p-value
Increased machine movement between different locations	4.593	0.695	9.275	0.000
Increased machine setting and adjustment	4.619	0.667	10.096	0.000
Increased operator training time	3.125	1.126	-1.698	0.070
Increased defect rate	3.200	1.398	-1.809	0.052
Raw material delays	3.273	1.555	-1.551	0.076
Poor coordination with supporting departments	2.400	1.502	-1.547	0.072
Insufficient number of operators	2.467	1.506	-1.372	0.096
Machine breakdowns	2.412	1.460	-1.661	0.058

As mentioned by Caro, & Martinez-de-Albeniz (2014) and Cachon, & Swinney (2011), fast fashion orders have minor to major style variations between the orders of same or different product mix. Therefore, the machine requirement and required operations to complete a particular fast fashion order may be more or less similar to other orders. As a result, each introduction of fast fashion order to the production department may require minor to major changes in machine layout. Changing of an existing machine layout includes rearrangement of the machines between different locations and, changing machine settings and adjustments (Sakhaii et al., 2016; Qudeiri et al., 2015). According to the t-test results of QE 1.2 (Table 4.1), the null hypothesis (i.e., problem is not frequent) was rejected for increased machine movement between different locations, and increased machine setting and adjustment, with 95% confidence level. Kentli et al. (2013), Karim (2013) and De Carlo et al. (2013) stated that these two problems are the key contributors of increased changeover costs in production department in terms of fast fashion orders. Use of an inappropriate machine layout is the main reason for these problems (Forghani et al., 2013). Neumann, & Fogliatto (2013) emphasized that the implementation of appropriate machine layouts drastically reduces the number of layout changes and increased changeover costs.

Table 4.1 shows that null hypothesis for other problems was failed to reject with 95% confidence level. Hence, these problems being frequent are not statistically significant.

4.2.1.3 Summary of the results of QE 1.1 and QE 1.2

Manufacturing processes with high labor involvement results in increased changeover time than that of automated processes (Zhao, & Yang, 2011). Michelini, & Razzoli (2013) and Ahmad et al. (2012) stated that in case of fast fashion orders, labor-intensive apparel manufacturing factories must pay more attention to reduce changeover costs in production department. As per the results of QE 1.1, majority of the factories (97.62%) use semi-automatic machines in production department for fast fashion assembly operations and thereby it is highly labor-intensive. Therefore, selecting the production department for changeover costs reduction of fast fashion apparels can be justified.

According to the hypothesis test results of QE 1.2, highly frequent problems contributing to the increased changeover costs of fast fashion apparels in production department are;

1. Increased machine movement between different locations
2. Increased machine setting and adjustment

As per the study done by Neumann, & Fogliatto (2013), these two problems can be minimized by using a suitable production layout planning system. Therefore, altogether it is possible to conclude that the increased changeover costs of fast fashion orders due to the use of inappropriate production layout planning system in production department is major problem faced by Sri Lankan ready-made apparel manufacturers. Hence, the research problem can be justified based on the results of QE 1.1 and QE 1.2.

4.2.2 Selection of an appropriate layout type

Development of production layout planning system for fast fashion apparels was done by selecting an appropriate layout type as the basis. QE 1.3 was focused on identifying the factors to include in production layout planning system for fast fashion orders. Result analysis of QE 1.3 was used to determine the layout type with high layout flexibility that is suitable for fast fashion apparel production. Layout selection was done in four steps as follows.

1. Determining the factors to include in production layout planning system for fast fashion orders – These factors were obtained from literature review and their importance was analyzed through results of QE 1.3.
2. Identifying the relationship between factors to improve flexibility in layout design and layout flexibility parameters based on literature review
3. Analysis of the layout flexibility of available layout types to determine their appropriateness for fast fashion apparel production
4. Selection of a layout type with high flexibility for fast fashion apparel production

4.2.2.1 Determining the factors to include in production layout planning system

De Carlo et al. (2013) and Yang, & Peters (1998) emphasized that improving layout flexibility is vital to achieve reduced changeover costs under volatile demand scenarios. Layout flexibility is defined as the ability of a particular layout to withstand multiple demand scenarios with minimum disturbances to manufacturing process whilst maintaining low operating cost (Raman et al., 2009). Layout flexibility has a direct negative relationship with changeover time (Neumann, & Fogliatto, 2013; Egilmez et al., 2012; Raman et al., 2009). In other words, high layout flexibility results in reduced changeover costs and vice versa. Therefore, the identified research problem can be addressed by developing a production layout planning system with improved flexibility.

Islam, Mohiuddin et al. (2014), Lenin, Siva Kumar, Islam, & Ravindran (2013), Khan, & Tidke (2013), Moonis, Chung, & Hinde (2003) and Wang, & Kusiak (2000) have suggested several factors that should be included in a layout design to improve flexibility. They are; Reduce total machine set-up time, Minimize machine movements, Reduce material handling cost, Reduce WIP, Reduce material handling complexity, and Increase the ease of supervision.

Results of QE 1.3 were used to determine the importance of these factors in terms of fast fashion orders. Table 4.2 shows summary of the hypothesis test results using t-test for each of the factors given in QE 1.3.

Table 4.2 – Summary of the t-test results of the QE 1.3

Factor	Mean	Standard deviation	t-value	p-value
Reduce total machine set-up time	4.686	0.748	9.974	0.000
Minimize machine movements	4.712	0.455	17.002	0.000
Reduce material handling complexity	4.102	0.478	2.309	0.011
Reduce WIP	4.288	0.752	4.161	0.000
Reduce material handling cost	4.348	0.696	5.419	0.000
Increase the ease of supervision	4.153	0.699	2.369	0.009

Table 4.2 shows that null hypothesis (i.e., factor is not important) for all the factors was rejected with 95% confidence level. Hence it is possible to determine that these factors are highly important and must be included in the production layout planning system design for fast fashion orders.

4.2.2.2 Relationship between the identified factors and layout flexibility parameters

As mentioned by Neumann, & Fogliatto (2013), Gupta, & Lambert (2007), Kachru (2009), Kulturel-Konak (2007) and Leondes (2003), layout flexibility can be increased by using five parameters (Section 2.5.1) as; Routing flexibility, Material handling flexibility, Robustness, Ease of re-configuration, and Level of distribution of machine duplicates throughout the plant floor.

Shafigh et al. (2017), Islam, Mohiuddin et al. (2014), Neumann, & Fogliatto (2013), and Joseph, & Sridharan (2011) stated that factors given in Section 4.2.2.1 (Table 4.2) can be directly related to the layout flexibility parameters as given in Table 4.3.

Table 4.3 – Relationship between factors to include in production layout planning system design and layout flexibility parameters

Factors to include in production layout planning system design	**Related layout flexibility parameter**
Reduce total machine set-up time	Robustness, Ease of re-configuration, Routing flexibility
Minimize machine movements	
Reduce material handling cost	Material handling flexibility
Reduce WIP	
Reduce material handling complexity	
Increase the ease of supervision	Material handling flexibility, Robustness, Ease of re-configuration, Level of distribution of machine duplicates throughout the plant floor

As mentioned by Shafigh et al. (2017) and Neumann, & Fogliatto (2013), due to the relationships given in Table 4.3, presence of a particular layout flexibility parameter in a layout type fulfills its respective factors to include in layout design to improve flexibility. As an example, improved material handling flexibility in a particular layout type implies that its design has considered reducing material handling cost, WIP and material handling complexity (Neumann, & Fogliatto, 2013). Result analysis of QE 1.3 in Section 4.2.2.1 shows that it is highly important to include all the mentioned factors in Table 4.2 when designing production layout planning system for fast fashion apparels. Since these factors are directly related with layout flexibility parameters, available layout types are analyzed based on each of the parameter to determine their flexibility.

4.2.2.3 Analysis of the layout flexibility of available layout types

According to Kumar, & Moulick (2016), Niakan (2015), and Nomden (2011), the existing layout types are; Process layout, Product layout, Cellular layout (Static cellular layout, Dynamic cell layout, Virtual cells on distributed layout), and Fractal layout.

These layout types are analyzed based on the layout flexibility parameters given in Section 4.2.2.2.

Layout flexibility of available layout types with respect to five parameters can be summarized as given in Table 4.4.

Table 4.4 – Summary of the layout flexibility evaluation of available layout types

Layout type	**Layout flexibility parameter**				
	Routing flexibility	Material handling flexibility	Robustness	Ease of reconfiguration	Level of distribution of machine duplicates throughout the plant
Process	High	Low	High	Not applicable	Low
Product	Low	High	Low	Low	Low
Static cellular	Low	Low	High	Not applicable	Low
Dynamic cellular	High	High	High	High	High
Virtual cells on distributed	High	High	High	High	High
Fractal	High	High	High	Not applicable	High

4.2.2.4 Selection of a layout type with high flexibility for fast fashion apparel production

According to Table 4.4, virtual cells on distributed layout, fractal layout, and dynamic cellular layout have the highest level of layout flexibility. As stated by Neumann, & Fogliatto (2013), Egilmez et al. (2012) and Raman et al. (2009) layout type with higher flexibility is beneficial to achieve reduced changeover times. Michelini, & Razzoli (2013), Ahmad et al. (2012) and Zhao, & Yang (2011) argued that selection of a layout type greatly depends on the extent of labor involvement in production processes. Hence, both factors, i.e., layout flexibility and labor-intensiveness, are considered when selecting an appropriate layout type for fast fashion apparel production department.

4.2.2.4.1 Analysis of the suitability of virtual cells on distributed layout, fractal layout and dynamic cellular layout for fast fashion apparel production

Table 4.6 – Features of virtual cells, dynamic cells, and fractal layout in terms of labor-intensiveness

Layout type	Features related with labor-intensiveness
Virtual cells	Complexity of coordination and limited specialization of workers and machines (Modrak, & Pandian, 2011; Nomden, & Slomp, 2003). Frequent re-grouping of workers at each product change result in complicated incentive schemes, difficulty in visual management, operator unrest and de-motivation (Aljuneidi, 2013; Koufteros, Vonderembse, & Doll, 1998).
Fractal	Require additional supervision due to the large number of machines and employees operating under one cell (Ang et al., 2014). Requires major alterations to plant floor structure and high investment cost for additional resources (Silva, 2010).
Dynamic cellular	Facilitates autonomous teams to complete manufacturing of a product. Improves team building, learning and problem solving. As per the studies done by Bayram, & Sahin (2016), Ulutas, & Islier (2015), Dalfard (2013), Ahkioon et al. (2009) and Asgharpour, & Javadian (2002), dynamic cellular layouts showed significant minimization of changeover times in labor-intensive industries with volatile demand conditions

4.2.2.4.2 Summary of the analysis of virtual cells on distributed layout, fractal cells layout and dynamic cellular layout for fast fashion apparel production

Based on the analysis in Section 4.2.2.4.1, dynamic cellular layout type was identified as the most appropriate for assembling fast fashion orders in production department. Type of layout being used provides the basis for manufacturing systems (Egilmez et al., 2012). Using dynamic cellular layouts as the basis for layout planning of a production environment is referred as DCMS design (Bayram, & Sahin, 2016; Mahdhavi et al., 2013; Rafiei, & Ghodsi, 2013). Consequently, DCMS is used as the foundation for the developed production layout planning system for fast fashion apparels.

As mentioned by Aljuneidi (2013), Khan, & Tidke (2013) and Bajic (2001) DCMS design depends on the nature of particular industry. Even within a same industry, there can be variations in product design, product demand, operation data and machine types used. Similarly, fast fashion apparel industry consists of different product categories with different demand scenarios (Caro, & Martinez-de-Albeniz, 2014). Designing of a DCMS for multiple different product categories leads to increased solution complexity and may not give optimum layout type for each product category (Rafiei, & Ghodsi, 2013). Therefore, it is essential to consider individual characteristics of product categories and alter the layout development stage accordingly. Hence, a single product category was selected to design the DCMS for production department of fast fashion apparels. It was done by identifying the product category with highest demand for fast fashion orders.

4.2.2.5 Identified product category for the development of DCMS for production department

As stated in Section 4.1, order quantities of fast fashion orders typically vary from 50 to 4000 pieces per order. Hence, fast fashion orders can be identified based on respective order quantities. QE 1.4 was used to identify the product category with highest demand for fast fashion orders based on respondents' experience.

EDB, Sri Lanka (2014) stated that there are seven product categories under ready-made apparel exports as; Intimate apparels, Casual wear, Sportswear, Workwear, Swimwear, Bridal wear, and Children's wear. Selection of the product category for the developed system is done based on the percentage of responses for each category. Product categories are arranged in descending order of the percentage of responses as shown in Table 4.6.

Table 4.7 – Percentage of responses on fast fashion apparel product categories

Product category	Percentage of responses
Intimate apparels	45.76%
Casual wear	18.64%
Sportswear	10.17%
Swimwear	9.32%
Bridal wear	8.47%
Children's wear	7.63%
Workwear	0.00%

Table 4.7 shows that the intimate apparels category is with the highest percentage of responses. Hence, it was selected as the product category for case studies, development of production layout planning system, and validation of the developed system.

4.3 Summary of the result analysis of QE 1

Result analysis of QE 1 can be summarized as follows.

1. Majority of the ready-made apparel manufacturers use semi-automatic machines to assemble fast fashion apparels in production department. Hence, production department can be considered as labor-intensive.
2. In case of fast fashion apparels, increased machine movement between different locations, and increased machine setting and adjustment are highly frequent problems that contribute to increased changeover costs in production department.
3. Dynamic cellular layout is the most appropriate layout type for the development of production layout planning system for fast fashion orders.
4. Intimate apparel product category has higher demand for fast fashion apparel orders compared to other categories. Hence, it was considered for the subsequent stages of this research.

CHAPTER 5: CASE STUDY ON A FACTORY, SELECTION OF DCMS DESIGN APPROACH, AND IDENTIFICATION OF DESIGN ATTRIBUTES FOR DCMS DESIGN

5.1 Introduction

Initial case study was carried out in an intimate apparel manufacturing factory and it is referred as Factory 1. Factory 1 manufactures women's intimate fast fashion apparel products, which comprise of women's bras and briefs. Observations in production department related with changeover procedure and machine layouts of fast fashion orders are discussed in this chapter.

Based on case study of Factory 1 and literature review, mathematical programming approach was selected for the developed DCMS based production layout planning system for fast fashion apparels. Furthermore, worker-oriented single U-shaped layout was selected as the basis for the developed of mathematical model for intra-cell layout. Baton-touch operating mode with SMD UALBP-1 category was identified as the appropriate line balancing approach of intra-cell layout.

A questionnaire (QE 2) was conducted to select the design attributes that are included in the developed system.

5.2 Observations on changeover process and layouts used in production department of Factory 1

5.2.1 Sample selection for the observations in Factory 1

In Factory 1, there are 32 assembly lines excluding the training lines. Using a single product as the sample of dynamic cellular layout development reduces the solution complexity (Khan, & Tidke, 2013). According to the Master Production Schedule (MPS) for past one year period, fast fashion order quantities of women's briefs products are higher than that of women's bra products in Factory 1. Hence, briefs products were selected for the observations.

5.2.2 Production strategy and respective production requirements of fast fashion orders in Factory 1

According to Dickersbach (2009), production strategies are divided in to three main categories as Make-To-Order (MTO), Assemble-To-Order (ATO), and Make-To-

Stock (MTS). Factory 1 follows MTO production strategy for manufacturing fast fashion apparel products. Product designs manufactured within Factory 1 are adhered to the specifications provided by customer. After the trial production, minor alterations to the product designs are done (if needed) based on customer approval. According to the planning department, the order details of each of the fast fashion orders are known in advance for upcoming 1 to 2 months period.

As stated by Mungwattana (2000), four basic types of production requirement are considered in GT based cellular layout designs as; static, dynamic, stochastic, and deterministic. Production requirement in any industry can be represented by using one or more of these types. Fast fashion apparel products are characterized with dynamic production requirement. Since the details of upcoming orders are known in advance with certainty, the production requirement of fast fashion orders received for briefs products in Factory 1 can be categorized as dynamic-deterministic.

5.2.3 Planning process of fast fashion orders in Factory 1

Parent company of Factory 1 uses a centralized facility to control the production processes of its subsidiary factories. Factory 1 receives details of upcoming orders through this facility. Prior to order confirmation, centralized facility communicates with relevant factories operating under the company and checks the available capacities and capability of producing the ordered product designs. The centralized facility prepares operation breakdowns with Standard Minute Values (SMV). Thereafter, order details and garment construction details are sent to the merchandising department of the relevant factory, which are subsequently delivered to the planning, production and work-study departments. Based on the requirement, minor amendments to the received SMVs are done at the product development stage in Factory 1 and the resultant SMVs are referred as “actual SMVs”.

Planning department in Factory 1, prepare the order schedule for assembly lines by considering factors such as available capacities, supply chain related data, due dates, etc. Initially, planning department generates a “detail plan” on monthly basis. The detail plan consists of all the required data to complete an order. They are; identification numbers for assembly lines, style numbers, material descriptions, order quantity, planned order quantity for respective period, cutting start date and end date, production start date and end date, customer, targeted daily production, expected daily efficiency, actual SMV, shipment date, etc. Variations from the detail plan occur due to issues with supply chain, end-customer and internal resources within Factory 1. Planning department prepares the “freeze plan” after reconciliation of the issues raised. Freeze plan includes summary of the data extracted from detail plan and format is given in assembly line wise. Data provided in freeze plan are relevant to daily production processes in production department. They are; line number, production shift number, target daily production, actual SMV, expected daily efficiency, and number of operators. Freeze plan is sent to the work-study department at the beginning of each month. Afterwards, the work-study officers generate assembly line layouts by using data provided in freeze plan, machine requirements, and operation breakdowns with respective actual SMV for each operation.

5.2.4 Observations related with machines and operators

Production department of Factory 1 uses semi-automatic machines for fast fashion orders. Therefore, full-time involvement of the operators is needed to perform operations on respective machines. Machines used in assembly lines are capable of processing one or more operations after either performing set-up activities or not.

Available working time for machines is reduced due to production downtimes in Factory 1. Production downtime data of assembly lines in Factory 1 are collected by a team assigned for monitoring it.

Multiple machine duplicates are available on assembly lines to balance the workload. Each machine is operated by a single operator and hence machine sharing between operators was not done in the observed assembly lines of Factory 1.

In Factory 1, line balancing is done by assuming zero absenteeism, and all the operators are multi-skilled. According to the observations of selected assembly lines, there are variations in individual operator efficiency. In addition, each operator is capable of performing a limited number of different operations on different machines. These observations are corresponding to multi-level flexibility and heterogeneous worker flexibility defined by Hamedi et al. (2012) (Section 2.11).

80% of plateau efficiency level is considered for each assembly line regardless of production quantity and production starting efficiency during changeovers of new or repeated orders.

Operator training is done according to individual operator skill grading system prepared by human resources department. If the operators are not multi-skilled, adequate training is given prior to assigning the particular operators to assembly lines. It is done to increase the number of operators in multi-skill operator pool.

5.2.5 Layout designing process and current layout type used for assembling fast fashion orders

Product layout type is used as the basis when designing assembly lines in Factory 1. Example of machine layout and material flow within an assembly line is shown in Figure 5.1.

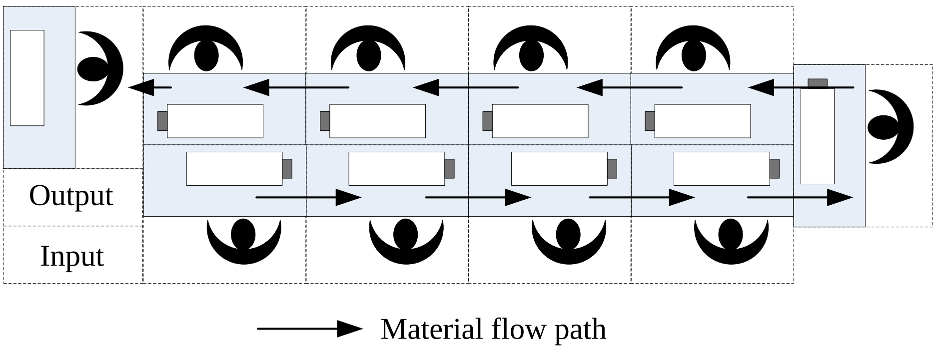

Figure 5.1 Example for machine layout and material flow of assembly lines in Factory 1

After balancing the assembly lines, respective machine types and number of machines allocated for each assembly line are virtually organized in a pre-defined space using computer software. In Factory 1, the observed assembly lines are responsible to complete assigned product within the line itself including end-line inspection and packing operations. Equal sized rectangular shapes are used to represent the machine and operator as a single unit. In addition, it is used to represent manual operations that require a separate table such as lace cutting, end-line inspection, and packing. Possible variations in machine or table dimensions are not considered in this stage. Due to that, after the physical machine arrangement, machines are often overlapped on the aisles provided for resource movement between adjacent assembly lines.

When designing the layouts in Factory 1, it is assumed that adequate lighting and environmental conditions required for the operations are provided throughout the plant floor. Additional light bulbs are attached to machine work area when needed.

5.2.5.1 Material handling

Material handling between operators is done manually in the observed assembly lines. Maximum allowable WIP for each operation is set to be 5 pieces as a company standard.

5.2.6 Changeover procedure in production department of Factory 1

5.2.6.1 Nature of the style changes

In Factory 1, the products are categorized into two segments as new styles and repeat styles. If a particular style is not manufactured within the plant for past three months, it is considered as a new style; otherwise, it is a repeat style.

5.2.6.2 Pre-changeover activities

For both new and repeat styles, purchasing or renting of necessary machines and attachments is done at least one month prior to the planned production start date. Machine settings required for new/repeat style are done at the machine set-up area starting from minimum of five days prior to planned changeover date. If the operations in both previous and new/repeat style require similar and/or minor machine settings, such machines are rearranged and/or required minor settings are done within the line itself.

Operator training for new/repeat style is started at least two days prior to the changeover. After the machine settings, and operator training are completed, the previous assembly line is ready to change for new/repeat style.

5.2.6.3 Changeover procedure at assembly lines

Changeover process includes removing machines of previous style from particular line and replacing machines required for new or repeat style. Production executive of the respective line is responsible to inform the planned changeover time to the mechanics. Machines of the new or repeat style are brought near to the assembly line when the previous order is near to complete. Firstly, the machines required near to input point of the assembly line are transported from machine set-up area using hand trucks. Once the operator finishes the last piece of previous order, the mechanics start to feed new machines to the line whilst removing previous machines. This is done repeatedly until the complete assembly line is changed to the machines of new or repeat style. Operator start the production as soon as the machine assigned for the particular operator is placed at relevant location of the line. Mechanics have to rearrange the machines to ensure minimum machine overlaps on aisles. After completing the machine feeding, supervisors and technical team of the respective assembly line demonstrate and instruct the operators. It is to ensure that the operators are following procedures provided in standard work sheets whilst achieving expected efficiency level.

Efficiency ladders consist of daily target efficiency levels starting from production start date of new/repeat style. The daily target efficiency levels are generated based on the past performance of operators in production department. Two efficiency ladders are used to monitor efficiency of new and repeated styles as given in Table 5.1. In repeated styles, the operators have previous experience on operations. Therefore, the starting efficiency of repeat styles is higher than that of new styles.

Table 5.1 – Efficiency ladders of new and repeat styles

Number of days after changeover	**Expected efficiency**	
	New style	**Repeated style**
1	30	40
2	35	50
3	40	55
4	45	60

5.2.6.4 Summary of the changeover activities related with assembly line layouts

The observed changeover activities related with assembly line layouts of Factory 1 can be summarized as follows.

- Removing and replacing machine attachments

- Adjusting the machine settings
- Moving machines from/to machine set-up area to/from respective assembly lines
- Moving machines between different assembly lines and within the same assembly line

Some machine attachments are changed by the operator after set-up period under certain situations. As an example, some machines are capable of processing more than one operation with same settings but with different attachments. In such situations, easily replaceable attachments (such as rotatable foots) are provided if possible. Similarly, the needles are changed after the changeover period depending on the requirements of some styles. Machine threading is done by the operators after changing needles and for styles with multiple colors. In Factory 1, time taken for the operator for these settings is included in SMV calculation for particular operation.

5.2.7 Summary of the observations on changeover process and layout used for fast fashion orders in production department of Factory 1

Summary of the observations related with layouts and changeover process used for fast fashion orders in production department of Factory 1 is given below.

1. Fast fashion orders received by Factory 1 have dynamic-deterministic production requirement.
2. Production department of Factory 1 uses semi-automatic machines. These machines are capable of processing more than one operation on a single machine after performing machine set-up activities or not.
3. When preparing the machine layouts, Factory 1 considers a multi-skilled operators and mechanics pool to cover up absenteeism in production department. Furthermore, Factory 1 assumes that processing time of each operation is equal to the calculated actual SMVs.
4. Variations of individual machine dimensions are not considered in virtual layout design on used computer software.
5. Adequate lighting and other environmental conditions are provided throughout the plant floor.
6. Material handling between operators is done manually with a preset bundle size.

7. Machine set-up area is used for machine set-up activities and operator training prior to starting new/repeat style. The dimensions of machine set-up area are fixed and do not vary due to changes in machine layouts of plant floor.
8. Summary of the observations related with assembly line layouts during changeover process in Factory 1 are;

- Removing and replacing machine attachments
- Adjusting the machine settings
- Moving machines from/to machine set-up area to/from respective assembly lines
- Moving machines between different assembly lines and within the same assembly line

5.3 Selection of an appropriate intra-cell layout type, operator assignment and line balancing approach

5.3.1 Introduction

Selection of an appropriate intra-cell layout type and operator assignment approach to operations is vital to amplify the benefits of DCMS design. It was done based on the observations of Factory 1 and literature review.

5.3.2 Analysis of the applicability of existing intra-cell layout types

According to Anbumalar et al. (2014) there are three basic categories of intra-cell layout types as single-row, multi-row and loop layout. These three intra-cell layout types and their sub-categories are analyzed based on observations of Factory 1.

The main reasons for inapplicability of multi-row, loop, and sub-categories of single row layouts except the U-shaped layout are given in Table 5.2.

Table 5.2 – Analysis of the applicability of intra-cell layout types

Intra-cell layout type	Reasons for inapplicability
L-shaped	Used for machines with high relocation cost and/or machines fixed to the plant floor, large machines that require excessive space or with heavy products those are difficult to move manually.
T-shaped	Often used for heavy machines those are fixed or difficult to move. Simultaneous processing of multiple products using common machines. Uses machine-sharing.
W-shaped	Commonly used in machine-intensive cells. Simultaneous processing of multiple products using common machines. Uses machine-sharing.
S or Z-shaped	Commonly used in machine-intensive industries, when the products require large number of operations. Uses operator sharing.
Comb and Spine layouts	Supervision is significantly difficult if used in labor-intensive industries. Simultaneous assembling multiple products with different number of operations increases the WIP of products with higher number of operations.
Straight-line layouts	Limit the operators' ability to operate multiple machines. Underutilization of operators and machines, Operator-sharing leads to excessive walking
Semi-circular layout	Usually a robotic device is placed at the center of semi-circle to operate the highly automated machines.
Multi-row layout	Generally designed for machine- intensive industries. Each operator perform all the operations assigned to a particular machine with same level of proficiency. Highly complicated material movement between machines and often need computerized material handling methods.
Loop layout	Used in fully automated industries. A robotic device is implemented at the center of the loop to move materials between machines. Operators involve in loading, unloading of raw material/ half-assembled products and monitoring the machine settings.

Based on Table 5.2, it is possible to conclude that L-shaped, T-shaped, W-shaped, S or Z-shaped, Comb and Spine layouts, Straight-line layouts, Semi-circular layout, Multi-row layout, and Loop layout are inappropriate to assemble the fast fashion apparels in production department.

Stand up operations increase the operator mobility between machines and therefore operators can handle multiple machines (Kumar, & Sampath, 2012). Glock, & Kunz

(2005) stated that the U-shaped layout with stand up operators is the best approach to improve both operator flexibility and layout flexibility under volatile demand scenarios. Operators can move between machines with minimum walking distances in U-shaped layouts. In contrast to straight-line layouts, U-shaped layouts can balance the workload on different machines with minimum interruptions to operator movement (Sarkar, 2015; Chase et al., 2008). Protzman et al. (2010) stated that operators in U-shaped layout are more productive due to reduced walking distances than that of straight-line layouts. Both machine and operator utilization in U-shaped layout is higher than that of straight-line layouts (Malakooti, 2014; Suo, 2012). Furthermore, Protzman et al. (2010) and Bukchin et al. (2006) mentioned that many labor-intensive industries replace the straight-line layouts with U-shaped layouts since it accounts for increased communication between workers. Having less number of operators within compact area in U-shaped layouts facilitates the ease of supervision (Stevenson, & Sum, 2002). Furthermore, application of U-shaped layout with standing operators for apparel industry has shown significant improvements in line balancing (Sudarshan, & Rao, 2014). Due to these reasons the U-shaped layout with standing operators was selected as the suitable intra-cell layout.

5.3.3 Analysis of the applicability of existing U-shaped layout types

According to Iravani et al. (1997), U-shaped layouts can be divided into two main categories as worker-oriented, and machine-oriented U-shaped layouts. In worker-oriented U-shaped layouts, the operator must continually attend the machine to complete respective operation. Conversely, in machine-oriented U-shaped layouts, once the operator loads the part to the machine, machine can operate automatically with minimum operator involvement.

Machine-oriented single U-shaped layouts require the assigned operators to perform all the operations assigned to machines in the U-shaped layout. Generally, maximum of one to two operators are assigned to a machine-oriented single U-shaped layout. Results of QE 1.1 (Section 4.2.1.1) show that majority of the fast fashion apparel manufacturers use semi-automatic machines in production department. Furthermore, in order to mitigate the effect of forgetting the maximum allowable number of operations assigned per operator should be limited to three (Badri et al., 2016;

Chacosky, 2015). According to observations in Factory 1, all the fast fashion products require at least seven operations and therefore machine-oriented single U-shaped layouts with one to two operators are inappropriate for apparel production department. Due to these reasons, the worker-oriented single U-shaped layout was selected as the appropriate intra-cell layout type for the development of production layout planning system for fast fashion apparels.

5.3.4 Selecting an appropriate operating mode for U-shaped layout

After selecting intra-cell layout type, next step is to determine an operating mode for operator assignment in U-shaped layout. Pan (2014), De Carlo et al. (2013), De Garmo et al. (2011), Baudin (2007) and Silva, & Alves (2006), and Bartholdi, & Eisenstein (2005) suggested three main operating modes for the operator assignment problem in U-shaped layouts. They are caravan or rabbit-chase, bucket-brigade, and baton-touch.

According to the case study on Factory 1, operators have different performance levels and homogeneous worker flexibility is limited in production department. In addition, order details in Factory 1 shows that the minimum number of operations per fast fashion apparel product is seven. Badri et al. (2016) and Chacosky (2015) stated that, maximum allowable number of operations per operator is limited to three. Hence, application of caravan or rabbit-chase and bucket-brigade operating modes in the U-shaped intra-cell layout for fast fashion apparel products can be considered as inappropriate.

As mentioned by Pan (2014) and Baudin (2007), baton-touch is the most commonly used operating mode in labor-intensive U-shaped cells. Reasons for that are the simplified design steps, ease of operator supervision, requirement of limited skill sets to operate the assigned machines, and balanced workload between operators. According to the observations of selected assembly lines in Factory 1, there are variations in individual operator efficiency and each operator is capable of performing a limited number of different operations. Thus, baton-touch operating mode was selected as the operator assignment approach in the developed production layout planning system.

5.3.5 U-shaped assembly line balancing problem (UALBP)

After selecting the U-shaped cell operating method, next step is the line balancing. According to Kriengkorakot, N., & Kriengkorakot, P., (2014), Pachghare, & Dalu (2012) and Sirovetnukul, & Chutima (2010), balancing problems of U-shaped layouts can be classified into four categories as; UALBP-1, UALBP-2, UALBP-E, and UALBP-F. UALBP can be further classified into four categories as; SMD, SMS, MMD, and MMS (Guo, 2016; Sharma et al., 2014). Detailed descriptions of these categories are provided in Section 2.11.3.

Fast fashion orders in Factory 1 follow the MTO strategy with a defined targeted period for the completion of assembling in sewing/production department. Hence, the fast fashion orders have fixed target cycle times for assembly process. According to Factory 1, line balancing approach should minimize the total idle time whilst ensuring balanced workload among the operators. This approach corresponds to the UALBP-1 category (i.e., *minimizing number of stations for a fixed cycle time*) as stated by Pachghare, & Dalu (2012) and Ajenblit, & Wainwright (1998).

Case study of Factory 1 shows that simultaneous processing of multiple fast fashion apparel products in same assembly line is undesirable due to possible complexities in material handling and limited number of allowable operations per operator. Furthermore, line balancing in Factory 1 is done by assuming the actual processing time of operations is equal to predefined SMV values for each of the operations. These factors comply with SMD category of UALBP defined by Guo (2016) and Sharma et al. (2014). Therefore, SMD UALBP-1 category was used as the line balancing approach in the developed production layout planning system.

5.3.6 Summary of selection of an appropriate intra-cell layout type, operator assignment and UALBP approach

Worker-oriented single U-shaped layout was selected as the appropriate intra-cell layout for the developed system for fast fashion apparels. Baton-touch operating mode and SMD UALBP-1 were the selected operator assignment and workload balancing approach in intra-cell layout.

5.4 Selection of a suitable technique for the DCMS design

DCMS provides the basis for developed production layout planning system for fast fashion apparels. It is essential to select an appropriate DCMS design technique to match with characteristics of fast fashion orders assembled in actual production environment. As mentioned by Suresh, & Kay (2012), existing techniques for DCMS design are; Classification and coding systems, Clustering methods: Array-based/ Hierarchical/ Non-hierarchical, Graph theoretic approaches, Knowledge based and pattern recognition methods, Fuzzy clustering and modeling approaches, Neural network approaches, Mathematical programming approaches, and Meta-heuristic algorithms.

Suresh, & Kay (2012) mentioned that, mathematical programming approaches are flexible to incorporate multiple objective functions and constraints to accurately represent the characteristics and requirements of actual production environment. As stated by Bayram & Sahin (2016), Houshyar et al. (2014), Singh, & Rajamani (2012), Mahadevan (2008), and Abdi (2005), majority of the researches on DCMS design are done by using mathematical programming technique. Reason for that is its ability of incorporating number of variables that directly affect the layout decisions in real-world applications (Papaioannou, & Wilson, 2010; Kamrani, Parsaei, & Liles, 1995).

According to Papaioannou, & Wilson (2010), higher number of variables results in longer computational time when using mathematical programming approaches for cell formation problem. Leon, Mendez, & Pimiento (2013), and Saidi-Mehrabad, & Mirnezami-ziabari (2011) suggested to use meta-heuristic algorithms or neural networks to overcome this issue. However, El-Kebbe, & Danne (2009) stated that these approaches follow sequential solution approach to form machine cells and part families, and thereby the solution accuracy gradually deteriorates when used in DCMS design for real world applications. Mathematical programming models are easy to alter when compared to meta-heuristic algorithms or neural networks. As a result, industrial application of mathematical programming models is higher than that of meta-heuristic algorithms, and neural networks (Papaioannou, & Wilson, 2010). Due to these reasons, Hafezalkotob et al. (2015), Nourie et al. (2013), Syberfeldt, &

Lidberg (2012), and Goncalves, & Resende (2004) suggested that best approach is to develop unique algorithms to suit the requirement of layout design and developed mathematical programming models.

Hence, the production layout planning system for fast fashion apparels is developed using mathematical programming approach with a suitable algorithm development.

5.5 Key considerations in formulating mathematical programming models of the developed system

As stated by Williams (2013), Luenberger (2008) and Takriti, Fourer, Gay, & Kernighan (1994), mathematical programming models consist of four major segments as model assumptions, decision variables, constraints and objective function/s. Mathematical programming models aims to optimize objective function/s to generate optimal or near-optimal solutions for a defined problem.

According to Singh, & Rajamani (2012) and Kamrani, Parsaei, & Liles (1995), two common problems that encounter in development of cellular layouts using mathematical programming approaches are;

1. Difficulty of determining the appropriate assumptions, input data, objective function/s, and constraints to accurately represent the characteristics of particular industry and cell layout requirements
2. Formation of mathematical equations to accurately represent the objective cost functions and constraints in a precise and simplistic manner.

Kamrani, Parsaei, & Liles (1995) suggested that most appropriate approach to overcome these problems is by adopting or modifying the similar developments from prior studies instead of developing new models from scratch. However, the researches on layout development for fast fashion orders in production department are lacking in existing literature. Therefore, the applicability of mathematical programming models used in other industries with similar dynamic environments was analyzed.

Mungwattana (2000) stated that analyzing the design attributes (i.e., assumptions, input data, objective function/s, and constraints) of both static and virtual cellular manufacturing systems is beneficial to develop a well-designed DCMS. Therefore, literature review was carried out to identify the design attributes used for mathematical programming models in Cellular Manufacturing Systems (CMS) design problems in general.

Summary of the literature review on CMS design attributes is given in Appendix A. According to the Appendix A, large number of assumptions, input data, objective function/s and, constraints are used by different authors for CMS design using mathematical programming approach. Pillai et al. (2011) stated that higher the number of design attributes included in mathematical programming model, there is a higher possibility of producing solutions that distort from the optimality. Furthermore, it results in increased solution complexity and thus significantly increases the time taken to obtain solutions. In order to overcome these problems, it is essential to select the most appropriate design attributes.

Selection of the design attributes to include in mathematical programming model for cellular layout designs depends on two main factors as; suitability to address the identified research problem and the fulfillment of data quality dimensions by the used input parameters to formulate the objective function/s and constraints (Rudolph et al., 2013; Barzdins, & Caplinskas, 2013; Weinberg, 2007; Roberts, 1994). As stated by Barzdins, & Caplinskas (2013), if a system is developed by using standard set of data and validated, it does not guarantee that the developed model will produce similar results for actual manufacturing data. Since this research addresses a practical problem faced by Sri Lankan fast fashion apparel manufacturers, most suited design attributes for relevant factories must be used for the development of mathematical models of production layout planning system.

Selection of appropriate design attributes can be done by using a questionnaire. Appendix A shows that over 250 design attributes are used for the CMS design using mathematical programming approach in existing literature. Study done by Streiner, Norman, & Cairney (2015) and Mooi, & Sarstedt (2011) shows that significantly longer questionnaires with higher number of questions resulted in low response rates than that of comparatively shorter questionnaires. In order to avoid that issue, preliminary selection of design attributes is done with the help of respective managers in Factory 1. Mahdavi, Aalaei et al. (2010), Mehmood, Cherfi, & Comyn-Wattiau (2009), and Rothenberg (1997) emphasized that the ability of generalizing any system designed based on a particular firm depends on the applicability of used DCMS design attributes on other different firms with similar settings. Mathematical models designed based only on Factory 1 may be incompatible for apparel manufacturing factories other than that. Furthermore, there can be design attributes that are not completely applicable for current state but the factories decide them as important in determining the accuracy of the developed production layout planning system and those factories are willing to adhere to such attributes in near future. Hence based on preliminary selection, a questionnaire (QE 2) was developed to identify the essential design attributes to include in the developed production layout planning system for fast fashion apparels.

5.5.1 Preliminary selection of design attributes based on Factory 1

Following factors are considered when selecting the appropriate design attributes.

1. Machine types considered in CMS design: Design attributes that are formulated specifically for heavy-weight and automated machines are excluded. Example is machine installation cost of large sized machines in metal industry.
2. Nature of demand: Dynamic production requirement with small order quantities are inherent characteristics of fast fashion apparel products. Design attributes focused on traditional mass production and static demand requirement are neglected. Furthermore, Factory 1 stated that the fast fashion order details are deterministic and thus stochastic design attributes are excluded.
3. Machine procurement and outsourcing of orders: According to Factory 1, the developed system should use the existing machines in particular planning horizon without causing additional machine procurement costs. Furthermore, as per the discussions had with relevant management staff of Factory 1, development of production layout planning system should focus on fast fashion orders that are currently assembled within the factory itself during considered planning horizon.

Hence, design attributes such as machine procurement cost, and sub-contracting cost are excluded.

4. Physical re-construction of plant floor: According to Factory 1, only the available space for layouts must be used when developing cells for fast fashion apparels and therefore modifications to the existing building must be avoided when forming and/or rearranging the cells.
5. Intra-cell layout type: Since the worker-oriented single U-shaped layout with standing operators and baton touch operating mode is selected as the most appropriate (Section 5.3.6), design attributes related with other intra-cell layout types and operating modes are excluded.

5.5.1.1 Summary of the preliminary selected design attributes

In addition to the design attributes selected from literature, Factory 1 suggested some attributes that are considered as essential to include in the developed production layout planning system. This section discusses the summary of the suitable design attributes (i.e., assumptions, input data, objective function/s, and constraints) based on the viewpoint of Factory 1.

5.5.1.1.1 Summary of the assumptions based on Factory 1

1. Adequate number of machines and operators are available for each planning period.
2. Multi-skilled pool of operators and mechanics is available to cover up absenteeism.
3. SMVs for each operation and each machine set-up activity are defined.
4. Fixed machine set-up area is provided for machine set-up activities and operator training during changeovers, and to store additional machines.
5. Production requirement for fast fashion orders during considered planning horizon is dynamic-deterministic.
6. Simultaneous processing of multiple part types in a single cell is prohibited.
7. All the operators are in stand-up position.
8. Machine sharing between operators is not allowed.

9. Layout reconfiguration (if any) includes machine set-up activities and machine relocations between and/or within the cells. In addition, machines are moved from/to machine set-up area to/from cells.
10. Physical partitioning of the cells is prohibited. Furthermore, layout reconfiguration does not require modifications to the buildings.
11. Adequate lighting and environmental conditions required for the operations are provided. Additional light bulbs are attached to the machines when necessary.
12. Existing machines are utilized when developing the layouts.
13. Machine working time is reduced due to production downtimes.
14. Bundle size for material handling between the machines and/or cells is defined.

5.5.1.1.2 Summary of the input data based on Factory 1

Production data of fast fashion apparel orders

Length of planning horizon with confirmed order details, planned number of pieces per day for each part type, bundle size for part types, operation sequence, SMVs of each operation, average time taken to load and unload machines to/from the hand truck, cost per standard minute value for part types, production downtime data, total working minutes per day, total number of days available to produce each part type in production department, expected daily production efficiency for each part type, planned order sequence, and number of working days in considered planning horizon

Production layout related data of fast fashion apparel orders

Machine setting requirements for operations, times taken for settings on each machine, total number of available machines of each machine type, coordinates of the machine set-up area, average number of turning motions (45 to 90 degrees) when moving materials between layouts, maximum number of layouts that can be simultaneously changed by mechanics, required minimum distance between adjacent machine rows, and dimensions of the machines, input/output boxes, and usable area for layouts

5.5.1.1.3 Summary of the objective function/s based on Factory 1

As discussed in Section 5.5.1, elements of objective function/s can be represented in cost terms. Increased machine movement between different locations, and increased time for machine setting and adjustment are highly frequent problems contributing to the increased changeover time of fast fashion apparels in production department (Section 4.2.1.3). Hence it is essential to minimize cost terms related with these two problems. As stated by Rafiei, & Ghodsi (2013), Mahdavi, Aalaei, et al. (2010) and Defersha, & Chen (2006) these two problems are often minimized by using machine relocation costs and machine set-up cost. Machine relocation costs can be further divided into inter-, and intra- cell machine relocation costs.

Material handling cost is the most prominent cost term minimized in available studies on DCMS design (Moradgholi, Paydar, Mahdavi, & Jouzdani, 2016; Malakooti, 2014; Kamrani, Azimi, & Al-Ahmari, 2013; Raminfar, Zulkifli, & Vasili, 2013; Jiang, & Tai, 2012; Heragu, 2008; Wang, & Kusiak, 2000). Mahdavi, Aalaei, et al. (2010) stated that total material handling cost comprises of inter-cell and intra-cell material handling costs.

Due to abovementioned reasons, inter-, and intra- cell machine relocation costs, machine set-up cost, inter-, and intra- cell material handling costs were selected by Factory 1.

As stated by Nabi et al. (2015), Jaganathan (2014) and Paneru (2011) takt time is a common measure used to balance workload among workstations. As mentioned by Kumari, Quazi, & Kumar (2015), Hu et al. (2013), Dal, Akcagun, & Yilmaz (2013) and Paneru (2011), balancing each operation to the takt time may infeasible in apparel production lines due to variations of individual operation SMVs, different skill levels, production downtimes, etc. Case study on Factory 1 showed that machine capacities are reduced due to production downtimes. In that situation, Paneru (2011) stated that most appropriate measure is the target cycle time per bundle. The developed system uses production plans prepared by planning department. According to Factory 1, each part type has a target hourly production rate. As stated by Krajewski, & Ritzman (2005) "*the target cycle time is the reciprocal of defined target hourly production rate. It is the maximum time allowed to work on a unit at each workstation*".

In the developed system, cycle time of a single workstation is defined as the time to perform all the operations assigned to that workstation, starting from first machine and walking time between machines of the workstation until the operator returns to first machine after completing all the operations with defined bundle size. As stated by Paneru (2011) and Luyster, & Tapping (2006), workstation cycle times which are significantly less than target time leads to overproduction. Conversely, workstation cycle times that exceed target time limit the ability of the production line to meet expected lead-time (Gomes, 2012). Hence, Factory 1 suggested to balance the workload between workstations to ensure minimum deviation between target cycle time per bundle and individual workstation cycle times.

After balancing the cell based on target time, it is possible to have bottleneck workstations. Eryuruk (2013) and Kitaw, Matebu, & Tadesse (2010) stated that bottleneck workstations leads to operator idling in other workstations of the apparel assembly lines. In order to minimize that, workload among workstations must be balanced in a manner that result in minimum cycle time deviation between bottleneck workstations and other workstations.

Based on above discussion, Factory 1 suggested that minimization of two cost terms is important in line balancing. They are; Cost of deviation between target cycle time per bundle and workstation cycle times, and Cost of cycle time deviation between bottleneck workstation and other workstations.

Altogether, Factory 1 selected the minimization of abovementioned seven cost terms as appropriate elements for objective function/s in production layout planning system development for fast fashion apparels.

5.5.1.1.4 Summary of the constraints based on Factory 1

Logical constraints: Ensure only one part type is assembled at a time in each cell, prevent the assignment of a single machine to more than one cell, assign each operator to a single workstation only, assign one machine only to a single location, and limit the maximum allowable number of operations per operator.

Cell size constraints: Limit the maximum number of cells in a single part family, balance the workload between cells, and prevent utilizing of machine by exceeding its capacity.

Physical constraints: Use only the available machines on plant floor, ensure non-overlapping of machines, layouts, and gangways, prevent the developed cells from exceeding available floor dimensions, and improve area utilization

Modeling constraints: Limit the part processing capability of all machine types based on total machine capacity available for individual machine types, ensure that the resultant daily efficiency is greater than or equal to planned daily efficiency for each part type assembled in each cell, ensure that each workstation cycle time is less than or equal to the target cycle time of defined bundle size, and theoretical number of operator/machines should be greater than or equal to resultant number of operators in developed cells.

5.5.2 Development and result analysis of QE 2

QE 2 was used to identify the importance of selected design attributes for the system development by Factory 1 (Section 5.5.1.1) based on the viewpoint of other intimate apparel manufacturing factories that are currently manufacturing fast fashion apparels. In addition, QE 2 identified the applicability of each design attribute for current production environments. Furthermore, respondents were allowed to mention any additional design attributes other than the given options.

Questions of QE 2 are referred as QE 2.1, QE 2.2, etc. These questions are generated based on Section 5.5.1.1. Appendix C shows the QE 2 and its results.

According to the results of QE 2 (Appendix C), each of the design attributes mentioned in QE 2 (i.e., design attributes given in Section 5.5.1.1) received over 70% of responses stating as important to consider them in the production layout planning system for fast fashion apparels. Therefore, these design attributes were used in the developed system. Furthermore, results of QE 2 (Appendix C) identified the factories with these design attributes being applicable to current production environments. Hence, it was used to select the factories for the validation of developed system.

CHAPTER 6: DEVELOPED PRODUCTION LAYOUT PLANNING SYSTEM FOR FAST FASHION APPARELS

6.1 Introduction

Design process of DCMS was used as the basis for the developed production layout planning system. According to Mahdhavi et al. (2013), Rafiei, & Ghodsi (2013), Mutingi, & Onwubolu (2012) and Hachicha et al. (2008), the overall process of designing layout planning system using DCMS for the plant floor involves the following four stages:

1. ***DCFP***: involves grouping of parts and corresponding machines into part families.
2. ***GL***: includes layout of machines within each cell (intra-cell layout problem/ machine layout problem) and layout of cells with respect to one another (inter-cell layout)
3. ***GS***: involves scheduling of parts for production
4. ***Resource allocation***: assignment of operators

The developed system solves DCFP, GL and operator assignment in simultaneous approach. GS problem is related with the decisions of planning department as mentioned by Factory 1. Since this research focuses on production department, this problem is not addressed in the developed system.

The production layout planning system was developed in two phases and an algorithm as follows.

Phase 1: Dynamic cell formation – Generates part families and machine groups simultaneously

Phase 2: Intra-cell layout and operator assignment – Determines the physical arrangement of machines within the dynamic cells whilst ensuring balanced workload between operators.

An algorithm was formulated by combining these two phases with inter-cell layout decision to obtain optimal solutions with reduced computational time. Data collected from case study on Factory 1 were used to evaluate and modify the developed system.

According to the case study, brief products in Factory 1 can be further categorized in to various sub-product types such as boy-shorts, hip-huggers, thongs etc and each sub-product type contains different styles based on customer and product specifications. In the developed production layout planning system, the term part type is used to represent different individual styles. Part families generated by the developed system consist of multiple part types (i.e., styles). In the developed system, the dynamic cells of each part family are grouped and it is referred as a part family group.

Planning horizon of the developed system is defined as the length of period with confirmed upcoming order details. In the developed system, each planning horizon is divided into planning periods. According to the detail plans of Factory 1, different orders have different production requirements and therefore, using a fixed length of planning period for each part family group will lead to underutilized cells. In the developed system, layout changes occur at the beginning of planning periods if necessary. If same length of planning periods is assigned for all the part family groups, it results in simultaneous changes of all the cells in plant floor. It will cause increased interruptions to machine movements and result in overburden to mechanics. Furthermore, Factory 1 stated that, it will create additional waiting times due to limited number of mechanics available. In order to minimize these issues, the developed system determines the optimal number of planning periods for each part family group. Bayram, & Sahin (2016) and Balakrishnan, & Cheng (2007) stated that the length of planning periods must be determined to balance the costs of material handling and re-layout. Hence, the developed system finds the optimal number of planning periods that result in highest cost saving percentage for the considered planning horizon. If the part family groups have completely different lengths of planning periods, mechanics assigned to a particular group can assist the layout changes of other groups. Otherwise, mechanics have to complete all the layout changes of assigned part family group. Case study on Factory 1 shows that in terms of machines, only a limited number of simultaneous layout changes can be handled by the mechanics. In such situation, assigning higher number of cells to a particular part family group will increase the workload of mechanics. Hence the maximum number of machines in each part family group is constrained based on that.

As per the case study on Factory 1 and results of QE 2, it is essential to maximize the area utilization of dynamic cells. According to the observations on Factory 1, machines are often overlapping on gangways due to lack of consideration on dimensional aspects. The developed system considers all the relevant dimensional data to overcome this issue. Depending on the size of sub-assembled materials and WIP, it may be inconvenient to use the machine bed to store the WIP waiting to be picked by the subsequent operator/s. In that situation, it may be necessary to use WIP storage boxes or machine table extensions based on the size of garment pieces and WIP. Machine dimensions of the developed system include the area occupied by machine, workspace required for operator usage, and dimensions of WIP storage boxes (if any). Manual operations that need to occupy a table such as lace cutting, ironing, packing, and inspection are referred as machines in the developed system. Cell dimensions of the developed system include the dimensions of input and output boxes, and machines.

Bayram, & Sahin (2016), Sundar et al. (2014) and Sharma, Phanden, & Singhal (2013) emphasized that most suitable way to validate a newly introduced layout system for labor-intensive industries is the use of computer program to compare the developed system with current state. Hence, the outputs of the developed system were generated by developing a program code on LINGO 15.0. Sample of the program code generated for the developed system is given in Appendix D.

6.1.1 Use of work measurement systems to determine walking times

Cost terms of machine relocation and material handling used in the developed system consist of times taken to move between different locations. It is possible to establish standard times based on an approapriate work measurement technique. Method Time Measurement (MTM) is the most widely used technique to establish time standards for manual operations. It is used to calculate walking times for machine relocation and material handling in the developed system as given in Appendix E. As stated by Mital, & Desai (2017) and Karger and Bahya (1987), walking time per foot is 17.0

TMU (0.0102 min) for obstructed paths and 37.2 TMU (0.02232 min) per operator turning motion (45 to 90 degrees).

Kanawaty (1992) stated that allowance percentages must be added based on working environment conditions and task complexity. Since these conditions can be varied between different factories, allowance percentages can be customized in the developed system. If the SMVs for particular activities are not readily available, respective allowances must be added to basic times when necessary before using them as input data for the developed system.

6.1.2 Outputs of the developed production layout planning system

1. Part family groups with respective part types, and dynamic cells for considered planning horizon/s
2. Machine grouping to the dynamic cells
3. Coordinates of dynamic cell locations
4. Coordinates of each machine location in dynamic cells
5. Assignment of operators to the operations in dynamic cells
6. Cost saving percentages of individual cost terms and total cost of developed system compared with current state

6.2 General information of the developed system

6.2.1 Assumptions

1. Adequate number of machines and operators are available for each planning period.
2. Multi-skilled pool of operators and mechanics is available to cover up absenteeism.
3. SMVs for each operation and each machine set-up activity are defined.
4. Fixed machine set-up area is provided for machine set-up activities, operator training during changeovers, and to store additional machines.
5. Production requirement for fast fashion orders during considered planning horizon is dynamic-deterministic.
6. Simultaneous processing of multiple part types in a single cell is prohibited.

7. All the operators are in stand-up position.
8. Machine sharing between operators is not allowed.
9. Layout reconfiguration (if any) includes machine set-up activities and machine relocations between and/or within the cells. In addition, machines are moved from/to machine set-up area to/from cells.
10. Physical partitioning of the cells is prohibited. Furthermore, layout reconfiguration does not require modifications to the buildings.
11. Adequate lighting and environmental conditions required for the operations are provided. Additional light bulbs are attached to the machines when necessary.
12. Existing machines are utilized when developing the layouts.
13. Machine working time is reduced due to production downtimes.
14. Bundle size for material handling between the machines and/or cells is defined.

6.2.2 Indices

$t: Index\ for\ part\ type;\ t = 1,2,\dots\dots,T$

$n: Index\ for\ operations\ number;\ n = 1,2,\dots\dots,N$

$O_{t,n}: Index\ for\ operations\ of\ part\ type\ t;\ \forall t,n$

$i: Index\ for\ machine\ types;\ i,i^{'},i'' = 1,2,\dots\dots,I$

$j: Index\ for\ machines\ in\ each\ type;\ j,j^{'},j'' = 1,2,\dots\dots,J$

$m_{i,j}: Index\ for\ individual\ machines;\ \forall i,j$

$w_r: Index\ for\ operator;\ r = 1,2,\dots\dots,R$

$S_l: Index\ for\ machine\ setting;\ l,l' = 1,2,\dots\dots,L$

$C_k: Index\ for\ cells;\ k,k^{'} = 1,2,\dots\dots,K$

$G_b: Index\ for\ part\ family\ group;\ b = 1,2,\dots\dots,B$

$G_{b,h}: Index\ for\ planning\ periods\ of\ part\ family\ group\ b;\ h = 1,2,\dots\dots,H$

$g: Index\ for\ machine\ locations; g,g' = 1,2,\dots\dots,\vartheta_{C_k G_{b,h}}$

$V_z: Index\ for\ workstation; z, z^{'} = 1,2, \dots \dots, Z$

$t_\tau: Index\ for\ days\ producing\ part\ type\ t\ in\ production\ department;$

$\tau = 1,2, \dots \dots, d_t$

6.2.3 Input parameters

$D_{t,\tau}: Planned\ number\ of\ pieces\ of\ part\ type\ t\ for\ day\ \tau$

$B_t: Bundle\ size\ for\ part\ type\ t$

$\eta_{O_{t,n} m_{i,j}}: SMV\ of\ operation\ n\ of\ part\ type\ t\ on\ machine\ m_{i,j}$

$U_{m_{i,j}}: Average\ time\ taken\ to\ load\ and\ unload\ machine\ m_{i,j}\ to\ the\ hand\ truck$

$\gamma_t: Cost\ per\ standard\ minute\ for\ part\ type\ t$

$$\omega_{m_{i,j} S_l O_{t,n}} = \begin{cases} 1\ if\ operation\ n\ of\ part\ type\ t\ requires\ machine\ m_{i,j}\ with\ setting\ l \\ 0\ otherwise \end{cases}$$

$\varphi_{m_{i,j} S_l}: Time\ taken\ for\ machine\ setting\ l\ on\ machine\ m_{i,j}$

$x_D: x - coordinate\ of\ the\ center\ of\ set-up\ area$

$y_D: y - coordinate\ of\ the\ center\ of\ set-up\ area$

$\lambda: Average\ number\ of\ turning\ motions\ when\ moving\ materials\ between\ cells$

$\tau_{G_{b,h}}: Non-negative\ random\ number\ for\ production\ downtime\ during\ period\ G_{b,h}$

$\psi: Maximum\ number\ of\ machines\ that\ can\ be\ simultaneously\ changed\ by\ mechanics$

$\xi: Total\ working\ minutes\ per\ day$

$\alpha, \beta, \gamma: Allowances\ for\ activities$

$d_t: Available\ number\ of\ days\ to\ assemble\ part\ type\ t$

$\delta_{t,t_\tau}: Expected\ daily\ production\ efficiency\ for\ part\ type\ t\ in\ day\ \tau$

$\delta: Number\ of\ working\ days\ in\ considered\ planning\ horizon$

$L_{m_{ij}}: Length\ of\ the\ machine\ m_{ij}$

$W_{m_{ij}}: Width\ of\ the\ machine\ m_{ij}$

$L_{PF}: Length\ of\ the\ area\ usable\ for\ dynamic\ cells$

$W_{PF}: Width\ of\ the\ area\ usable\ for\ dynamic\ cells$

$L_{oC_k}: Length\ of\ the\ input, output\ box\ provided\ for\ cell\ C_k$

$W_{oC_k}: Width\ of\ the\ input, output\ box\ provided\ for\ cell\ C_k$

$W_\beta\ : Required\ minimum\ distance\ between\ adjacent\ machine\ rows$

6.2.4 Variables

6.2.4.1 Integer variables

$D_{t,G_{b,h}}: Demand\ quantity\ for\ part\ type\ t\ during\ period\ G_{b,h}$

$\vartheta_{m_{i,j}G_{b,h}}: Total\ number\ of\ machines\ of\ each\ type\ in\ plant\ floor\ during\ period\ G_{b,h}$

$f_{tm_{i,j}m_{i',j'}}: Number\ of\ times\ that\ an\ operation\ at\ machine\ m_{i,j}\ immediately\ follows$

$an\ operation\ at\ machine\ m_{i',j'}\ or\ vice\ versa$

$Z: Total\ number\ of\ workstations$

$\vartheta_{C_kG_{b,h}}: Number\ of\ machines\ in\ cell\ C_k\ during\ period\ G_{b,h}$

$A_{O_{t,n}}: Theoritical\ number\ of\ machines\ required\ for\ operation\ O_{t,n}\ of\ part\ type\ t$

$\alpha_{fC_kG_{b,h}}: Number\ of\ machines\ at\ front\ machine\ row\ of\ cell\ C_k\ during\ period\ G_{b,h}$

$\beta_{sC_kG_{b,h}}: Number\ of\ machines\ at\ side\ machine\ row\ of\ cell\ C_k\ during\ period\ G_{b,h}$

$\gamma_{bC_kG_{b,h}}: Number\ of\ machines\ at\ back\ machine\ row\ of\ cell\ C_k\ during\ period\ G_{b,h}$

6.2.4.2 Non-integer variables

$dis_{1,C_kC_{k'}}: Distance\ between\ cell\ C_k\ and\ C_{k'}\ during\ two\ consecutive\ periods$

$dis_{2,C_kC_{k'}}: Distance\ between\ cell\ C_k\ and\ C_{k'}\ within\ a\ single\ period$

$dis_{C_kD}: Distance\ between\ cell\ C_k\ and\ machine\ set-up\ area$

$x_{C_kG_{b,h}}: x-coordinate\ of\ the\ center\ of cell\ C_k\ during\ period\ G_{b,h}$

$y_{C_k G_{b,h}}: y - coordinate\ of\ the\ center\ of cell\ C_k\ during\ period\ G_{b,h}$

$E_{C_k t, t_\tau}: Efficiency\ of\ cell\ C_k\ for\ part\ type\ t\ in\ day\ \tau$

$dis_{g g'}: Distance\ between\ two\ machine\ locations$

$x_{m_{i,j} g C_k G_{b,h}}: x\ coordinate\ of\ machine\ m_{i,j}\ at\ location\ g\ of\ cell\ C_k\ during\ period\ G_{b,h}$

$y_{m_{i,j} g C_k G_{b,h}}: y\ coordinate\ of\ machine\ m_{i,j}\ at\ location\ g\ of\ cell\ C_k\ during\ period\ G_{b,h}$

$B_{w_r V_z C_k}: Walking\ distance\ for\ operator\ w_r\ assigned\ to\ workstation\ V_z\ in\ cell\ C_k$

$Q_{V_z C_k}: Cycle\ time\ of\ workstation\ V_z\ in\ cell\ C_k$

$F_{t,C_k}: Target\ cycle\ time\ per\ unit\ \ for\ part\ type\ t\ in\ cell\ C_k during\ day\ d$

$l_{m_{i,j} m_{i',j'} V_z C_k}: Distance\ between\ adjacent\ machines\ m_{i,j}\ and\ m_{i',j'}\ assigned\ to$

$workstation\ V_z\ in\ cell\ C_k$

$c_{m_{i,j} m_{i',j'} V_z C_k}: Crossover\ distance\ between\ machines\ m_{i,j}\ and\ m_{i',j'}\ assigned\ to$

$workstation\ V_z\ in\ cell\ C_k$

$r_{m_{i,j} m_{i',j'} V_z C_k}: Return\ distance\ between\ \ machines\ m_{i,j}\ and\ m_{i',j'}\ assigned\ to$

$workstation\ V_z\ in\ cell\ C_k$

$\varepsilon: Length\ of\ a\ single\ planning\ period\ (days)$

$L_{C_k G_{b,h}}: Length\ of\ intra - cell\ layout\ C_k\ during\ period\ G_{b,h}$

$W_{C_k G_{b,h}}: Width\ of\ intra - cell\ layout\ C_k\ during\ period\ G_{b,h}$

$W_{a C_k G_{b,h}}: Distance\ between\ front\ and\ back\ machine\ rows\ of\ intracell\ layout\ C_k$

$during\ period\ G_{b,h}$

$L_{G_b G_{b,h}}: Length\ of\ part\ family\ group\ G_b\ during\ period\ G_{b,h}$

$W_{G_b G_{b,h}}: Width\ of\ part\ family\ group\ G_b\ during\ period\ G_{b,h}$

$x_{G_b G_{b,h}}: x\ coordinate\ of\ the\ center\ of\ part\ family\ group\ G_b during\ period\ G_{b,h}$

$y_{G_b G_{b,h}}: y\ coordinate\ of\ the\ center\ of part\ family\ group\ G_b during\ period\ G_{b,h}$

6.2.4.3 Binary variables

$$\delta_{m_{i,j}G_{b,h}} = \begin{cases} 1\ if\ machine\ m_{i,j}\ is\ at\ machine\ set-up\ area\ during\ period\ G_{b,h} \\ 0\ otherwise \end{cases}$$

$$b_{m_{i,j}C_k G_{b,h}} = \begin{cases} 1\ if\ machine\ m_{i,j}\ is\ in\ cell\ C_k\ during\ period\ G_{b,h} \\ 0\ otherwise \end{cases}$$

$$e_{m_{i,j}S_l G_{b,h}} = \begin{cases} 1\ if\ machine\ m_{i,j}\ is\ with\ setting\ S_l\ during\ period\ G_{b,h} \\ 0\ otherwise \end{cases}$$

$$\mu_{m_{i,j}O_{t,n}} = \begin{cases} 1\ if machine\ m_{i,j}\ is\ assigned\ for\ operation\ n\ of\ part\ type\ t \\ 0\ otherwise \end{cases}$$

$$\theta_{tC_k G_{b,h}} = \begin{cases} 1\ if\ part\ type\ t\ is\ assigned\ to\ cell\ C_k\ during\ period\ G_{b,h} \\ 0\ otherwise \end{cases}$$

$$\varepsilon_{t,G_b} = \begin{cases} 1\ if\ part\ type\ t\ belongs\ to\ part\ family\ group\ b \\ 0\ otherwise \end{cases}$$

$R'_{m_{i,j}G_{b,h}G_{b,(h+1)}}, R''_{m_{i,j}G_{b,h}G_{b,(h+1)}}: Machine\ location\ conditions\ in\ period\ G_{b,h}G_{b,(h+1)}$

$$\varpi_{m_{i,j}gC_k G_{b,h}} = \begin{cases} 1\ if\ machine\ m_{i,j}\ is\ at\ location\ g\ of\ cell\ C_k\ during\ period\ G_{b,h} \\ 0\ otherwise \end{cases}$$

$$A_{w_r O_{t,n} V_z C_k} = \begin{cases} 1\ if\ operator\ w_r\ is\ assigned\ to\ operation\ n\ of\ part\ type\ t \\ at\ workstation\ V_z\ in\ cell\ C_k \\ 0\ otherwise \end{cases}$$

$$Y_{n,tV_z C_k} = \begin{cases} 1\ if\ operation\ n\ of\ part\ type\ t\ is\ assigned\ to \\ workstation\ V_z\ in\ cell\ C_k \\ 0\ otherwise \end{cases}$$

$$\sigma_{m_{i,j}V_z C_k G_{b,h}} = \begin{cases} 1\ if\ machine\ m_{i,j}\ is\ assigned\ to\ workstation\ V_z\ in\ cell\ C_k \\ during\ period\ G_{b,h} \\ 0\ otherwise \end{cases}$$

$$\tau_{C_k G_b} = \begin{cases} 1\ if\ cell\ C_k\ is\ in\ part\ family\ group\ G_b \\ 0\ otherwise \end{cases}$$

6.3 Phase 1: Developed mathematical model for dynamic cell formation

In Phase 1, summation of the machine relocation costs due to machine movement between cells, and machine movement between cells and machine set-up area is referred as inter-cell machine relocation cost. Inter-cell material handling accounts for material movements between cells.

Objective function of Phase 1 minimizes the total cost of inter-cell machine relocation, machine set-up, and inter-cell material handling.

6.3.1 Mathematical model of Phase 1

6.3.1.1 Objective function and constraints of Phase 1

$$Minimize \quad (EMRC + MSC + EMHC) \tag{1}$$

$$EMRC = MRC_1 + MRC_2 \tag{1.1}$$

$$MRC_1 = \sum_{\substack{b=1\\h=1}}^{G_{B,H}} \sum_{\substack{k\neq k'\\k=1\\k'=1}}^{C_K} \sum_{\substack{i=1\\j=1}}^{m_{I,J}} \begin{pmatrix} R'_{m_{i,j}G_{b,h}G_{b,(h+1)}}. \\ \left(U_{m_{i,j}} + 0.0102(1+\gamma)dis_{1,C_kC_{k'}}\right).\gamma_t \end{pmatrix} \tag{1.2}$$

$$MRC_2 = \sum_{\substack{b=1\\h=1}}^{G_{B,H}} \sum_{\substack{k\neq k'\\k=1\\k'=1}}^{C_K} \sum_{\substack{i=1\\j=1}}^{m_{I,J}} \begin{pmatrix} R''_{m_{i,j}G_{b,h}G_{b,(h+1)}}. \\ \left(U_{m_{i,j}} + 0.0102(1+\gamma)dis_{C_kD}\right).\gamma_t \end{pmatrix} \tag{1.3}$$

$$MSC = \sum_{\substack{b=1\\h=1}}^{G_{B,H}} \sum_{k=1}^{C_K} \sum_{\substack{i=1\\j=1}}^{m_{I,J}} \sum_{\substack{l'\neq l'\\l=1\\l'=1}}^{S_L} \sum_{\substack{t=1\\n=1}}^{O_{T,N}} \begin{pmatrix} b_{m_{i,j}C_kG_{b,(h+1)}}.\mu_{m_{i,j}O_{t,n}}.\omega_{m_{i,j}S_{l'}O_{t,n}} \\ .e_{m_{i,j}S_lG_{b,h}}.e_{m_{i,j}S_{l'}G_{b,(h+1)}}.\varphi_{m_{i,j}S_l}.\gamma_t \end{pmatrix} \tag{1.4}$$

$$EMHC =$$

$$\sum_{\substack{b=1\\h=1}}^{G_{B,H}} \sum_{\substack{i\neq i'\\j\neq j'\\i,i'=1\\j,j'=1}}^{m_{I,J}} \sum_{\substack{k\neq k'\\k=1\\k'=1}}^{C_K} \sum_{\substack{t=1\\n=1}}^{O_{T,N}} \sum_{t=1}^{T} \begin{pmatrix} \frac{D_{t,G_{b,h}}}{B_t}.b_{m_{i,j}C_kG_{b,h}}.b_{m_{i',j'}C_{k'}G_{b,h}}.\mu_{m_{i,j}O_{t,n}}.\mu_{m_{i',j'}O_{t,(n+1)}} \\ .f_{tm_{i,j}m_{i',j'}}.(0.0102(1+\alpha)dis_{2,C_kC_{k'}}).\gamma_t + \\ (0.02232(1+\beta)\lambda).\gamma_t \end{pmatrix}$$

$$\tag{1.5}$$

Subject to;

$$R'_{m_{i,j}G_{b,h}G_{b,(h+1)}} =$$

$$\left\{\left(1-b_{m_{i,j}C_{k'}G_{b,h}}\right)\left(1-b_{m_{i,j}C_kG_{b,(h+1)}}\right).b_{m_{i,j}C_kG_{b,h}}.b_{m_{i,j}C_{k'}G_{b,(h+1)}}\right\} \;;\forall k\neq k' \tag{2}$$

$$R''_{m_{i,j}G_{b,h}G_{b,(h+1)}} =$$

$$\left\{\left(1-b_{m_{i,j}C_kG_{b,h}}\right)\left(1-b_{m_{i,j}C_{k'}G_{b,h}}\right).\delta_{m_{i,j}G_{b,h}}.b_{m_{i,j}C_kG_{b,(h+1)}}\right\} \;;\forall k\neq k' \tag{3}$$

$$dis_{1,C_kC_{k'}} = \left\{\left(\left|x_{C_{k'}G_{b,(h+1)}} - x_{C_kG_{b,h}}\right|\right) + \left(\left|y_{C_{k'}G_{b,(h+1)}} - y_{C_kG_{b,h}}\right|\right)\right\} \;;\forall k\neq k' \tag{4}$$

$$dis_{2,C_kC_{k'}} = \{(|x_{C_{k'}G_{b,h}} - x_{C_kG_{b,h}}|) + (|y_{C_{k'}G_{b,h}} - y_{C_kG_{b,h}}|)\} \; ; \forall k \neq k' \quad (5)$$

$$dis_{C_kD} = \left\{\left(\left|x_{C_kP_{(h+1)}} - x_D\right|\right) + \left(\left|y_{C_kP_{(h+1)}} - y_D\right|\right)\right\} \quad (6)$$

$$f_{tm_{i,j}m_{i',j'}} = \sum_{n=1}^{O_{t(N-1)}} (\mu_{m_{i,j}O_{t,n}} . \mu_{m_{i',j'}O_{t,(n+1)}} + \mu_{m_{i'j'}O_{tn}} . \mu_{m_{i,j}O_{t(n+1)}}) \; ; \forall t, k \neq k' \quad (7)$$

$$\vartheta_{m_{i,j}G_{b,h}} \geq \sum_{k=1}^{C_K} \sum_{\substack{i=1 \\ j=1}}^{m_{I,J}} b_{m_{i,j}C_kG_{b,h}} + \sum_{\substack{i=1 \\ j=1}}^{m_{I,J}} \delta_{m_{i,j}G_{b,h}} \; ; \forall m_{i,j}, k, h \quad (8)$$

$$\sum_{\substack{i=1 \\ j=1}}^{m_{I,J}} \sum_{t=1}^{T} \sum_{t,n}^{O_{tn}} D_{t,G_{b,h}} . \eta_{O_{t,n}m_{i,j}} =$$

qKk=1CKi=1j=1mI,Jt=1Tt=1n=1OT,NDt,Gb,h.ηOt,nmi,j ;∀mi,j,k,h *(9)*

$$q = 0 \leq q \leq 1 \quad (10)$$

$$\sum_{\substack{b=1 \\ h=1}}^{G_{B,H}} \sum_{k=1}^{C_K} \sum_{\substack{t=1 \\ n=1}}^{O_{T,N}} \sum_{t=1}^{T} \sum_{\substack{i=1 \\ j=1}}^{m_{I,J}} \eta_{O_{t,n}m_{i,j}} . D_{t,G_{b,h}} . \mu_{m_{i,j}O_{t,n}} . b_{m_{i,j}C_kG_{b,h}} \leq$$

i=1j=1mI,Jbmi,jCkGb,h.ξ−τGb,h+l=1Sli=1j=1mI,Jφmi,jSl;∀k *(11)*

$$\sum_{t=1}^{T} \theta_{tC_kG_{b,h}} = 1 \; ; \forall k, h \quad (12)$$

$$\sum_{\substack{i=1 \\ j=1}}^{m_{I,J}} b_{m_{i,j}C_kG_{b,h}} \sum_{k=1}^{C_K} \varepsilon_{t,G_b} . b_{m_{i,j}C_kG_{b,h}} . \theta_{tC_kG_{b,h}} \leq \psi \; ; \forall b, h \quad (13)$$

$$D_{t,G_{b,h}}, \vartheta_{m_{i,j}G_{b,h}}, f_{tm_{i,j}m_{i',j'}} \geq 0 \; and \; integer \; ; \forall h, k, t, m_{i,j} \quad (14)$$

$$\delta_{m_{i,j}G_{b,h}}, b_{m_{i,j}C_kG_{b,h}}, e_{m_{i,j}S_lG_{b,h}}, \mu_{m_{i,j}O_{t,n}}, \theta_{tC_kG_{b,h}}, \varepsilon_{t,G_b}, R'_{m_{i,j}G_{b,h}G_{b,(h+1)}},$$

$$R''_{m_{i,j}G_{b,h}G_{b,(h+1)}} \in \{0,1\} \quad (15)$$

Objective function of Phase 1

The objective function of Phase 1 is given in Equation (1). Total machine relocation cost for considered planning periods is calculated by Equation (1.1). Equation (1.2) calculates the machine relocation cost between cells whereas machine relocation cost between cells and set-up area is calculated by Equation (1.3). Set-up activities are performed when two operations are processed at same machine but with different settings in consecutive periods. If the machine requires same setting for two consecutive periods, no set-up activity for such machines is performed. Machine set-up cost is calculated as given in Equation(1.4). Inter-cell material handling cost is calculated as given in Equation(1.5).

Constraints of Phase 1

Equation (2) and Equation (3) determine the machine locations during considered periods. Distances between machine locations are calculated in Equations (4), (5) and (6). Equation (7) determines the number of times that an operation at machine $m_{i,j}$ immediately follows an operation at machine $m_{i',j'}$.

Constraint (8) guarantees that the total number of machines in plant floor should be greater than or equal to summation of number of machines in cells and machine set-up area for a particular period. It prevents additional machine procurement when generating dynamic cells.

Constraint (9) and Equation (10) balances the workload between cells. The factor $q \in [0,1]$ is used to determine the extent of workload balance between the dynamic cells.

In ideal situation, the total machine capacity i.e. shift operating time can be utilized for assemblying the parts. However, in practical situation the machine working times are reduced due to possible production downtimes. Using shift time as the available machine capacity is erroneous in this situation. Production downtime in the developed system is calculated by generating random numbers based on past data. Downtime caused due to machine relocations and machine set-up activities are excluded from past data when calculating the production downtime for developed system. Constraint (11) limits the part assemblying capability of all machine types based on total machine capacity available for individual machine types.

Simultaneous processing of multiple different part types within a single cell will lead to forgetting effect, complicated supervision and increased machine stoppages due to variable machine settings. Hence, the maximum number of part types assigned to a single cell is limited to one at a time by using Constraint (12). Constraint (13) limits the maximum number of cells in a single part family. Equation(14) and Equation (15) are used to define integer and binary variables.

6.4 Phase 2: Developed mathematical model of intra-cell layout and line balancing problem

Objective function of Phase 2 simultaneously minimizes the following four cost terms.

1. Intra-cell machine relocation cost (AMRC)
2. Intra-cell material handling cost (AMHC)
3. Cost of time deviation between target cycle time per bundle and workstation cycle times (DT)
4. Cost of cycle time deviation between bottleneck workstation and other workstations (DB)

In the developed mathematical model for Phase 2, legs of U-shaped layout are referred as front, side and back machine rows where the material flow starts from front machine row and proceeds to side machine row. Output parts are collected from the machine at the end of back machine row. Example for machine assignment to operators is illustrated in Figure 6.1.

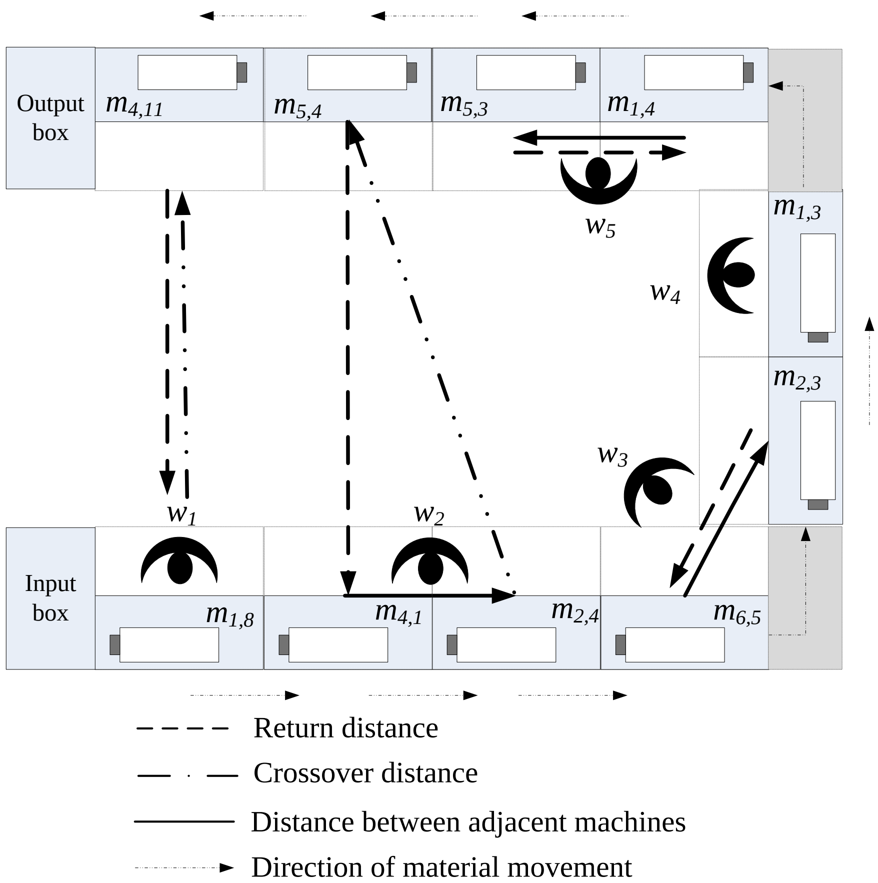

Figure 6.1 – Example of operator assignment to machines in the developed system

For the given example, operator w_2 is assigned to a single workstation which consist of machines $m_{4,1}$ and $m_{2,4}$ and $m_{5,4}$. After completing assigned operation on machine $m_{4,1}$ operator moves to subsequent machines of his/her assigned workstation ($m_{2,4}$ and $m_{5,4}$) and returns to machine $m_{4,1}$. In the given example, machine $m_{5,4}$ is located at back machine row and therefore operator has to crossover the area provided for operator movement within the cell.

6.4.1 Mathematical model of Phase 2

6.4.1.1 Objective functions and constraints of Phase 2

$$Minimize\ \ (AMRC + AMHC + DT + DB) \qquad (16)$$

$$AMRC = \sum_{\substack{b=1\\h=1}}^{G_{B,H}} \sum_{\substack{k\neq k'\\k=1\\k'=1}}^{C_K} \sum_{\substack{i=1\\j=1}}^{m_{I,J}} \begin{pmatrix} \varpi_{m_{i,j} g C_k G_{b,h}} . \varpi_{m_{i,j} g' C_k G_{b,(h+1)}} \\ .\left(U_{m_{ij}} + 0.0102(1+\gamma) dis_{gg'}\right) . \gamma_t \end{pmatrix} ; \forall g \neq g' \qquad (16.1)$$

$AMHC =$

$$\sum_{\substack{b=1\\h=1}}^{G_{B,H}} \sum_{\substack{i\neq i'\\j\neq j'\\i,i'=1\\j,j'=1}}^{m_{I,J}} \sum_{k=1}^{C_K} \sum_{\substack{k\neq k'\\k'=1}}^{C_K} \sum_{\substack{t=1\\n=1}}^{O_{T,N}} \sum_{t=1}^{T} \left(\begin{array}{c} \frac{D_{t,G_{b,h}}}{B_t} . b_{m_{i,j}C_kG_{b,h}} . b_{m_{i',j'}C_kG_{b,h}} \\ . \mu_{m_{i,j}O_{t,n}} . \mu_{m_{i',j'}O_{t,(n+1)}} . f_{tm_{i,j}m_{i',j'}} . \\ \left(0.0102(1+\alpha)B_{w_rV_zC_k} + 0.02232(1+\beta)\phi\right) . \gamma_t \end{array} \right) \tag{16.2}$$

$$DT = \left(\sqrt{\sum_{k=1}^{C_K} \left(F_{t,C_k} . B_t - Q_{V_zC_k}\right)^2} \right) . \gamma_t \tag{16.3}$$

$$DB = \left(\sqrt{\sum_{z=1}^{V_Z} \left(max\{Q_{V_zC_k}\} - Q_{V_zC_k}\right)^2} \right) . \gamma_t \tag{16.4}$$

Subject to:

$$dis_{gg'} = \left(\left| x_{m_{i,j}gC_kG_{b,h}} - x_{m_{i,j}g'C_kG_{b,h}} \right| + \left| y_{m_{i,j}gC_kG_{b,h}} - y_{m_{i,j}g'C_kG_{b,h}} \right| \right) \; ; \forall t, g \neq g' \tag{17}$$

$$\sum_{k=1}^{C_K} b_{m_{i,j}C_kG_{b,h}} = 1 \; ; \forall k, h \tag{18}$$

$$E_{C_kt,t_\tau} = \frac{D_{t,\tau} . \sum_{z=1}^{V_z} Q_{V_zC_k}}{\xi . \sum_{z=1}^{V_z} A_{w_rO_{t,n}V_zC_k}} \times 100\% \tag{19}$$

$$\delta_{t,t_\tau} \leq E_{C_kt,t_\tau} ; \; \forall k, t, \tau \tag{20}$$

$$\sum_{z=1}^{Z} A_{w_rO_{t,n}V_zC_k} = 1 \; ; \forall z \tag{21}$$

$$\sum_{\substack{i=1\\j=1}}^{m_{I,J}} \varpi_{m_{i,j}gC_kG_{b,h}} = 1 \; ; \forall i, j \tag{22}$$

$$F_{t,C_k} = \left(\frac{d_t . \xi . max\{\delta_{t,t_\tau}\}}{\sum_{\tau=1}^{d_t} D_{t,\tau}} \right) ; \forall t, d, k \tag{23}$$

$$F_{t,C_k} . B_t \geq Q_{V_zC_k} \tag{24}$$

$$A_{O_{t,n}} = \left\lceil \frac{\sum_{\tau=1}^{d_t} D_{t,\tau} . \eta_{O_{t,n}m_{i,j}}}{60 d_t . \xi . max\{\delta_{t,t_\tau}\}} \right\rceil \tag{25}$$

$$\sum_{n=1}^{N} A_{O_{t,n}} . \mu_{m_{i,j}O_{t,n}} . b_{m_{i,j}C_kG_{b,h}} \geq \sum_{z=1}^{Z} \sum_{r=1}^{R} A_{w_rO_{t,n}V_zC_k} \tag{26}$$

$$\sum_{n=1}^{O_{T,N}} A_{w_rO_{t,n}V_zC_k} \leq 3 \; ; \forall t, n, z \tag{27}$$

$$Q_{V_zC_k} = \sum_{n=1}^{O_{T,N}} \sum_{\substack{i=1\\j=1}}^{m_{I,J}} \begin{pmatrix} A_{w_rO_{t,n}V_zC_k} . \mu_{m_{i,j}O_{t,n}} . \sigma_{m_{i,j}V_zC_kG_{b,h}} . Y_{n,tV_zC_k} . B_t . \eta_{O_{t,n}m_{i,j}} \\ \left(0.0102(1+\alpha)B_{w_{rV_z}C_k} + 0.02232(1+\beta)\phi\right) \end{pmatrix} ;\forall z \tag{28}$$

$$B_{w_{rV_z}C_k} = l_{m_{i,j}m_{i',j'}V_zC_k} + c_{m_{i,j}m_{i',j'}V_zC_k} + r_{m_{i,j}m_{i',j'}V_zC_k} ;\forall z,i,j \tag{29}$$

$$l_{m_{i,j}m_{i',j'}V_zC_k} = \left|x_{m_{i,j}gC_kG_{b,h}} - x_{m_{i',j'}gC_kG_{b,h}}\right| + \left|y_{m_{i,j}gC_kG_{b,h}} - y_{m_{i',j'}gC_kG_{b,h}}\right|$$

$$;\forall z, i = i' \, or \, j = j' \tag{30}$$

$$c_{m_{i,j}m_{i',j'}V_zC_k} = \sqrt{\left(\left(x_{m_{i,j}gC_kG_{b,h}} - x_{m_{i',j'}gC_kG_{b,h}}\right)^2 + \left(y_{m_{i,j}gC_kG_{b,h}} - y_{m_{i',j'}gC_kG_{b,h}}\right)^2\right)}$$

$$;\forall z, i \neq i' \, or \, j \neq j' \tag{31}$$

$$r_{m_{i,j}m_{i',j'}V_zC_k} = \sqrt{\left(\left(x_{m_{i,j}gC_kG_{b,h}} - x_{m_{i',j'}gC_kG_{b,h}}\right)^2 + \left(y_{m_{i,j}gC_kG_{b,h}} - y_{m_{i',j'}gC_kG_{b,h}}\right)^2\right)} ;\forall z, i \neq i' \, or \, j \neq j' \tag{32}$$

$$\phi = \begin{cases} 4; \forall x_{m_{i,j}gC_kG_{b,h}} = x_{m_{i',j'}gC_kG_{b,h}} \; or \; y_{m_{i,j}gC_kG_{b,h}} = y_{m_{i',j'}gC_kG_{b,h}} \\ 6; \forall x_{m_{i,j}gC_kG_{b,h}} \neq x_{m_{i',j'}gC_kG_{b,h}} \; and \; y_{m_{i,j}gC_kG_{b,h}} \neq y_{m_{i',j'}gC_kG_{b,h}} \\ 6; \forall x_{m_{i,j}gC_kG_{b,h}} = x_{m_{i',j'}gC_kG_{b,h}} = x_{m_{i'',j''}gC_kG_{b,h}} \; or \\ y_{m_{i,j}gC_kG_{b,h}} = y_{m_{i',j'}gC_kG_{b,h}} = y_{m_{i'',j''}gC_kG_{b,h}} \\ 8; \forall x_{m_{i,j}gC_kG_{b,h}} = x_{m_{i',j'}gC_kG_{b,h}} \neq x_{m_{i'',j''}gC_kG_{b,h}} \; or \\ y_{m_{i,j}gC_kG_{b,h}} = y_{m_{i',j'}gC_kG_{b,h}} \neq y_{m_{i'',j''}gC_kG_{b,h}} \end{cases} \tag{33}$$

$$\sum_{k=1}^{C_K} \sum_{\substack{i=1\\j=1}}^{m_{I,J}} b_{m_{i,j}C_kG_{b,h}} = \sum_{k=1}^{C_K} \sum_{\substack{i=1\\j=1}}^{m_{I,J}} \sum_{z=1}^{V_Z} \sigma_{m_{i,j}V_zC_kG_{b,h}} ;\forall k,i,j \tag{34}$$

$$\vartheta_{C_kG_{b,h}} = \sum_{\substack{i=1\\j=1}}^{m_{I,J}} \sum_{z=1}^{V_Z} \sigma_{m_{i,j}V_zC_kG_{b,h}} ;\forall k,i,j,h \tag{35}$$

$$\vartheta_{m_{i,j}G_{b,h}} \geq \sum_{k=1}^{C_K} \sum_{\substack{i=1\\j=1}}^{m_{I,J}} b_{m_{i,j}C_kG_{b,h}} ;\forall i,j,k,h \tag{36}$$

$$\sum_{z=1}^{V_Z} Y_{n,tV_zC_k} \leq \sum_{z=1}^{V_Z} Y_{(n+1),tV_{(z+1)}C_k} \tag{37}$$

$Z, \vartheta_{C_k G_{b,h}} \in \{0,1,2,\ldots\}$; $\forall h, k, z, r$ and

$$\varpi_{m_{i,j} g C_k G_{b,h}}, A_{w_r O_{t,n} V_z C_k}, Y_{n,t V_z C_k}, \sigma_{m_{i,j} V_z C_k G_{b,h}} \in \{0,1\} \quad (38)$$

Objective functions of Phase 2

Objective function of Phase 2 is given in Equation (16). It seeks to minimize the summation of intra-cell machine relocation cost, intra-cell material handling cost, cost of time deviation between target cycle time per bundle and workstation cycle times, and cost of cycle time deviation between bottleneck workstation and other workstations.

Intra-cell machine relocation cost occurs when machines can be relocated within the intra-cell layout itself without transporting from machine set-up area or a different cell. This may require performing machine set-up activities depending on the requirement, which is minimized in Phase 1. Equation (16.1) calculates the intra-cell machine relocation cost. Intra-cell material handling cost is calculated as given in Equation (16.2). Equation (16.3) and Equation (16.4) calculate the cost of time deviation between target cycle time per bundle and workstation cycle times, and cost of cycle time deviation between bottleneck workstation and other workstations, respectively.

Constraints of Phase 2

Equation (17) determines the distances between machine locations in each cell. Constraint (18) prevents the assignment of a single machine to more than one cell. Daily efficiency for each cell is calculated by Equation (19).Constraint (20) ensures that the resultant daily efficiency is greater than or equal to planned daily efficiency for each part type assembled in each cell. Each operator is assigned to a single workstation only by Constraint (21). It is to avoid machine sharing between operators. Constraint (22) assigns one machine only to a single location in order to avoid machine overlapping. Target cycle time per unit for each part type is calculated using Equation (23). Constraint (24) ensures that each workstation cycle time is less than or equal to the target cycle time of defined bundle size. Theoretical number of operators required for each operation is calculated using Equation(25). Constraint

(26) ensures that the number of machines should be greater than or equal to resultant number of operators in developed cells. Maximum allowable number of operations per operator is limited by Constraint (27). Equation (28) determines the cycle time of each workstation including walking times. Walking distances in each workstation are calculated by Equations $(29) - (32)$. Corresponding number of turning motions for respective machine locations are given in Equation (33). Constraints $(34) - (36)$ ensure that no additional machines are procured when forming intra-cell layout. Precedence constraint is given in Equation (37). Used variables in Phase 2 are defined by Equation (38).

6.5 Developed algorithm to obtain optimal solutions for mathematical models of Phase 1, Phase 2, and group layout problem

Developed mathematical models of Phase 1 and Phase 2 assume that cell reconfigurations due to product variations do not require modification to the plant floor building structure. Furthermore, it is assumed that physical partitioning of cells is prohibited (Section 6.3.2.1). As a result, it is essential to arrange the dynamic cells within a predefined floor area. Section 6.3 and Section 6.4 shows that optimization of objective functions given in Phase 1 and Phase 2 is vital to design production layout planning system for fast fashion apparels. Hence, the developed algorithm seeks to optimize the objective functions of Phase 1 and Phase 2 while maximizing the area utilization.

Decision on length of the planning periods affects the resultant costs of cellular layouts (Yang, & Peters, 1998). According to the study conducted by Yang, & Peters (1998), selecting higher length of planning period increase the material handling costs while minimizing the changeover related costs such as machine relocation, machine set-up costs. Conversely, shorter length of periods drastically increase the changeover related costs but with minimum material handling costs. Phase 1 and Phase 2 of the developed model minimizes these costs and the optimum lengths of planning periods to balance these costs for individual part family groups are determined by the developed algorithm.

6.5.1 Developed algorithm

Steps of the developed algorithm are discussed in this section. Outputs of each step are recorded by using the generated program code.

Step 1: Set the value for h as 1 and generate the part families for all the part types in considered planning horizon. It is done by solving mathematical models of Phase 1 and Phase 2 simultaneously. Record all the possible part families with respective design outputs of intra-cell layouts.

Step 2: Randomly select a set of part families to represent all the part types arrive to production department during considered planning horizon.

Step 3: Generate all the possible values for h for the selected set of part families from Step 2. For Step 3, $h = 2,3, \ldots, H$; where $H = \frac{\delta}{h}; min\,\{d_t\} \leq H$. Constraint (39) ensures that the total demand volume of a particular part type for considered planning horizon is achieved by part family groups.

$$\sum_{\substack{b=1 \\ h=1}}^{G_{B,H}} D_{t,G_{b,h}} = \sum_{\tau=1}^{d_t} D_{t,\tau} \quad (39)$$

Step 4: Randomly assign a set of values for h generated from Step 3 for the selected part families from Step 2.

Step 5: There can be one or more possible machine arrangements for a defined number of machines. Step 5 of the algorithm records all the possible machine arrangements for each of the intra-cell layouts of selected part families after completing Step 4.

Front and back machine rows in the developed intra-cell layouts are arranged while keeping minimum distance between the machines at front/back and side without overlapping on the provided workspace for operators. It is advised to use a material handling aid (Examples: side table, bin, etc) between front/back machine row and side row if necessary. Variables and input parameters of cells used for the algorithm are indicated in Figure 6.3.

Equation (40) and (41) ensures that the machines do not overlap on each other.

$$\frac{L_{m_{i,j}}+L_{m_{i',j'}}}{2} \leq \left| x_{m_{i,j} g C_k G_{b,h}} - x_{m_{i',j'} g' C_k G_{b,h}} \right| \quad (40)$$

$$\frac{W_{m_{i,j}}+W_{m_{i',j'}}}{2} + \beta_{s C_k G_{b,h}} . \left(max \left\{ L_{m_{i,j}} \right\} \right) \leq \left| y_{m_{i,j} g C_k G_{b,h}} - y_{m_{i',j'} g' C_k G_{b,h}} \right| \quad (41)$$

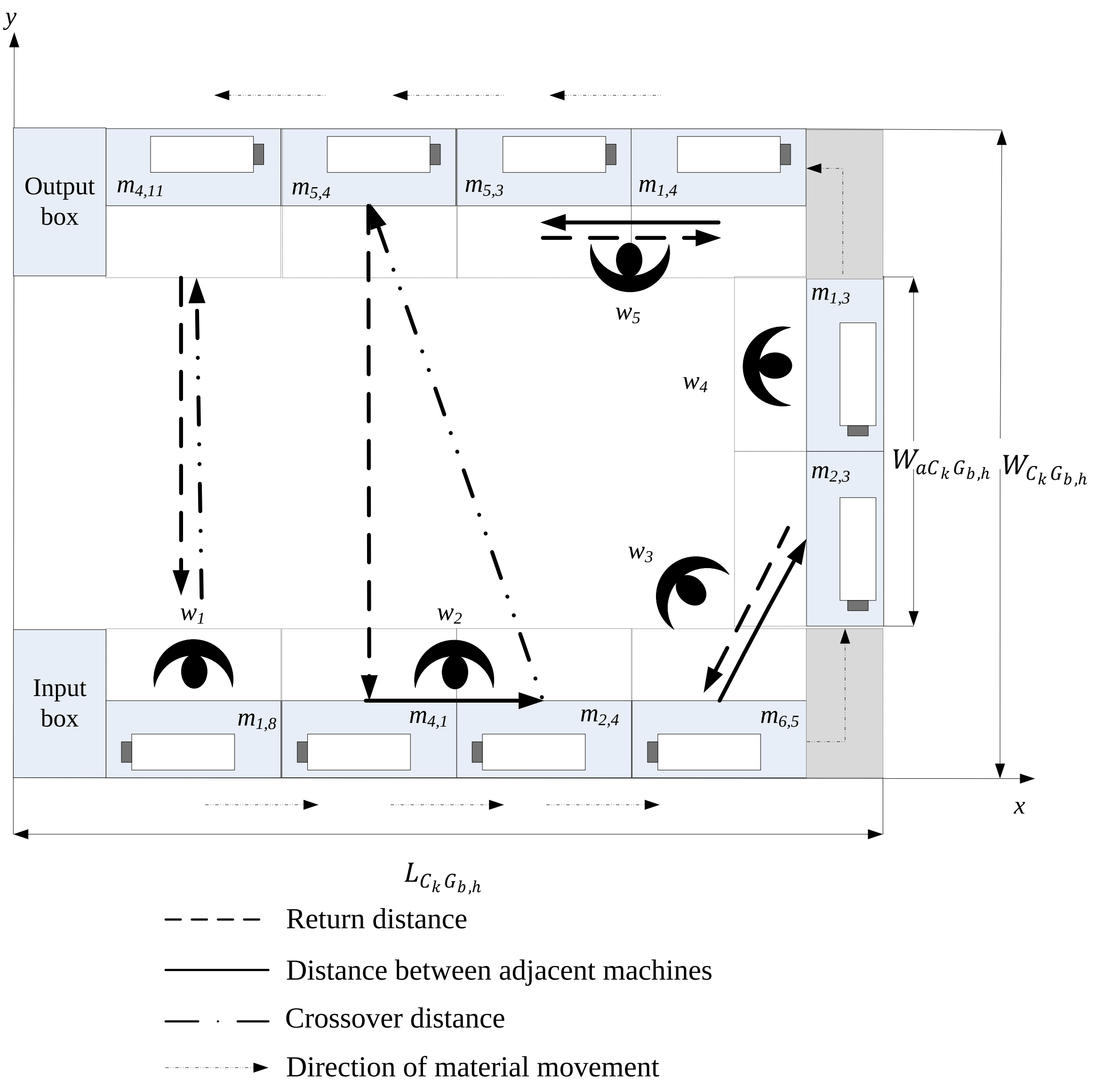

Figure 6.3 – Illustration of intra-cell layout with dimensional variables

Calculate the length and width of each cell for all the possible machine arrangements based on constraints (42) to (46).

Total number of machines in U-shaped layout equals to summation of machines located at front, side and back machine rows as given in Equation (42).

$$\vartheta_{C_k G_{b,h}} = \alpha_{f C_k G_{b,h}} + \beta_{s C_k G_{b,h}} + \gamma_{b C_k G_{b,h}} \tag{42}$$

Number of machines in side machine row of U-shaped layout is calculated by Equation (43).

$$\beta_{s C_k G_{b,h}} = \left\lceil \frac{min\left\{W_{a C_k G_{b,h}}\right\}}{max\left\{L_{m_{i,j}}\right\}} \right\rceil \tag{43}$$

Distance between front, and back machine rows in U-shaped layout should be greater than or equal to minimum width of the space provided for operator movement within the cell. It corresponds to Equation (44).

$$W_{a C_k G_{b,h}} \geq W_\beta \tag{44}$$

Width of the cell is limited by Constraint (45).

$$W_{C_k G_{b,h}} \geq \beta_{s C_k G_{b,h}} . \left(max\left\{L_{m_{i,j}}\right\}\right) + 2max\left\{W_{m_{i,j}}, W_{o C_k}\right\} \tag{45}$$

Constraint (44) limits the length of the cell.

$$L_{C_k G_{b,h}} \geq max\left\{\left(\alpha_{f C_k G_{b,h}} L_{m_{i,j}} + L_{o,C_k} + \frac{W_{m_{i,j}}}{2}\right), \left(\gamma_{b C_k G_{b,h}} L_{m_{i,j}} + L_{o C_k} + \frac{W_{m_{i,j}}}{2}\right)\right\} \tag{46}$$

Record the calculated lengths and widths for all the possible machine arrangements.

Step 6: Randomly select a set of possible machine arrangements from Step 5 by representing all of the cells.

Step 7: As stated by Drira et al. (2007) and Fruggiero et al. (2006) there are two possible arrangements when planning cell locations on plant floor layout as discrete, and continuous formulation (Section 2.9.1). Drira et al. (2007), Dunker et al. (2005), Meller et al. (1999), and Das (1993) stated that using continuous formulation in cell level leads to difficulties in supervision and complicated input/output material handling. Hence, the developed system uses discrete formulation for the arrangement of dynamic cells within a part family group.

In order to form the discrete formulation, dynamic cells in a part family group should have similar dimensions in either lengthwise or widthwise directions. Step 7 compares the lengths and widths of all the possible machine arrangements of cells in each part family. If the dimensions of the cells in a particular part family are not equal in either lengthwise or widthwise, repeat from Step 6 to Step 7. Otherwise, continue to Step 8. Generate possible alternatives of part family groups for selected machine arrangements and record resultant length and width of each part family group under the constraints given in Equation (47) and (48).

$$L_{G_b G_{b,h}} = \max\left\{\left(\sum_{k=1}^{C_K} W_{C_k G_{b,h}} . \tau_{C_k G_b} + W_\beta . \left(\sum_{k=1}^{C_K} \tau_{C_k G_b} - 1\right)\right), max\left\{L_{C_k G_{b,h}}\right\}\right\}$$
$$Or\ L_{G_b G_{b,h}} = \max\left\{\left(\sum_{k=1}^{C_K} L_{C_k G_{b,h}} . \tau_{C_k G_b} + W_\beta . \left(\sum_{k=1}^{C_K} \tau_{C_k G_b} - 1\right)\right), max\left\{W_{C_k G_{b,h}}\right\}\right\} \quad (47)$$

$$W_{G_b G_{b,h}} = min\left\{\left(\sum_{k=1}^{C_K} W_{C_k G_{b,h}} . \tau_{C_k G_b} + W_\beta . \left(\sum_{k=1}^{C_K} \tau_{C_k G_b} - 1\right)\right), max\left\{L_{C_k G_{b,h}}\right\}\right\}$$
$$Or\ W_{G_b G_{b,h}} = min\left\{\left(\sum_{k=1}^{C_K} L_{C_k G_{b,h}} . \tau_{C_k G_b} + W_\beta . \left(\sum_{k=1}^{C_K} \tau_{C_k G_b} - 1\right)\right), max\left\{W_{C_k G_{b,h}}\right\}\right\} \quad (48)$$

Overlapping of cells on each other is prevented by Constraints (49), (50) and (51).

$$\frac{L_{C_k G_{b,h}} + L_{C_{k'} G_{b,h}}}{2} + W_\beta \leq \left|x_{C_k G_{b,h}} - x_{C_{k'} G_{b,h}}\right| \ and$$
$$\frac{W_{C_k G_{b,h}} + W_{C_{k'} G_{b,h}}}{2} + W_\beta \leq \left|x_{C_k G_{b,h}} - x_{C_{k'} G_{b,h}}\right| ;\ \forall y_{C_k G_{b,h}} = y_{C_{k'} G_{b,h}} \quad (49)$$

$$\frac{L_{C_k G_{b,h}} + L_{C_{k'} G_{b,h}}}{2} + W_\beta \leq \left|y_{C_k G_{b,h}} - y_{C_{k'} G_{b,h}}\right| \ and$$
$$\frac{W_{C_k G_{b,h}} + W_{C_{k'} G_{b,h}}}{2} + W_\beta \leq \left|y_{C_k G_{b,h}} - y_{C_{k'} G_{b,h}}\right| ;\ \forall x_{C_k G_{b,h}} = x_{C_{k'} G_{b,h}} \quad (50)$$

$$\frac{L_{C_k G_{b,h}} + W_{C_{k'} G_{b,h}}}{2} + W_\beta \leq \left|x_{C_k G_{b,h}} - x_{C_{k'} G_{b,h}}\right| \ and$$
$$\frac{L_{C_k G_{b,h}} + W_{C_{k'} G_{b,h}}}{2} + W_\beta \leq \left|y_{C_k G_{b,h}} - y_{C_{k'} G_{b,h}}\right| ;\ \forall x_{C_k G_{b,h}} \neq x_{C_{k'} G_{b,h}} \ and\ y_{C_k G_{b,h}} \neq y_{C_{k'} G_{b,h}} \quad (51)$$

Step 8: Part family groups are arranged on plant floor to maximize the area utilization. Total usable area for machine layouts in plant floor is considered when formulating dimensional constraints. Constraints (52), (53) and (54) ensure that the part family groups do not overlap on each other.

$$\frac{L_{G_b G_{b,h}} + L_{G_{b'} G_{b,h}}}{2} + W_\beta \leq \left| x_{G_b G_{b,h}} - x_{G_{b'} G_{b,h}} \right| \; and$$

$$\frac{W_{G_b G_{b,h}} + W_{G_{b'} G_{b,h}}}{2} + W_\beta \leq \left| x_{C_k G_{b,h}} - x_{C_{k'} G_{b,h}} \right| ; \; \forall y_{G_b G_{b,h}} = y_{G_{b'} G_{b,h}} \tag{52}$$

$$\frac{L_{G_b G_{b,h}} + L_{G_{b'} G_{b,h}}}{2} + W_\beta \leq \left| y_{C_k G_{b,h}} - y_{C_{k'} G_{b,h}} \right| \; and$$

$$\frac{W_{G_b G_{b,h}} + W_{G_{b'} G_{b,h}}}{2} + W_\beta \leq \left| y_{C_k G_{b,h}} - y_{C_{k'} G_{b,h}} \right| ; \; \forall x_{G_b G_{b,h}} = x_{G_{b'} G_{b,h}} \tag{53}$$

$$\frac{L_{G_b G_{b,h}} + W_{G_{b'} G_{b,h}}}{2} + W_\beta \leq \left| x_{C_k G_{b,h}} - x_{C_{k'} G_{b,h}} \right| \; and$$

$$\frac{L_{G_b G_{b,h}} + W_{G_{b'} G_{b,h}}}{2} + W_\beta \leq \left| y_{C_k G_{b,h}} - y_{C_{k'} G_{b,h}} \right| ; \; \forall x_{G_b G_{b,h}} \neq x_{G_{b'} G_{b,h}} \; and \; y_{G_b G_{b,h}} \neq y_{G_{b'} G_{b,h}} \tag{54}$$

Step 9: Check if all groups are arranged on plant floor by using Equation (55). If not, repeat from Step 6.

$$\sum_{\substack{b=1 \\ h=1}}^{G_{B,H}} \sum_{k=1}^{C_K} \sum_{t=1}^{T} \sum_{b=1}^{G_B} \theta_{t C_k G_{b,h}} . \tau_{C_k G_b} \left(L_{G_b G_{b,h}} . W_{G_b G_{b,h}} \right) \leq L_{PF} W_{PF} \tag{55}$$

If there are no possible arrangements that satisfy plant floor dimensions, discard the current selection of part families and repeat from Step 2.

Step 10: Calculate area utilization for each possible arrangement of part family groups on plant floor as given in Equation (56).

$$\left(\frac{\sum_{\substack{b=1 \\ h=1}}^{G_{B,H}} \sum_{k=1}^{C_K} \sum_{t=1}^{T} \sum_{b=1}^{G_B} \theta_{t C_k G_{b,h}} . \tau_{C_k G_b} \left(L_{G_b G_{b,h}} . W_{G_b G_{b,h}} \right)}{L_{PF} W_{PF}} \times 100\% \right) \tag{56}$$

Select the part family groups arrangement with highest area utilization.

Step 11: Calculate costs of objective functions given in Phase 1 and Phase 2 for the selected part family groups arrangement with highest area utilization.

Step 12: Discard the current set of assigned values for h. Repeat from Step 4 to Step 10 for all the possible values of h.

Step 13: Repeat from Step 2 to Step 12 for each possibility of part families.

As stated by Shafigh et al. (2017) and Iqbal (2010) cost saving percentage can be used to measure the level of improvement of a developed layout system with respect to the current layout system. Cost saving percentage is calculated as given in Equation (57) (Shafigh et al., 2017; Iqbal, 2010). Cost of current layout system is calculated for the same cost terms used in developed mathematical models of Phase 1 and Phase 2 (Section 6.3.2.5 and Section 6.4.2.5).

$$cost\ saving\ percentage = \left(\frac{T_{current} - T_{developed}}{T_{current}}\right) \times 100\% \quad (57)$$

Where;

$T_{current}$: $Cost\ of\ current\ layout\ system$

$T_{developed}$: $Cost\ of\ developed\ layout\ system$

Record the design outputs of the developed system (Section 6.2). Stopping criteria reaches when there is no significant improvement of cost saving percentage.

Step 14: Continue to generate layouts for consecutive planning horizons by considering the preceding layout as the existing layout.

CHAPTER 7: RESULTS AND DISCUSSION

7.1 Introduction

Initial evaluation of the developed system was done by using data collected from Factory 1 and thereafter the required modifications to the program code was done accordingly. Internal secondary data collected from five intimate apparel manufacturing factories were used to validate the developed production layout planning system.

7.2 Initial evaluation of the developed system

Data collected from Factory 1 were used for initial evaluation of the developed system. As mentioned by Shafigh et al. (2017), Malakooti (2014) and Iqbal (2010), if the same input data sets are used for comparison, DCMS based layouts should result in minimum of 30% cost saving when compared with product layouts. It is considered as the acceptable level of improvement to determine the validity of a cellular layout system. According to the computer program, developed system resulted in 41.51% cost saving for Factory 1. Hence, it is possible to determine that the developed system is capable of improving the current layout. Input and output data of the initial evaluation are given in Appendix F.

7.3 Summary of the case studies on factories selected for validation

Validation of developed system is done based on case studies of five intimate apparel manufacturing factories which are currently producing fast fashion orders. These factories are referred as Factory 2,3,4,5, and 6. All five factories are manufacturing both fast fashion and mass production orders, and fast fashion orders are assembled in a separate section within the plant floors. It is done to facilitate the ease of management as mentioned by the respective managers. Summary of the production layout related data in these factories is given in Table 7.1.

In all five factories, the production details of upcoming fast fashion orders are known in advance for a certain period. Hence, according to the definitions stated by Mungwattana (2000), these factories have dynamic-deterministic production requirement.

Table 7.1 – Summary of the layout related data in selected factories

	Factory 2	**Factory 3**	**Factory 4**	**Factory 5**	**Factory 6**
Product with highest demand for fast fashion orders	Bras	Brazilian knickers	Shorts	Shape wear	Bridal lingerie
Location of bra-cup molding machines	Located in a separate area	Not applicable	Not applicable	Located in a separate area	Located in a separate area
Layout used for machine arrangement of individual production lines	Straight single-line double-row layout without center table	U-shaped layout	U-shaped layout	Straight single-line double-row layout without center table	Straight single-line double-row layout with center table
Operators' work position	Sitting	Standing	Standing	Sitting	Sitting

Product types manufacturing in Factory 2, 5 and 6 require bra cup molding machines that are located in a separate area adjacent to the plant floor. Molded bra cups are transported to the relevant production lines by the material handlers responsible for distributing raw materials in plant floor.

All the selected factories use product layout type as the basis for machine arrangements in assembly lines. Machine arrangements and material flows of individual assembly lines in the selected factories are illustrated in Figure 7.1 to 7.4.

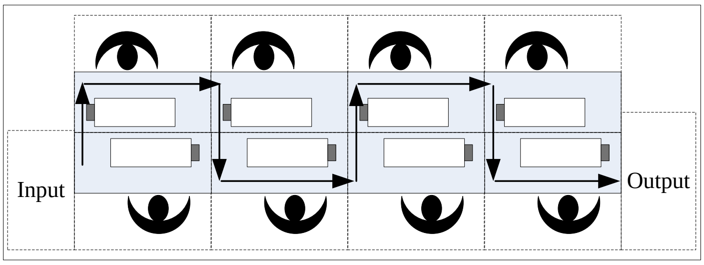

Figure 7.1 – Machine arrangements of production lines in Factory 2

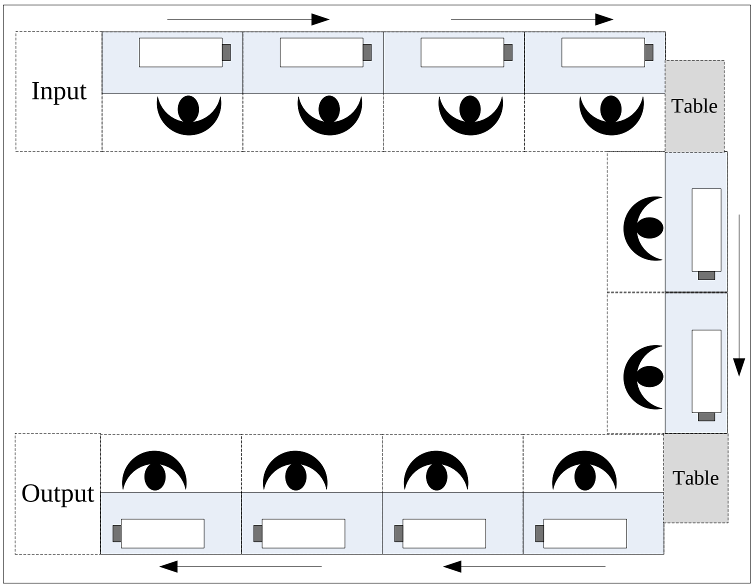

Figure 7.2 – Machine arrangements of production lines in Factory 3, and 4

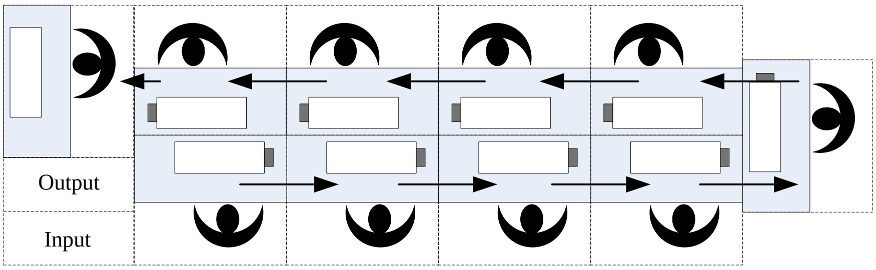

Figure 7.3 – Machine arrangements of production lines in Factory 5

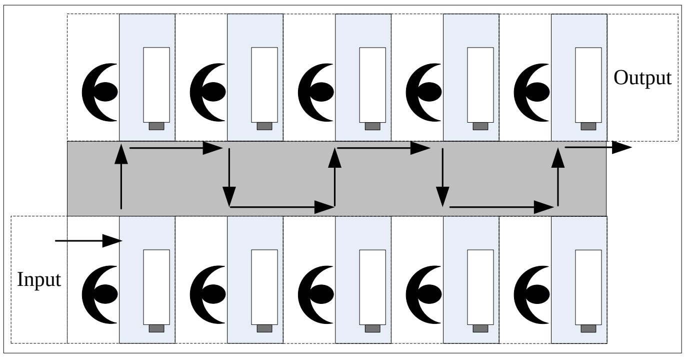

Figure 7.4 – Machine arrangements of production lines in Factory 6

As given in Figure 7.2, Factory 3 and 4 are using U-shaped machine arrangement for production lines. U-shaped layouts used in these two factories can be categorized as work-oriented with baton-touch operating mode and SMD UALBP-1 line balancing approach. Hence, the level of operator intervention, operating mode and line balancing approach are similar to the developed system. However, the effect of walking time on the total workstation time is neglected when balancing the assembly lines. Furthermore, these factories have lack of focus on underlining principles of U-shaped layout design for reduced changeover time i.e. cell formation based on GT principles. In addition, determination of U-shaped layout locations on plant floor is done without considering the resultant machine relocation costs and material handling costs.

Selected five factories use manual material handling methods. These factories have recommended minimum bundle size for material movement between production lines as given in Appendix G.

Depending on the requirement, all the factories perform machine set-up activities and operator training within the lines and/or in the machine set-up area.

7.4 Validation of the developed production layout planning system

Problem sizes tested for the system validation are given in Table 7.2. Input and output data of the system validation for Factory 2 to 6 are given in Appendix G and Appendix H.

Table 7.2 – Problem sizes used for system validation

Factory	Number of parts	Number of machine types
2	12	14
3	23	15
4	28	12
5	21	15
6	21	16

Outputs of the developed system validation results for Factory 2 are presented as an example. Input and output data tables are presented according to the standard representation stated by Mahdavi, & Mahadevan (2008).

Outputs of the developed system are as follows (Section 6.2).

1. Part family groups with respective part types, and dynamic cells for considered planning horizon/s
2. Machine grouping to the dynamic cells
3. Coordinates of dynamic cell locations
4. Coordinates of each machine location in dynamic cells
5. Assignment of operators to the operations in dynamic cells
6. Cost saving percentages of individual cost terms and total cost of developed system compared with current state

Table 7.3 shows the respective part types, and dynamic cells of each part family group. In Table 7.3, the terms b, t, and k denotes the part family group number, part type, and the dynamic cell, respectively.

Table 7.3 – Results of part family groups for the example

b	t	k
1	6,7,10,11,12	6,7,11,12,13,14
2	2,5,8	2,5,8,9
3	1,3,4,10	1,3,4,10

Table 7.4 shows the number of machines of each machine type assigned to dynamic cells. The terms i, and k denotes the machine type, and dynamic cell respectively. As an example, dynamic cell 2 consists of five machines of type 1 as given in Table 7.4.

Table 7.4 – Number of machines of each machine type in the dynamic cells

i	k													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	5	2	4	1	3	3	2	2	4	2	3	2	2
2	1	1	3	2	3	2	2	1	1	2	1	1	1	1
3	2	1	1	2	5	1	1	4	4	2	2	1	4	4
4	2	1	0	0	0	0	0	0	0	0	0	0	0	0
5	3	0	2	0	0	0	0	0	0	0	0	0	0	0
6	0	0	1	3	0	0	0	2	2	3	0	0	0	0
7	0	0	0	0	4	0	0	2	2	0	0	0	2	2
8	0	0	0	0	0	2	2	0	0	0	0	0	0	0
9	0	1	0	0	2	3	3	1	1	0	8	4	2	2
10	0	0	0	0	0	0	0	0	0	0	0	1	0	0
11	1	2	1	1	1	2	2	1	1	1	1	1	0	0
12	0	0	1	1	0	0	0	0	0	1	0	0	1	1
13	1	0	0	0	0	1	1	1	1	0	0	0	2	2
14	2	2	2	2	1	3	3	2	2	2	2	2	2	2

Operator assignment to operations of each dynamic cell is given in Table 7.5. In Table 7.5, the terms n, and k denotes the operation numbers, and dynamic cells respectively. As an example, there are 12 operators assigned to dynamic cell 1 according to the Table 7.5. Operation 1 and 2 are assigned to the operator 1 in dynamic cell 1. Operator assignments for each of the operations in dynamic cells are done in similar manner as represented in Table 7.5.

Table 7.5 – Operator assignment to operations in dynamic cells

n	k							
	1	2	3	4	5	6	7	8
1	1	1	1	1	1	1	1	1
2	1	2,3,4	2	2	1,2	2	2	1
3	2	5	3	2	3	2	2	2
4	3	6	3	3,4	3	4	3	3,4
5	4,5	7	4	5,6	4	5	4	5
6	5,6,7	8	2	7	5,6	5	5	6
7	8	9	5	7	7	6,7	5	7
8	9	10	6	8	8	8	6,7	8
9	10	4	7	9	9	9	8	9
10	11	11	8	10	10	10	9	10,11
11	12	12	9,10	11	11	11	10	12
12		12	11	12	11	12	11	13
13			11	13	11	13	12	14
14			1	14	12	14	13	14
15			12		12	14	14	15
16			13		13	1	14	16
17					14	15	1	
18					15	16	15	
19					15		16	
20					16			
21					16			

Table 7.5 – Operator assignment to operations in dynamic cells continued

n	k					
	9	10	11	12	13	14
1	1	1	1	1	1	1
2	1	1	1	2,3	1	1
3	2	2	2	3,4	2	2
4	3,4	3	2	5	3,4	3,4
5	5	4,5	3	5	5	5
6	6	6	3	6	6	6
7	7	6	4	7	7	7
8	8	7	5	8	8,9	8,9
9	9	8	6	9	10	10
10	10,11	9	6	10	11	11
11	12	10	7	11	12	12
12	13	11	7	12	13	13
13	14	12	8		13	13
14	14	13	9		14	14
15	15		9		14	14
16	16		10			
17			11			
18			11			
19			12			
20			12			
21			13			
22			14			
23			14			
24			15			
25			15			

Dynamic cell locations in plant floor are given in Table 7.6. Respective coordinate values represent the center of each dynamic cell. In Table 7.6, the terms k denotes the dynamic cells. All the dimensional related data are given in meters.

Table 7.6 – Coordinates of dynamic cell locations of numerical example

k	x	y
1	12.97	4.255
2	7.97	3.645
3	13.58	3.645
4	13.58	12.435
5	7.97	13.045
6	2.36	13.045
7	2.36	15.485
8	7.97	4.865
9	7.97	15.485
10	12.97	14.265
11	2.36	4.865
12	2.36	3.645
13	7.97	4.865
14	7.97	15.485

Table 7.7 shows the machine types assigned to each location of the dynamic cell. The terms g, and k denotes the machine locations, and dynamic cells respectively. Machine type 1 of dynamic cell 1 located at location 1 as given in Table 7.7. Similarly, two machines of machine type 4 are assigned to location 4 and 5 of the dynamic cell 1. Total number of machines in dynamic cell 1 is 13 and the machine arrangement in intra-cell layout follows the given sequence. Machine placement at each location of other dynamic cells is done in similar manner.

Table 7.7 – Machine type at each location

g	*k*													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	1	12	12	1	14	14	1	1	12	14	1	1	
2	3	1	1	1	7	2	2	3	3	1	2	1	1	1
3	2	1	2	1	7	1	1	7	7	1	3	1	3	3
4	4	1	2	1	2	9	9	7	7	1	9	9	7	7
5	4	3	3	6	9	2	2	2	2	6	9	9	7	7
6	5	1	2	6	3	8	8	1	1	6	1	9	2	2
7	5	2	1	3	7	1	8	3	3	3	9	10	1	1
8	5	4	6	2	2	1	1	9	9	2	9	2	3	3
9	11	11	5	1	3	9	1	3	3	1	9	11	9	9
10	3	11	5	6	7	3	9	6	6	6	9	3	9	9
11	13	9	11	3	2	9	3	6	6	3	9	9	3	3
12	14	14	14	2	3	11	9	11	11	2	3	14	12	12
13	14	14	14	11	3	11	11	3	3	11	9	14	3	3
14				14	11	13	11	13	13	14	11		13	13
15				14	9	14	13	14	14	14	14		14	14
16					14	14	14	14	14				14	14
17							14							

Coordinate values for each machine location in dynamic cells are given in Table 7.8 and Table 7.9.

Table 7.8 – x-coordinate values for machine locations in dynamic cells

g	*k*													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	13.605	6.935	13.87	13.87	6.935	0.53	0.53	7.2	7.2	13.87	0.53	0.53	7.2	7.2
2	13.605	6.935	13.87	13.87	6.935	0.53	0.53	7.2	7.2	13.87	0.53	0.53	7.2	7.2
3	13.605	6.935	13.87	13.87	6.935	0.53	0.53	7.2	7.2	13.87	0.53	0.53	7.2	7.2
4	13.605	6.935	13.87	13.87	6.935	0.53	0.53	7.2	7.2	13.87	0.53	0.53	7.2	7.2
5	13.605	6.935	13.87	13.87	6.935	0.53	0.53	7.2	7.2	13.87	0.53	0.53	7.2	7.2
6	13.605	8.34	15.01	13.87	6.935	0.53	0.53	7.2	7.2	13.87	0.53	1.67	7.2	7.2
7	15.01	9.56	16.23	15.01	6.935	0.53	0.53	7.2	7.2	15.01	0.53	2.89	7.2	7.2
8	16.23	10.78	17.45	16.23	8.34	1.67	1.67	8.34	8.34	16.23	1.67	4.11	8.34	8.34
9	17.37	11.92	18.59	17.45	9.56	2.89	2.89	9.56	9.56	17.45	2.89	5.25	9.56	9.56
10	17.37	11.92	18.59	18.59	10.78	4.11	4.11	10.78	10.78	18.59	4.11	5.25	10.78	10.78
11	17.37	11.92	18.59	18.59	11.29	5.25	5.25	11.92	11.92	18.59	5.25	5.25	11.92	11.92
12	17.37	11.92	18.59	18.59	11.29	5.25	5.25	11.92	11.92	18.59	5.25	5.25	11.92	11.92
13	17.37	11.92	18.59	18.59	11.29	5.25	5.25	11.92	11.92	18.59	5.25	5.25	11.92	11.92
14				18.59	11.29	5.25	5.25	11.92	11.92	18.59	5.25		11.92	11.92
15				18.59	11.29	5.25	5.25	11.92	11.92	18.59	5.25		11.92	11.92
16					11.29	5.25	5.25	11.92	11.92				11.92	11.92
17							5.25							

Table 7.9 – y-coordinate values for machine locations in dynamic cells

g	*k*													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	7.77	6.55	6.55	16.48	17.7	17.7	20.14	8.46	20.14	20.14	8.46	6.55	8.46	20.14
2	6.55	5.33	5.33	15.26	16.48	16.48	18.92	7.77	18.92	18.92	7.77	5.33	7.77	18.92
3	5.33	4.11	4.11	14.04	15.26	15.26	17.7	6.55	17.7	17.7	6.55	4.11	6.55	17.7
4	4.11	2.89	2.89	12.82	14.04	14.04	16.48	5.33	16.48	16.48	5.33	2.89	5.33	16.48
5	2.89	1.67	1.67	11.6	12.82	12.82	15.26	4.11	15.26	15.26	4.11	1.67	4.11	15.26
6	1.67	0.53	0.53	10.38	11.6	11.6	14.04	2.89	14.04	14.04	2.89	0.53	2.89	14.04
7	0.53	0.53	0.53	9.24	10.38	10.38	12.82	1.67	12.82	12.82	1.67	0.53	1.67	12.82
8	0.53	0.53	0.53	9.24	9.24	9.24	11.68	0.53	11.68	11.68	0.53	0.53	0.53	11.68
9	0.53	1.67	1.67	9.24	9.24	9.24	11.68	0.53	11.68	11.68	0.53	1.67	0.53	11.68
10	1.67	2.89	2.89	10.38	9.24	9.24	11.68	0.53	11.68	12.82	0.53	2.89	0.53	11.68
11	2.89	4.11	4.11	11.6	10.38	10.38	12.82	1.67	12.82	14.04	1.67	4.11	1.67	12.82
12	4.11	5.33	5.33	12.82	11.6	11.6	14.04	2.89	14.04	15.26	2.89	5.33	2.89	14.04
13	5.33	6.55	6.55	14.04	12.82	12.82	15.26	4.11	15.26	16.48	4.11	6.55	4.11	15.26
14				15.26	14.04	14.04	16.48	5.33	16.48	17.7	5.33		5.33	16.48
15				16.48	15.26	15.26	17.7	6.55	17.7	18.92	6.55		6.55	17.7
16					16.48	16.48	18.92	7.24	18.92				7.24	18.92
17							20.14							

7.4.1 Analysis of cost saving percentages of the selected factories

Saving percentages of the individual cost terms and the total cost of developed system compared to current state in Factory 2 to 6 are given in Table 7.10.

Table 7.10 – Cost saving percentages of the developed system compared to current state

	Cost saving percentages				
Cost term	**Factory 2**	**Factory 3**	**Factory 4**	**Factory 5**	**Factory 6**
EMRC	69.65%	65.62%	57.92%	62.98%	71.39%
MSC	60.32%	51.06%	61.90%	64.27%	59.58%
EMHC	28.79%	21.48%	29.69%	27.17%	19.69%
AMRC	45.64%	45.06%	42.25%	47.20%	31.51%
AMHC	58.18%	44.65%	41.08%	45.85%	23.43%
DB	25.65%	25.37%	20.11%	26.12%	24.37%
DT	22.25%	24.29%	17.06%	39.30%	26.96%
Total cost of the developed system	49.05%	41.82%	42.80%	48.67%	44.76%

All the selected factories (Factory 2 to 6) are currently using variations of product layout for the production lines (Section 7.3). Shafigh et al. (2017) and Iqbal (2010) stated that, in order to validate the improvements, DCMS based layouts should result in minimum of 30% cost saving when compared with product layouts, for the same input data sets. Since the sample size is 5 factories, t-test was used to test the validity of the developed system.

Hypothesizes of the t-test are as follows.

Null hypothesis: Developed system does not show an acceptable level of improvement in terms of cost saving

Alternative hypothesis: Developed system shows an acceptable level of improvement in terms of cost saving

$$H_o: \mu = 30\%$$

$$H_a: \mu > 30\%$$

Degree of freedom for hypothesis test is 4, and confidence level is 95%. Hypothesis test results are given in Table 7.11.

Table 7.11 – Hypothesis test results of validation

Mean	**Standard deviation**	**t-value**	**p-value**
45.42%	0.033	10.396	0.0002

According to the t-test results, the null hypothesis was rejected with 95% confidence level. Therefore, it is possible to confirm the validity of developed production layout planning system in minimization of the considered cost terms in different factories with different layout configurations.

In the developed system, costs of machine relocation (i.e., EMRC and AMRC) and machine set-up cost (MSC) occur at the beginning of planning periods whereas rest of the cost terms exist in between beginning and end of planning periods. Table 7.10 shows that EMRC, AMRC and MSC are having higher saving percentages than that of other cost terms. As stated by Rafiei, & Ghodsi (2013) and Mahdavi, Aalaei, et al. (2010), changeover cost is measured by using these three cost terms in mathematical models of DCMS designs. Based on that, it is possible to determine that the developed production layout planning system is capable of addressing the identified research problem. Although the main focus is on minimizing changeover costs, considering only the changeover related cost terms (i.e., machine relocation costs and machine set-up costs) may not guarantee effective performance during assembly process. Other four cost terms i.e., Inter-cell material handling cost (EMHC), Intra-cell material handling cost (AMHC), Cost of time deviation between target cycle time per bundle and workstation cycle times (DT) and Cost of cycle time deviation between bottleneck workstation and other workstations (DB) are used to address this issue.

It was observed that some fast fashion orders consist of different product types that are assembled in more than one production line and later packed as a single product. Example is the bridal lingerie manufactured in Factory 6 which include minimum of two of the following product types i.e. bra, knickers, garter, and corset. Factory 6 used a separate packing section for this type of fast fashion orders. Location of this packing section is fixed in current state of Factory 6 and operators have to transport the output pieces from respective production lines to packing section. The developed system assumes that no physical re-configuration to the plant floor is done during cell formation. Hence, the current locations of production floor and packing section are considered for validation. That may be the reason for comparatively low saving percentage of EMHC than that of other cost terms in Factory 6.

Currently used bundle sizes in the selected factories are considered when calculating cost saving percentages given in Table 7.10. It is considered as a constant for current layouts used in each of the factories and developed system. Therefore, the intra-cell material handling cost saving percentages in Table 7.10 are independent from bundle sizes. Hence, it is possible to deduce that the observed saving percentages in material handling are due to minimization of the travelled distances.

As mentioned by resource personnel in Factory 2, 5, and 6, iron tables are usually located at the end of production lines before or after end line examine and packing. It is done to minimize the possible injuries due to operators and supervisors movements within the production line. According to the observations, some operations require to iron and/or press the sub-assembled pieces depending on operation requirement and/or fabric characteristics. As given in Figure 7.1, 7.3, and 7.4, Factory 2, 5 and 6 are currently using straight-line layouts (Section 2.9.2.3.7). In case of these three factories, going to the iron table and returning causes increased intra-cell material handling distances. This issue is minimized in Factory 3 and 4 due to the use of U-shaped layout. Line balancing approach and nature of layout directly influences the intra-cell material handling distances (Hassan, 1995). Selected factories are currently balancing the assembly lines by neglecting the possible walking times. Conversely, the developed system considers the walking time between machines when balancing the workload. Hence, saving percentages of DT and DB are the lowest when compared to other cost terms. Effect of consideration of walking time in workload balancing is mitigated by the considerable saving percentages of AMHC in all the factories as shown in Table 7.10.

CHAPTER 8: CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

8.1 Introduction

This chapter presents a summary of the major findings of this research, and possible future research directions.

8.2 Conclusions

This research addresses the problem of increased changeover costs related with production layout planning systems that are currently used for fast fashion apparels. The developed production layout planning system consist of mathematical models, an algorithm and a computer program to generate optimal layout solutions to minimize costs of machine relocations, machine set-ups, material handling and workload balancing. The developed system was validated using data collected from five intimate apparel manufacturing factories. According to the validation results, the developed system showed significant cost saving percentages when compared with current state of them.

The developed production layout planning system uses the DCMS concept as the basis. Optimal layouts generated through the developed system changes only at the beginning of planning period. Therefore, the dynamic cells in plant floor remain robust between the beginning and end of each planning period for one or more products. Since the developed system identify the number of planning periods with maximum cost saving for the specified planning horizon, it ensures that resultant layouts balance the machine relocation and machine set-up costs, with material handling costs. Therefore, the developed production layout planning system has the features of both robust and flexible layout approaches used for DCMS designs. Literature review showed that best approach of DCMS design is the balancing of robust and flexible features in resultant layout. Hence, it is possible to state that the developed production layout planning system for fast fashion apparels is a well-designed DCMS.

Validation results of the developed system shows that EMRC, AMRC and MSC of the developed system are having significant cost saving percentages when compared to current state. According to literature review, changeover cost is measured by using these three cost terms in mathematical models of DCMS designs. Therefore, it is possible to conclude that the developed production layout planning system addresses the identified research problem.

Validation of the developed system was done by using internal secondary data. Reliability of these data depends on the employees who are currently engaged in data collection and current data recording practices. Hence, it is possible to have minor alterations in the input data used for system validation.

Although the intimate apparel manufacturing factories were used for validation, it may be possible to use the developed system in industries with similar production environments.

8.3 Future research directions

According to literature review, the maximum benefits of cell layout is achievable by incorporating production control, process planning, incentive schemes, accounting, purchasing, and determining staff levels.

The developed system considers the production plans prepared by planning departments of apparel manufacturing factories. Case studies on selected factories show that these plans are prepared by forecasting learning curves. These learning curves are prepared based on historical data on operator performance and nature of the received orders. Literature review showed that there can be unpredictable variations of actual learning curves due to individual operator related factors (i.e., skill level, age, experience, confidence, etc), organizational related factors (i.e., ergonomics conditions, amount of training provided, incentives, motivational programs, etc) and operation related factors (i.e., number of repetitions, complexity, etc). Hence, it may be possible to extend the developed system by incorporating an appropriate method to forecast the possible variations in learning curves. Case studies on factories showed that skill matrices are maintained to record the operator skill levels. It is possible to extend the developed system to consider these skill matrices in line balancing stage.

Bundle sizes specified in selected factories are used for the validation of the developed system. It may be possible to incorporate an appropriate method to determine optimum bundle sizes for fast fashion orders.

Based on abovementioned factors, the developed production layout planning system for fast fashion apparels can be extended into following future research directions.

- Establishing links between front-end processes, scheduling decisions and layout development
- Developing a method to accurately forecast the learning curves used for dynamic cell layout design
- Incorporating skill matrices in line balancing stage of dynamic cells
- Improving workplace ergonomic conditions and workplace design in dynamic cells
- Determining optimal bundle sizes for fast fashion apparels
- Developing an interactive software program to facilitate ease of modifications to the developed system under industrial usage

LIST OF REFERENCES

Abdi, M. R. (2005). Selection of a layout configuration for reconfigurable manufacturing systems using the AHP. ISAHP, Honolulu, Hawaii.

Abernathy, F. H., Volpe, A., & Weil, D. (2006). The future of the apparel and textile industries: prospects and choices for public and private actors. *Environment and Planning A*, 38(12), 2207-2232.

Agrawal, A. K., Bhardwaj, P., Kumar, R., & Sharma, S. (2015, March). Particle Swarm Optimization for natural grouping in context of group technology application. In Industrial Engineering and Operations Management (IEOM), 2015 International Conference on (pp. 1-8). IEEE.

Ahkioon, S., Bulgak, A. A., & Bektas, T. (2009). Cellular manufacturing systems design with routing flexibility, machine procurement, production planning and dynamic system reconfiguration. International Journal of Production Research, 47(6), 1573-1600.

Ahmad, S., Bagum, N., Rashed, A., Khalil, A. B. & Iqbal, M., (2012). The impacts of ALB in apparel supply chain, *Asian Journal of Management Sciences and Education*, 1(1), pp12-20

Ahuja, I. P. S., & Khamba, J. S. (2008). Total productive maintenance: literature review and directions. *International Journal of Quality & Reliability Management*, 25(7), 709-756.

Ajenblit, D. A., & Wainwright, R. L. (1998, May). Applying genetic algorithms to the U-shaped assembly line balancing problem. In Evolutionary Computation Proceedings, 1998. IEEE World Congress on Computational Intelligence., The 1998 IEEE International Conference on (pp. 96-101). IEEE.

Alim, M. A., & Hasan, M. R. (2010). Factors Affecting Supply Chain Management Efficiency in Cross Border Outsourcing-A case study of H&M and it´ s Outsourcing Operations in Bangladesh.

Aljuneidi, T. (2013). A Mathematical Approach to the Design of Cellular Manufacturing System Considering Dynamic Production Planning and Worker Assignments (Doctoral dissertation, Concordia University).

Anbumalar, V., & Raja Chandra Sekar, M. (2015). Methods for solving cell formation, static layout and dynamic layout cellular manufacturing system problems: a review. *Asian Journal of Science and Technology*, Vol.6No.12, pp.2107-2112

Anbumalar, V., Mayandy, R., & Prasath, K. A. (2014). Implementation and Selection of Optimum Layout Design in Cellular Manufacturing for Process Industry–A Case Study.

Ang, D., Khadanga, D., & Ho, J. (2014). Reflections on Hybrid Production Layouts. World, 4(2).

Arn, E. A. (1975). Group Technology: An Integrated Planning and Implementation Concept for Small and Medium Batch Prodution.

Arnold, J. T. (2011). Introduction to materials management. Pearson Education India.

Arora, P. K., Haleem, A., & Singh, M. K. (2013). Recent development of cellular manufacturing systems. Sadhana, 38(3), 421-428.

Asgharpour, M. J., & Javadian, N. (2004). Solving a stochastic cellular manufacturing model by using genetic algorithms. International Journal of Engineering Transactions A, 17, 145-156.

Attwood, D. A., Deeb, J. M., & Danz-Reece, M. E. (2004). Ergonomic solutions for the process industries. Gulf Professional Publishing.

Aus, R. (2011). *Trash to Trend – Using Upcycling in Fashion Design*. Retrieved from: http://vana.artun.ee/popFile.php?id=2269.

Avikal, S., Jain, R., Mishra, P. K., & Yadav, H. C. (2013). A heuristic approach for U-shaped assembly line balancing to improve labor productivity. Computers & Industrial Engineering, 64(4), 895-901.

Azadeh, A., Haghighi, S. M., & Saedi, H. (2012, December). An integrated simulation-DEA algorithm for layout optimization. In Computer Systems and Industrial Informatics (ICCSII), 2012 International Conference on (pp. 1-6). IEEE.

Azadeh, A., Moghaddam, M., Nazari–Doust, B., and Jalalvand, F. (2015). Fuzzy and stochastic mathematical programming for optimisation of cell formation problems in random and uncertain states. *International Journal of Operational Research*, Vol.22No.2, pp.129-147.

Babin, B. J., & Zikmund, W. G. (2015). Exploring marketing research. Cengage Learning.

Badri, H. M., Deros, B. M., Syahri, M., Saleh, C., & Fitria, A. (2016, February). Implementation Learning and Forgetting Curve to Scheduling in Garment Industry. In IOP Conference Series: Materials Science and Engineering (Vol. 114, No. 1, p. 012068). IOP Publishing.

Bagheri, M., & Bashiri, M. (2014). A new mathematical model towards the integration of cell formation with operator assignment and inter-cell layout problems in a dynamic environment. Applied Mathematical Modelling, 38(4), 1237-1254.

Bajic, M. M. (2001). Design of Dynamic Cellular Manufacturing Systems (Doctoral dissertation, University of Adelaide, Department of Mechanical Engineering).

Balakrishnan, J., & Hung Cheng, C. (2005). Dynamic cellular manufacturing under multiperiod planning horizons. Journal of manufacturing technology management, 16(5), 516-530.

Bangsow, S. (2010). Manufacturing simulation with plant simulation and simtalk: usage and programming with examples and solutions. Springer Science & Business Media.

Bartholdi III, J. J., & Eisenstein, D. D. (2005). Using bucket brigades to migrate from craft manufacturing to assembly lines. Manufacturing & Service Operations Management, 7(2), 121-129.

Barzdins, J., & Caplinskas, A. (Eds.). (2013). Databases and Information Systems: Fourth International Baltic Workshop, Baltic DB&IS 2000 Vilnius, Lithuania, May 1–5, 2000 Selected Papers. Springer Science & Business Media.

Basu, R., & Wright, J. N. (2005). Total operations solutions. Routledge.

Basu, S. K., Sahu, K. C., & Rajiv, B. (2012). Industrial Organization and Management. PHI Learning Pvt. Ltd..

Baudin, M. (2007). Working with machines: the nuts and bolts of lean operations with jidoka. CRC Press.

Bayram, H., & Şahin, R. (2016). A comprehensive mathematical model for dynamic cellular manufacturing system design and Linear Programming embedded hybrid solution techniques. Computers & Industrial Engineering, 91, 10-29.

Bellgran, M., & Safsten, E. K. (2009). Production development: design and operation of production systems. Springer Science & Business Media.

Benhabib, B. (2003). Manufacturing: design, production, automation, and integration. CRC Press.

Benjaafar, S., & Ramakrishnan, R. (1996). Modelling, measurement and evaluation of sequencing flexibility in manufacturing systems. International journal of production research, 34(5), 1195-1220.

Benjaafar, S., & Sheikhzadeh, M. (2000). Design of flexible plant layouts. Iie Transactions, 32(4), 309-322.

Benjaafar, S., Heragu, S. S., & Irani, S. A. (2002). Next generation factory layouts: research challenges and recent progress. Interfaces, 32(6), 58-76.

Benjafaar, S., Heragu, S. S., & Irani, S. A. (2000). Next Generation Factory Layouts: Research Challenges And Recent Progress. Retrieved from: http://www.isye.umn.edu/faculty/pdf/NGFL-1.pdf

Bernhardt, A. D., McGrath, S., & DeFilippis, J. (2007). Unregulated work in the global city: Employment and labor law violations in New York City. Brennan Center for Justice at New York University School of Law.

Bhangale, J. H., & Mahalle, A. M. (2013). Parametric Studies In Automobile Manufacturing Industry Using Cell Focused Plant Layout Simulation Approach. European Scientific Journal, ESJ, 9(9).

Bhardwaj, V., & Fairhurst, A. (2010). Fast fashion: response to changes in the fashion industry. The International Review of Retail, Distribution and Consumer Research, 20(1), 165-173.

Bidanda, B., Ariyawongrat, P., Needy, K. L., Norman, B. A., & Tharmmaphornphilas, W. (2005). Human related issues in manufacturing cell design, implementation, and operation: a review and survey. Computers & Industrial Engineering, 48(3), 507-523.

Black, J. T. (2007). Design rules for implementing the Toyota Production System. International Journal of Production Research, 45(16), 3639-3664.

Black, J. T., & Schroer, B. J. (1993). Simulation of an apparel assembly cell with walking workers and decouplers. Journal of Manufacturing Systems, 12(2), 170-180.

Bokhorst, J. A., & Gaalman, G. J. (2009). Cross-training workers in Dual Resource Constrained systems with heterogeneous processing times. International Journal of Production Research, 47(22), 6333-6356.

Bovey, W. H., & Hede, A. (2001). Resistance to organisational change: the role of defence mechanisms. Journal of managerial psychology, 16(7), 534-548.

Bratcu, A. I., & Dolgui, A. (2005). A survey of the self-balancing production lines ("bucket brigades"). Journal of Intelligent Manufacturing, 16(2), 139-158.

Brenner, T. (Ed.). (2012). Computational techniques for modelling learning in economics (Vol. 11). Springer Science & Business Media.

Brooks, A. (2015). Fast Fashion: A cut from Clothing Poverty with exclusive new content. Zed Books Ltd..

Bryson, J. (2006). Managing information services: a transformational approach. Ashgate Publishing, Ltd.

Bukchin, Y., Meller, R. D., & Liu, Q. (2006). Assembly system facility design. IIE Transactions, 38(1), 53-65.

Bychkov, I., Batsyn, M., & Pardalos, P. M. (2016, May). Heuristic for Maximizing Grouping Efficiency in the Cell Formation Problem. In International Conference on Network Analysis (pp. 11-26). Springer, Cham.

Cachon, G. P., & Swinney, R. (2011). The value of fast fashion: Quick response, enhanced design, and strategic consumer behavior. Management Science, 57(4), 778-795.

Cagliano, A. C., Mustafa, M. S., Rafele, C., & Zenezini, G. (2014, September). Logistics Performance Measurement for Sustainability in the Fast Fashion Industry. In HICL (Hamburg International Conference of Logistics), Next Generation Supply Chains-Trends and Opportunities. Hamburg, epubli GmbH (pp. 113-135).

Cakmakci, M. (2009). Process improvement: performance analysis of the set-up time reduction-SMED in the automobile industry, International Journal of Advanced Manufacturing Technology, Vol. 41, No. 18, pp. 168-179. Available from: Springer [Accessed 06 March 2014]

Caro, F., & Martinez-de-Albeniz, V. (2015). Fast fashion: business model overview and research opportunities. In Retail Supply Chain Management (pp. 237-264). Springer US.

Case, K., & Newman, S. T. (Eds.). (2004). Advances In Manufacturing Technology VIII: Proceedings Of The 10th National Conference On Manufacturing Research. CRC Press.

Centre for Australia-Asia Studies, Deaking University.

Chacosky, A. T. (2015). Allocation of Workers Utilizing Models with Learning, Forgetting, and Various Work Structures. Rochester Institute of Technology.

Chakravorty, S. S., & Hales, D. N. (2008). The evolution of manufacturing cells: An action research study. European Journal of Operational Research, 188(1), 153-168.

Chandrasekera, D.E. (2016). Fast fashion is the game for SL – Industry expert. Retrieved from: http://www.sundaytimes.lk/161016/business-times/fast-fashion-is-the-game-for-sl-industry-expert-212106.html

Chang, A. Y. (1999). An attribute approach to the measurement of manufacturing system flexibility (Doctoral dissertation, University of Warwick).

Chang, C. C. (2013). A Water Flow-like Algorithm for Cell Formation, Cell Layout, and Intracellular Machine Layout Problems. Journal of Convergence Information Technology, 8(4).

Chang, C. C., Wu, T. H., and Wu, C. W. (2013). An efficient approach to determine cell formation, cell layout and intracellular machine sequence in cellular manufacturing systems. *Computers and Industrial Engineering*, Vol.66No.2, pp.438-450.

Chase, R. B., Jacobs, F. R., Aquilano, N. J., & Agarwal, N.K. (2008). Operations management for competitive advantage. Irwin/McGraw-Hill.

Chen, J. C., Chen, C. C., Su, L. H., Wu, H. B., & Sun, C. J. (2012). Assembly line balancing in garment industry. Expert Systems with Applications, 39(11), 10073-10081.

Chen, J. C., Dugger, J., & Hammer, B. (2001). A kaizen based approach for cellular manufacturing system design: A case study.

Choi, T. M. (Ed.). (2013). *Fast fashion systems: Theories and applications*. CRC Press.

Chowdary, B. V., & Praveen, P. (2005). Formation of virtual manufacturing cells by incorporating flexibility. Global Journal of Flexible Systems Management, 6(1), 1.

Chowdary, B. V., Slomp, J., & Suresh, N. C. (2005). A New Concept of Virtual Cellular Manufacturing. West Indian Journal of Engineering, 28(1).

Christopher, M., Lowson, R., & Peck, H. (2004). Creating agile supply chains in the fashion industry. International Journal of Retail & Distribution Management, 32(8), 367-376. Zhelyazkov, G. (2011). Agile Supply Chain: Zara's case study analysis. Design, Manufacture & Engineering Management, Strathclyde University Glasgow, Velika Britanija, 2-11.

Chung, J., & Tanchoco, J. M. A. (2010). The double row layout problem. International Journal of Production Research, 48(3), 709-727.

Ciarniene, R., & Vienazindiene, M. (2014). Agility and Responsiveness Managing Fashion Supply Chain. Procedia-Social and Behavioral Sciences, 150, 1012-1019.

Clark, J. P. (2009). Case studies in food engineering. Case studies in food engineering. Springer, London.

Cummins, R. A. (1997). Comprehensive Quality of Life Scale: Adult (ComQol-A5): Manual. Centre for Australia-Asia Studies, Deaking University.

Cunningham K., Schrage L. (2004) The LINGO Algebraic Modeling Language. In: Kallrath J. (eds) Modeling Languages in Mathematical Optimization. Applied Optimization, vol 88. Springer, Boston, MA

Curry, G.L. & Feldman, R.M. (2010) Manufacturing Systems Modeling and Analysis, Springer Science & Business Media, 117-128

Dagli, C. H. (Ed.). (2012). Artificial neural networks for intelligent manufacturing. Springer Science & Business Media.

Dal V, Akcagun E, & Yilmaz A. (2013). Using Lean Manufacturing Techniques to Improve Production Efficiency in the Ready Wear Industry and a Case Study. FIBRES & TEXTILES in Eastern Europe; 21, 4(100): 16-22.

Dalfard, V.M. (2013). New mathematical model for problem of dynamic cell formation based on number and average length of intra and intercellular movements. Applied *Mathematical Modelling*, Vol.37 No.4, pp.1884-1896.

Das, S. K. (1993). A facility layout method for flexible manufacturing systems. International Journal of Production Research, 31(2), 279–297

De Carlo, F., Arleo, M. A., Borgia, O., & Tucci, M. (2013). Layout design for a low capacity manufacturing line: a case study. International Journal of Engineering Business Management, 5, 35.

De Carlo, F., Borgia, O., & Tucci, M. (2013). Bucket brigades to increase productivity in a luxury assembly line. International Journal of Engineering Business Management, 5, 28.

De Garmo, E. P., Black, J. T., & Kohser, R. A. (2011). DeGarmo's materials and processes in manufacturing. John Wiley & Sons.

Deep, K., & Singh, P. K. (2016). Dynamic cellular manufacturing system design considering alternative routing and part operation tradeoff using simulated annealing based genetic algorithm. Sādhanā, 41(9), 1063-1079.

Defersha, F. M., & Chen, M. (2006). Machine cell formation using a mathematical model and a genetic-algorithm-based heuristic. International Journal of Production Research, 44(12), 2421-2444.

Deljoo, V., Mirzapour Al-e-hashem, S. M. J., Deljoo, F., & Aryanezhad, M. B. (2010). Using genetic algorithm to solve dynamic cell formation problem. Applied Mathematical Modelling, 34(4), 1078-1092.

Depince, P., Chablat, D., & Woelk, P. O. (2007). Virtual Manufacturing: Tools for improving design and production. arXiv preprint arXiv:0708.0495.

Dickersbach, J. T. (2009). Supply Chain Management with SAP APOTM: Structures, Modelling Approaches and Implementation of SAP SCMTM 2008. Springer Science & Business Media.

Dissanayaka, D. M. I. K., Ranasinghe, T., & Senanayake, C. D. (2016, October). Analysis of efficiency ladders used in apparel manufacturing line performance forecasting. In Manufacturing & Industrial Engineering Symposium (MIES) (pp. 1-4). IEEE.

Doeringer, P., & Crean, S. (2006). Can fast fashion save the US apparel industry?. Socio-Economic Review, 4(3), 353-377.

Drira, A., Pierreval, H., & Hajri-Gabouj, S. (2007). Facility layout problems: A survey. Annual Reviews in Control, 31(2), 255-267.

Du, W., Leung, S. Y. S., & Kwong, C. K. (2015). A multiobjective optimization-based neural network model for short-term replenishment forecasting in fashion industry. Neurocomputing, 151, 342-353.

Dunker, T., Radons, G., & Westkamper, E. (2005). Combining evolutionary computation and dynamic programming for solving a dynamic facility layout problem. European Journal of Operational Research, 165(1), 55-69.

Dwijayanti, K., Dawal, S. Z. M., & Aoyama, H. (2010). A Proposed study on facility planning and design in manufacturing process. In International MultiConference of Engineers and Computer Scientists 2010, IMECS 2010.

Ebrahimi, A., Kia, R., & Komijan, A. R. (2016). Solving a mathematical model integrating unequal-area facilities layout and part scheduling in a cellular manufacturing system by a genetic algorithm. SpringerPlus, 5(1), 1254.

Egilmez, G., Suer, G. A., & Huang, J. (2012). Stochastic cellular manufacturing system design subject to maximum acceptable risk level. Computers & Industrial Engineering, 63(4), 842-854.

Egilmez, G., & Suer, G. A. (2011). Stochastic manpower allocation and cell loading in cellular manufacturing systems.

Elavia, S., (2014). "How the Lack of Copyright Protections for Fashion Designs Affects Innovation in the Fashion Industry". Senior Theses, Trinity College, Hartford

Elbenani, B., & Ferland, J. A. (2012). Cell formation problem solved exactly with the dinkelbach algorithm (Vol. 7). CIRRELT.

El-Kebbe, D. A., & Danne, C. (2009). On Adapting Neural Network to Cellular Manufacturing. In Complex Systems and Self-organization Modelling (pp. 83-93). Springer Berlin Heidelberg.

Eryuruk, S. H., Kalaoglu, F., & Baskak, M. (2008). Assembly line balancing in a clothing company. Fibres & Textiles in Eastern Europe, (1 (66)), 93-98.

Esmailnezhad, B., Fattahi, P., & Kheirkhah, A. S. (2015). A stochastic model for the cell formation problem considering machine reliability. Journal of Industrial Engineering International, 11(3), 375-389.

Ethical Fashion Forum. (2016). Fast fashion, "value" fashion, 2016, Retrieved from https://www.ethicalfashionforum.com/the-issues/fast-fashion-cheap-fashion

Fellows, R. F., & Liu, A. M. (2015). Research methods for construction. John Wiley & Sons.

Fernie, J., & Grant, D. B. (2015). Fashion Logistics. Kogan Page.

Ferreira, E. J., Erasmus, A. W., & Groenewald, D. (2010). Administrative management. Juta and Company Ltd.

Financial Executives International (FEI) (2016). Retrieved from: https://www.financialexecutives.org/Research.aspx

Fontana, G. L., & Miranda, J. A. (2016). The business of fashion in the nineteenth and twentieth centuries. Investigaciones de Historia Económica-Economic History Research, 12(2), 68-75.

Forghani, K., Mohammadi, M., & Ghezavati, V. (2013). Designing robust layout in cellular manufacturing systems with uncertain demands. International Journal of Industrial Engineering Computations, 4(2), 215-226.

Fraser, K., Harris, H., & Luong, L. (2007). Team-based cellular manufacturing: A review and survey to identify important social factors. Journal of Manufacturing Technology Management, 18(6), 714-730.

Fruggiero, F., Lambiase, A., & Negri, F. (2006, June). Design and optimization of a facility layout problem in virtual environment. In Proceeding of ICAD (pp. 13-16).

Gan, D. S. H. Y., & Gromiha, P. G. M. M. (2010). Advanced intelligent computing theories and applications.

Ghosh, S., & Gagnon, R. J. (1989). A comprehensive literature review and analysis of the design, balancing and scheduling of assembly systems. The International Journal of Production Research, 27(4), 637-670.

Ghosh, T., & Dan, P. K. (2012). An Effective Machine-Part Grouping Algorithm to Construct Manufacturing Cells. arXiv preprint arXiv:1212.5265.

Ghosh, T., Sengupta, S., Doloi, B., & Dan, P. K. (2014). AI-based techniques in cellular manufacturing systems: a chronological survey and analysis. International Journal of Industrial and Systems Engineering, 17(4), 449-476.

Gilliland, N. (2017). Four factors fuelling the growth of fast fashion retailers. Retrieved from: https://econsultancy.com/blog/69216-four-factors-fuelling-the-growth-of-fast-fashion-retailers

Giri, P. K. & Moulick, S.K. (2016) Comparison of Cell formation techniques in Cellular manufacturing using three cell formation algorithms. International Journal of engineering Research and Applications, 1(6), 98-101.

Glock, R. E., & Kunz, G. I. (2005). Apparel manufacturing: Sewn product analysis. Prentice Hall.

Goldengorin, B., Krushinsky, D., Pardalos, P. M., & Panos, M. (2013). Cell formation in industrial engineering. Springer Optimization and Its Applications, Springer.

Gomes, D. M. G. (2012). Lean manufacturing and the garment industry: A case study (Doctoral dissertation, Master's thesis, University of Porto, Porto, Portugal).

Goncalves, J. F., & Resende, M. G. (2004). An evolutionary algorithm for manufacturing cell formation. Computers & Industrial Engineering, 47(2), 247-273.

Guercini, S. (2001). Relation between branding and growth of the firm in new quick fashion formulas: analysis of an Italian case. Journal of Fashion Marketing and Management: An International Journal, 5(1), 69-79.

Guerrero, L. C., Lozano, S., Canca, D., Guerrero, F., Larrañeta, J., & Onieva, L. (2000). Cell formation using sequence information and neural networks.

Gugnani, A. (2012). How to effectively manage small order quantities, Retrieved from www.technopak.com

Guo, Z. (2016). Intelligent Decision-making Models for Production and Retail Operations. Springer.

Guo, Z. X., Ngai, E. W. T., Yang, C., & Liang, X. (2015). An RFID-based intelligent decision support system architecture for production monitoring and scheduling in a distributed manufacturing environment. International journal of production economics, 159, 16-28.

Gupta, S. M., & Lambert, A. F. (Eds.). (2007). Environment conscious manufacturing. CRC Press.

Hachicha, W., Masmoudi, F., & Haddar, M. (2008). Principal component analysis model for machine-part cell formation problem in group technology. arXiv preprint arXiv:0803.3343.

Hafezalkotob, A., Tehranizadeh, M. A., Rad, F., & Sayadi, M. K. (2015). An improved DPSO algorithm for cell formation problem. Journal of Industrial and Systems Engineering, 8(2), 30-53.

Hailemariam, D. A. (2010). Redesign of the Layout and the Materials Flow of a Production Plant: A Master Thesis Conducted at the Production Plant of Moxba-Metrex.

Halim, I., Omar, A. R., Saman, A. M., & Othman, I. (2011). A review on health effects associated with prolonged standing in the industrial workplaces. IJRRAS, 8(1), 14-21.

Hamedi, M., Esmaeilian, G. R., Ismail, N., & Ariffin, M. K. A. (2012). Capability-based virtual cellular manufacturing systems formation in dual-resource constrained settings using Tabu Search. Computers & Industrial Engineering, 62(4), 953-971.

Hamedi, M., Ismail, N., Esmaeilian, G., & Ariffin, M. (2012). Virtual cellular manufacturing system based on resource element approach and analyzing its performance over different basic layouts. International Journal of Industrial Engineering Computations, 3(2), 265-276.

Harashima, S., & Ohno, K. (2010). Flexible Production Systems developed and utilized in DENSO CORPORATION and their Evaluation. Service Robotics and Mechatronics, 205-210.

Hassan, M. M. (1995). Layout design in group technology manufacturing. International Journal of Production Economics, 38(2-3), 173-188.

Heilala, J. (1999). Use of simulation in manufacturing and logistics systems planning. VTT Manufacturing Technology.

Hellman, F. I. L. I. P., Lindahl, B. J. Ö. R. N., & Malmberg, J. O. N. A. S. (2011). Mixed-model assembly line at Volvo Construction Equipment (Doctoral dissertation, MS Thesis, Chalmers University of Technology, Goteborg, Sweden).

Heragu, S. S. (2008). Facilities design. CRC Press.

Hirano, H. (2009). JIT Implementation Manual: The Complete Guide to Just-in-time Manufacturing. Standardized Operations--Jidoka Amd Maintenance Safety. CRC Press.

Hirano, H. (2016). JIT Implementation Manual--The Complete Guide to Just-In-Time Manufacturing: Volume 2--Waste and the 5S's. CRC Press.

Ho, Y. C., & Moodie, C. L. (1998). Machine layout with a linear single-row flow path in an automated manufacturing system. Journal of manufacturing systems, 17(1), 1-22.

Hobbs, D. P. (2003). Lean manufacturing implementation: a complete execution manual for any size manufacturer. J. Ross Publishing.

Hofstede, Benatallah & Paik (2008). Business Process Management Workshops: BPM 2007 International Workshops, Revised Selected Papers, Springer Science & Business Media, pp 110

Holland, K. (2013). Lean Layout Fundamentals. Retrieved from: http://www.kaizen-news.com/

Hosseinpour, F., & Hajihosseini, H. (2009). Importance of simulation in manufacturing. World Academy of Science, Engineering and Technology, 51, 285-288.

Hyer, N., & Wemmerlov, U. (2001). Reorganizing the factory: Competing through cellular manufacturing. CRC Press.

International Journal of Production Research, Vol. 38 No. 3, pp. 481-507

Iqbal, A. (2010). Balancing and simulating inter-cell and intra-cell moves costs in a cellular manufacturing system. J Stud Manuf, 1(1), 48-53.

Iravani, S. M., Posner, M. J., & Buzacott, J. A. (1997). U-shaped lines with switchover times and costs.

Irizarry, M. D. L. A., Wilson, J. R., & Trevino, J. (2001). A flexible simulation tool for manufacturing-cell design, II: response surface analysis and case study. Iie Transactions, 33(10), 837-846.

Islam, I., Rahman, M. F., & LeHew, M. L. (2015). Predicting Total Assembling Time for Different Apparel Products Utilizing Learning Curve and Time Study Approaches: A Comparative Case Study.

Islam, M. A. (2014) Benefits of using Unit Production System (UPS) Line over Conventional Line in the Sewing Section of a Garment Industry. Proceedings of the 2014 International Conference on Industrial Engineering and Operations Management, Bali, Indonesia, January 7 – 9, 2014

Islam, M. S., & Liang, G. Q. (2012). Supply Chain Management on Apparel Order Process: A Case Study In Bangladesh Garment Industry. Asian Journal of Business and Management Sciences, 2(8), 60-72.

Islam, M., Mohiuddin, H. M., Mehidi, S. H., & Sakib, N. (2014). An optimal layout design in an apparel industry by appropriate line balancing: A case study. Global Journal of Research In Engineering, 14(5).

Jaakkola, H. (2008). Knowledge cluster systems for knowledge sharing, analysis and delivery among remote sites. Information Modelling and Knowledge Bases XIX, 166, 282.

Jacobs, F. R., Chase, R. B., & Aquilano, N. (2004). Operations management for competitive advantage. Boston: Mc-Graw Hill, 64, 70.

Jaganathan, V. P. (2014). Line balancing using largest candidate rule algorithm in a garment industry: a case study. International journal of lean thinking.

Jain, A. K., Khare, V. K., & Mishra, P. M. (2013). Facility planning and associated problems: a survey. Innovative systems design and engineering, 4(6), 1-8.

Jaramillo, J. R., & McKendall Jr, A. R. (2010). The generalised machine layout problem. International Journal of Production Research, 48(16), 4845-4859.

Jayaswal, S., & Agarwal, P. (2014). Balancing U-shaped assembly lines with resource dependent task times: A Simulated Annealing approach. Journal of Manufacturing Systems, 33(4), 522-534.

Johnson, D. J. (2003). A framework for reducing manufacturing throughput time. *Journal of manufacturing systems*, 22(4), 283.

Johnson, D. J., & Wemmerlov, U. (2004). Why does cell implementation stop? Factors influencing cell penetration in manufacturing plants. Production and Operations Management, 13(3), 272-289.

Joint Apparel Association Forum (JAAF) (2016), Fast fashion: Manufacturers embrace new production processes. Retrieved from: http://archive.jaafsl.com/news/1183-fast-fashion-manufacturers-embrace-new-production-processes

Joseph, O. A. & Sridharan, R. 2011a. Effects of routing flexibility, sequencing flexibility and scheduling decision rules on the performance of a flexible manufacturing system. International Journal Of Advanced Manufacturing Technology, 56, 291 - 306.

Jovanovic, V. M., & Mann, M., & Katsioloudis, P. J., & Dickerson, D. L. (2014, June), Enabling Multidisciplinary Perspective in Student Design Project: Fast Fashion and Sustainable Manufacturing Systems Paper presented at 2014 ASEE Annual Conference & Exposition, Indianapolis, Indiana. https://peer.asee.org/20370

Joy, A., Sherry, J.F., Venkatesh, A., Wang, J. & Chan, R. (2012). Fast Fashion, Sustainability, and the Ethical Appeal of Luxury Brands, *Fashion Theory*, Vol. 16, Issue 3, pp. 273–296 DOI: 10.2752/175174112X13340749707123

Kachru, U. (2009). Production & Operations Management. Excel Books India.

Kachwala, T. T., & Mukherjee, P. N. (2009). Operations management and productivity techniques. PHI Learning Pvt. Ltd..

Kahraman, C. (2012) *Computational Intelligence Systems in Industrial Engineering: With Recent Theory and Applications*, Springer Science and Business Media, pp.505-508

Kamrani, A. K., Azimi, M., & Al-Ahmari, A. M. (2013). Methods in Product Design: New Strategies in Reengineering. CRC Press.

Kamrani, A. K., Parsaei, H. R., & Liles, D. H. (Eds.). (1995). Planning, design, and analysis of cellular manufacturing systems (Vol. 24). Newnes.

Kanawaty, G. (Ed.). (1992). Introduction to work study. International Labour Organization.

Kara, Y., Ozguven, C., Yalcın, N., & Atasagun, Y. (2011). Balancing straight and U-shaped assembly lines with resource dependent task times. International Journal of Production Research, 49(21), 6387-6405.

Karger, D.W. and Bayha, F.H., (1987). *Engineered work measurement: the principles, techniques, and data of methods-time measurement background and foundations of work measurement and methods-time measurement, plus other related material*. Industrial Press Inc.

Karim, S., (2013), Impact of Changeover time on productivity: A case study, *International Journal of Engineering & Technology* IJET-IJENS Vol:13 No:06, Page 42-48

Kasimbeyli, R., Dincer, C., and Ozpeynirci, S. (2010). Sub-gradient based solution approach for cell formation problem with alternative routes. *International Conference 24th Mini EURO Conference "Continuous Optimization and Information-Based Technologies in the Financial Sector" (MEC EurOPT 2010) June 23–26, 2010, Izmir, Turkey*

Kelly, M. J., Ortiz, D. J., Folds, D. J., & Courtney, T. K. (1992). Ergonomic challenges in conventional and advanced apparel manufacturing. International Journal of Human Factors in Manufacturing, 2(1), 39-54.

Kentli, A., Dal, V., & Alkaya, A. F. (2013). Minimizing machine changeover time in product line in an apparel industry. *Journal of Textile & Apparel/Tekstil ve Konfeksiyon*, 23(2).

Khaewsukkho, S. (2008). New Approaches for Design of High-Mix Low-Volume Facilities (Doctoral dissertation, The Ohio State University).

Khan, A. J., & Tidke, D. J. (2013). Designing facilities layout for small and medium enterprises. International journal of Engineering research and General science Volume1, (2). Moonis, A., Chung, P., & Hinde, C. (Eds.). (2003). Developments in Applied Artificial Intelligence: 16th International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems, IEA/AIE 2003, Laughborough, UK, June 23-26, 2003, Proceedings (Vol. 2718). Springer.

Khannan, M. S. A., Maruf, A., Wangsaputra, R., Sutrisno, S., & Wibawa, T. (2016, February). Cellular Manufacturing System with Dynamic Lot Size Material Handling. In IOP Conference Series: Materials Science and Engineering (Vol. 114, No. 1, p. 012144). IOP Publishing.

Kia, R., Shirazi, H., Javadian, N., & Tavakkoli-Moghaddam, R. (2013). A multi-objective model for designing a group layout of a dynamic cellular manufacturing system. Journal of Industrial Engineering International, 9(1), 8.

Kincade, D. H., & Kanakadurga, K. S. (2013). An empirical investigation of apparel production systems and product line groups through the use of collar designs. Journal of Textile and Apparel, Technology and Management, 8(1).

Kitaw, D., Matebu, A., & Tadesse, S. (2010). Assembly line balancing using simulation technique in a garment manufacturing firm. Zede Journal, 27, 69-80.

Kohn, J. P. (1998). Ergonomics process management: a blueprint for quality and compliance. CRC Press.

Kono, H. (2000). Characteristics and Problems of Cell Manufacturing System in Assembly Processes: A Viewpoint as an Enabler of Improvement. Fifth International Conference, Asia-Pacific Region of Decision Sciences Institute

Koufteros, X. A., Vonderembse, M. A., & Doll, W. J. (1998). How to Cut Manufacturing Throughput Time.

Kovacheva, A. V. (2010). Challenges in Lean implementation: successful transformation towards lean enterprise. Unpublished Masters Thesis). University of Aarhus, Denmark.

Krajewski, L. J., & Ritzman, L. P. (2005). Operations management: processes and value chains. Prentice Hall.

Kreng, V. B., & Tsai, C. M. (2002). Use of a robustness index for flexible facility layout design in a changing environment. Asia Pacific Management Review, 7(4), 427-448.

Kriengkorakot, N., & Kriengkorakot, P. (2014). Heuristics comparison for u-shaped assembly line balancing in the apparel factory. KKU ENGINEERING JOURNAL, 41(2), 155-162.

Krishnananda Rao, P., 2014. A Multi Stage Heuristic for Manufacturing Cell Formation, International Journal of Research in Engineering and Technology, 3(2): 91-98

Kulturel-Konak, S. (2007). Approaches to uncertainties in facility layout problems: Perspectives at the beginning of the 21st Century. Journal of Intelligent Manufacturing, 18(2), 273.

Kulwiec, R. A. (Ed.). (1985). Materials handling handbook. New York et al.: Wiley.

Kumar, B. S., & Sampath, V. R. (2012). Garment manufacturing through lean initiative-an empirical study on WIP fluctuation in T-shirt production unit. Eur. J. Sci. Res, 73(92), 235-244.

Kumar, S. A., & Suresh, N. (2006). Production and operations management. New Age International.

Kumar, S., & Raj, T. (2016). Selection of material handling equipment for flexible manufacturing system using FAHP. Int. Jr. Recent Adv. Mech. Eng.(IJMECH), 5(1).

Kumari, R., Quazi, T. Z., & Kumar, R. (2015) Application of Lean Manufacturing Tools in Garment Industry. International Journal of Mechanical engineering and information technology, 3(1), 976-982

Lago, A., Martinez-de-Albeniz, V., Moscoso, P., Vall, A. (2013). *The Role of Quick Response in Accelerating Sales of Fashion Goods.* Retrieved from: http://webprofesores.iese.edu/valbeniz/RoleQRFashion_web.pdf . [Accessed 27 February 2014]

Lanarolle, G., & Ratnayake, V. (2014) Cellular Manufacturing and Teamwork Concepts in Garment Manufacturing. IOSR Journal of Business and Management (IOSR-JBM) Volume 16, Issue 6. Ver. III, PP 81-93

Lawler, B., & Wilson, H. (2002). Textiles Technology. Heinemann.

Lenin, N., Siva Kumar, M., Ravindran, D., & Islam, M. N. (2014). A tabu search for multi-objective single row facility layout problem. Journal of Advanced Manufacturing Systems, 13(01), 17-40.

Leondes, C. T. (2003). Computer Aided and Integrated Manufacturing Systems: A 5-volume Set. Computer techniques. Vol. 1 (Vol. 5). World Scientific.

Leonides, C.T. (2012). Control and Dynamic Systems V46: Manufacturing and Automation Systems: Techniques and Technologies: Advances in Theory and Applications. Academic Press

Li, C., Tang, Y., Li, C., & Li, L. (2013). A modeling approach to analyze variability of remanufacturing process routing. IEEE Transactions on Automation Science and Engineering, 10(1), 86-98.

Lieber, C. (2017). Is British Fast Fashion Too Fast?. Retrieved from: https://www.racked.com/2017/5/16/15643246/asos-boohoo-british-fast-fashion

Liu, C., Wang, J., & Leung, J. Y. T. (2016). Worker assignment and production planning with learning and forgetting in manufacturing cells by hybrid bacteria foraging algorithm. Computers & Industrial Engineering, 96, 162-179.

Liu, J. X. (2006). Focus on Robotics research. Nova Publishers.

Luyster, T. and Tapping, D., 2006. Creating Your Lean Future State, Productivity Press: 19-24, 44, and 83.

Lv, C., Liu, S., Wang, S. M., & Cai, B. (2013). The Production System Automatic Layout Based on Simulation. In Advanced Materials Research (Vol. 819, pp. 393-397). Trans Tech Publications.

Mahadevan, B. (2015). Operations management: Theory and practice. Pearson Education India.

Mahdavi, I., & Mahadevan, B. (2008). CLASS: An algorithm for cellular manufacturing system and layout design using sequence data. Robotics and Computer-Integrated Manufacturing, 24(3), 488-497.

Mahdavi, I., Aalaei, A., Paydar, M. M., & Solimanpur, M. (2010). Designing a mathematical model for dynamic cellular manufacturing systems considering production planning and worker assignment. Computers & Mathematics with Applications, 60(4), 1014-1025.

Mahdavi, I., Teymourian, E., Baher, N. T., & Kayvanfar, V. (2013). An integrated model for solving cell formation and cell layout problem simultaneously considering new situations. Journal of Manufacturing Systems, 32(4), 655-663.

Mahesh, O., & Srinivasan, G. (2002). Incremental cell formation considering alternative machines. International Journal of Production Research, 40(14): 3291-3310. doi:10.1080/00207540210146189

Malakooti, B. (2014). Operations and production systems with multiple objectives. John Wiley & Sons.

Marsh, R. F., Meredith, J. R., & McCutcheon, D. M. (1997). The life cycle of manufacturing cells. International Journal of Operations & Production Management, 17(12), 1167-1182.

Masmoudi, F., & Hachicha, W. (2013). A simulation approach for cellular manufacturing design from initial cell formation solutions. International Journal of Manufacturing Research, 8(1), 85-102.

Maurer, M. (2011). Skill formation regimes in South Asia: A comparative study on the path-dependent development of technical and vocational education and training for the garment industry (Vol. 21). Peter Lang.

McCreery, J. K., Krajewski, L. J., Leong, G. K., & Ward, P. T. (2004). Performance implications of assembly work teams. Journal of Operations Management, 22(4), 387-412.

Mehmood, K., Cherfi, S. S. S., & Comyn-Wattiau, I. (2009). Data Quality through Conceptual Model Quality-Reconciling Researchers and Practitioners through a Customizable Quality Model. ICIQ, 2009, 61-74.

Mehrjoo, M., & Pasek, Z. J. (2014). Impact of product variety on supply chain in fast fashion apparel industry. *Procedia CIRP*, *17*, 296-301.

Mehrotra, N., Syal, M., & Hastak, M. (2005). Manufactured housing production layout design. Journal of architectural engineering, 11(1), 25-34.

Mejia, G., & Velasco, N. (Eds.). (2012). Production Systems and Supply Chain Management in Emerging Countries: Best Practices: Selected Papers from the International Conference on Production Research (ICPR). Springer Science & Business Media.

Meller, R. D., Narayanan, V., & Vance, P. H. (1999). Optimal facility layout design. Operations Research Letters, 23(3–5), 117–127

Memic, M., & Minhas, F. N. (2011). The fast fashion phenomenon: Luxury fashion brands responding to fast fashion. *The Swedish School of Textiles April*.

Meng, G., Heragu, S. S., & Zijm, H. (2004). Reconfigurable layout problem. International Journal of Production Research, 42(22), 4709-4729.

Michelini, R.C. & Razzoli, R.P. (2013). Robotics in Clothes Manufacture, *International Journal of Mechanical Engineering and Applications*, 1 (1) pp.17-27

Michelini, R.C. & Razzoli, R.P. (2013). Robotics in Clothes Manufacture, *International Journal of Mechanical Engineering and Applications*, 1 (1) pp.17-27

Mihm, B. (2010). Fast fashion in a flat world: Global sourcing strategies. The International Business & Economics Research Journal, 9(6), 55.

Miltenburg, J. (2001). U-shaped production lines: A review of theory and practice. International Journal of Production Economics, 70(3), 201-214.

Mir, M. S. S., & Rezaeian, J. (2016). A robust hybrid approach based on particle swarm optimization and genetic algorithm to minimize the total machine load on unrelated parallel machines. Applied Soft Computing, 41, 488-504.

Mital, A. (Ed.). (1988). Recent Developments in Production Research: Collection of Refereed Papers Presented at the Ixth International Conference on Production Research (Vol. 6). Elsevier Publishing Company.

Mital, A., Desai, A. and Mital, A. (2017). *FUNDAMENTALS OF WORK MEASUREMENT: What Every Engineer Should Know.* CRC Press, Taylor & Francis Group

Mittlehauser, M. (1997), Employment trends in textiles and apparel, 1973-2005, *Monthly Labor Review, August, 1997*, 24-35

Mo, Z. (2015). Internationalization Process of Fast Fashion Retailers: Evidence of H&M and Zara. *International Journal of Business and Management*, 10(3), 217.

Modrak, V. (Ed.). (2011). Operations Management Research and Cellular Manufacturing Systems: Innovative Methods and Approaches: Innovative Methods and Approaches. IGI Global.

Modrak, V. and Pandian, R.S. (2011) Operations Management Research and Cellular Manufacturing Systems: Innovative Methods and Approaches, IGI Global, 69-345

Mohammadi, M., & Forghani, K. (2017). A hybrid method based on genetic algorithm and dynamic programming for solving a bi-objective cell formation problem considering alternative process routings and machine duplication. Applied Soft Computing, 53, 97-110.

Moin, C. J., Sarwar, F., & Doulah, A. S. (2013). Investigation of a Hybrid Production System for Mass-Customization Apparel Manufacturing. Journal of Textile and Apparel, Technology and Management, 8(3).

Moll, P., Schütte, U., Zöll, K., Molfino, R., Carca, E., Zoppi, M., ... & Montorsi, R. (2009). Automated Garment Assembly and Manufacturing Simulation. In Transforming Clothing Production into a Demand-driven, Knowledge-based, High-tech Industry (pp. 9-59). Springer London.

Mooi, E., & Sarstedt, M. (2011). A concise guide to market research: The process, data, and methods using IBM SPSS statistics. month.

Morad, N. (2000). Genetic algorithms optimization for the machine layout problem. International Journal of the Computer, the Internet and Management, 8(1).

Moradgholi, M., Paydar, M. M., Mahdavi, I., & Jouzdani, J. (2016). A genetic algorithm for a bi-objective mathematical model for dynamic virtual cell formation problem. Journal of Industrial Engineering International, 12(3), 343-359.

Moretta Tartaglione, A., & Antonucci, E. (2013). Value Creation Process in the Fast Fashion Industry: Towards a Networking Approach. In The 2013 Naples Forum on Service. Service Dominant Logic, Networks & Systems Theory and Service Science: Integrating Three Perspectives for a New Service Agenda (p. 91).

Mukerjee, P.N. (2006). Total Quality Management. PHI Learning Pvt. Ltd.

Mungwattana, A. (2000). Design of cellular manufacturing systems for dynamic and uncertain production requirements with presence of routing flexibility (Doctoral dissertation).

Murugan, M., & Selladurai, V. (2011). Formation of machine cells/part families in cellular manufacturing systems using an ART-modified single linkage clustering approach—a comparative study. Jordan Journal of Mechanical and Industrial Engineering, 5(3), 199-212.

Murugan, M., & Selladurai, V. (2011). Formation of machine cells/part families in cellular manufacturing systems using an ART-modified single linkage clustering approach—a comparative study. Jordan Journal of Mechanical and Industrial Engineering, 5(3), 199-212.

Muther, R. (2002). Planning Manufacturing Cells Workbook. Society of Manufacturing Engineers Dearborn, Michigan.

Mutingi, M., & Onwubolu, G. C. (2012). Integrated cellular manufacturing system design and layout using group genetic algorithms. In Manufacturing System. InTech.

Nabi, F., Mahmud, R., & Islam, M. M. (2015). Improving Sewing Section Efficiency through Utilization of Worker Capacity by Time Study Technique. International Journal of Textile Science, 4(1), 1-8.

Nagurney, A., & Yu, M. (2010). Fashion supply chain management through cost and time minimization from a network perspective.

Nenni, M. E., Giustiniano, L., & Pirolo, L. (2013). Demand forecasting in the fashion industry: a review. International Journal of Engineering Business Management, 5, 37.

Neumann, C.S.R. & Fogliatto, F.S. (2013) Systematic approach to evaluating and improving the flexibility of layout in dynamic environments, *Management & Production, 20 (2)*, 235-254

Niakan, F. (2015). Design and configuration of sustainable dynamic cellular manufacturing systems (Doctoral dissertation, Lyon, INSA).

Niakan, F., Baboli, A., Moyaux, T., & Botta-Genoulaz, V. (2016). A bi-objective model in sustainable dynamic cell formation problem with skill-based worker assignment. Journal of Manufacturing Systems, 38, 46-62.

Nicholas, J. (2011). Competitive Manufacturing Management. New Delhi: Tata McGraw Hill Education Private Limited. pp. 176-204, 397-399, 754-759

Nicholas, J. M. (1998). Competitive manufacturing management: continuous improvement, lean production, customer-focused quality. McGraw-Hill/Irwin.

Nicholas, J., & Soni, A. (2005). The portal to lean production: Principles and practices for doing more with less. CRC Press.

Nielsen, J. and Levy, J. (1994) Measuring Usability: Preference vs. Performance. Communications of the ACM, 37, p. 66-76

Niroomand, S. (2013). Studies on different types of facility layout problems (Doctoral dissertation, Eastern Mediterranean University (EMU)-Doğu Akdeniz Üniversitesi (DAÜ)).

Nomden, G. (2011). Virtual cellular manufacturing: relevance and development of heuristics for family-based dispatching (Doctoral dissertation, University of Groningen).

Nomden, G., & Slomp, J. (2003). The Operation of Virtual Manufacturing Cells in Various Physical Layout Situations. In Proc. GT/CM World Symposium, Columbus, OH (pp. 255-260).

Nourie, H., Tang, S. H., Tuah, B. H., Ariffin, M. K. A., & Samin, R. (2013). Metaheuristic techniques on cell formation in cellular manufacturing system. J Autom Control Eng, 1(1), 49-54.

Nunkaew, W., & Phruksaphanrat, B. (2013). Effective fuzzy multi-objective model based on perfect grouping for manufacturing cell formation with set-up cost constrained of machine duplication. Songklanakarin Journal of Science & Technology, 35(6).

Oke, A. (2013). Linking manufacturing flexibility to innovation performance in manufacturing plants. International Journals of Production Economics, 143, 242-247. doi:10.1016/j.ijpe.2011.09.014

Stephens, M. P., & Meyers, F. E. (2013). Manufacturing facilities design and material handling. Purdue University Press.

Oksuz, M. K., & Satoglu, S. I. (2014) Balancing U-Shaped Assembly Lines by Considering Human Factors. Proceedings of Global Conference on Engineering and Technology Management, Istanbul, Turkey.

Oliveira, A. R. S., & Alves, A. C. (2009). Operating modes in manufacturing cells: an action research study. In 5th International Conference on Intelligent Manufacturing & Logistics Systems and Symposium on Group Technology and cellular Manufacturing (GT/CM09), Kitakyushu, 2009.

Onwubolu, G. C. (2011). Cell formation in group technology: a similarity order clustering approach. The South African Journal of Industrial Engineering, 9(1).

Orcao, A. I. E., & Perez, D. R. (2014). Global production chains in the fast fashion sector, transports and logistics: the case of the Spanish retailer Inditex. Investigaciones Geográficas, Boletín del Instituto de Geografía, 2014(85), 113-127.

Orcao, A. I. E., & Pérez, D. R. (2014). Global production chains in the fast fashion sector, transports and logistics: the case of the Spanish retailer Inditex. Investigaciones Geográficas, Boletín del Instituto de Geografía, 2014(85), 113-127.

Osorno, S. C. (2015). Consumer behaviour towards the fashion industry. The fast fashion era (Doctoral dissertation).

Ozgurler, Ş., Endustri, B. Y., Gulsun, B., Guneri, A. F., & Yılmaz, O. (2010, September). Designing A Simple U-Shaped Production Line And Analysis of Effectiveness. In 14th International Research/Expert Conference.

Pachghare, V., & Dalu, R. (2012). Assembly Line Balancing Methods-A Case Study. International Journal of Science andResearch (IJSR), 3-1901.

Pai, Y. S., Yap, H. J., Dawal, S. Z. M., Ramesh, S., & Phoon, S. Y. (2016). Virtual Planning, Control, and Machining for a Modular-Based Automated Factory Operation in an Augmented Reality Environment. Scientific reports, 6, 27380.

Palmer, B. (2004). Overcoming resistance to change. Quality Progress, 37(4), 35.

Palominos, P., Valdivia, L., & Quezada, L. (2015). A methodology for designing multiple cell manufacturing systems with simultaneous balancing. In 23rd International Conference for Production Research, ICPR 2015. International Foundation for Production Research (IFPR).

Pan, G. (2014). A quantitative analysis of cellular manufacturing in apparel industry by using simulation. Journal of Industrial Engineering and Management, 7(5), 1385-1396.

Paneru, N. (2011). Implementation of lean manufacturing tools in garment manufacturing process focusing sewing section of men’s shirt.

Papaioannou, G., & Wilson, J. M. (2010). The evolution of cell formation problem methodologies based on recent studies (1997–2008): Review and directions for future research. European journal of operational research, 206(3), 509-521.

Parashar, B. N. (2008). Cellular manufacturing systems: An integrated approach. PHI Learning Pvt. Ltd.

Patel, J. N., & Patel, S. V. (2014). Approaches to solve cell formation, machine layout and cell layout problem: A Review. Transactions on Machine Learning and Artificial Intelligence, 2(5), 80-96.

Paydar, M. M., Saidi-Mehrabad, M., & Teimoury, E. (2014). A robust optimisation model for generalised cell formation problem considering machine layout and supplier selection. International Journal of Computer Integrated Manufacturing, 27(8), 772-786.

Pheasant, S., & Haslegrave, C. M. (2016). Bodyspace: Anthropometry, ergonomics and the design of work. CRC Press.

Pillai, V. M., Hunagund, I. B., & Krishnan, K. K. (2011). Design of robust layout for dynamic plant layout problems. Computers & Industrial Engineering, 61(3), 813-823.

Pinheiro, R. G., Martins, I. C., Protti, F., Ochi, L. S., Simonetti, L. G., & Subramanian, A. (2016). On solving manufacturing cell formation via Bicluster Editing. European Journal of Operational Research, 254(3), 769-779.

Prabu, M., & Kalaamani, P. (2012). A Multivariate Simultaneous Part Family Identification & Machine Part Cell Formation. Programmable Device Circuits and Systems, 4(1), 1-5.

Pradhan, T., & Mishra, S. R. (2015). Implementation of Machine Part Cell Formation Algorithm in Cellular Manufacturing Technology Using Neural Networks. International Journal of Hybrid Information Technology, 8(2), 173-178.

Prasath, K. A., & Johnson, R. D. J. (2015). Scrutiny of machine assignment in various intra-cell layout in cellular manufacturing using automation studios. International journal of applied engineering research and development ISSN(P): 2250-1584; ISSN(E): 2278-9383 Vol. 5, Issue 4, 1-8

Praveen, P., Chowdary, B. V., & Deshmukh, S. G. (2006). Design Of Virtual Manufacturing Cells: An Integrated Approach. West Indian Journal of Engineering, 29(1).

Priest, J., & Sanchez, J. (2001). Product development and design for manufacturing: a collaborative approach to producibility and reliability. CRC Press.

Prokopenko, J. (1987). Productivity management: A practical handbook. International Labour Organization.

Protzman, C., Mayzell, G., & Kerpchar, J. (2010). Leveraging lean in healthcare: Transforming your enterprise into a high quality patient care delivery system. CRC Press.

Purvis, L., Naim, M. M., & Towill, D. (2013). Intermediation in agile global fashion supply chains. International Journal of Engineering, Science and Technology, 5(2), 38-48.

PwC HK (2015). *Fashion and apparel*. Retrieved from: https://www.pwchk.com/en/retail-and-consumer/rc-outlook-201516-re-fashion.pdf

Qudeiri, J. A., Umer, U., Khadra, F. A., Hussein, H. M. A., Al-Ahmari, A., Darwish, S., & Abidi, M. H. (2015). Layout design optimization of dynamic environment flexible manufacturing systems. Advances in Mechanical Engineering, 7(6), 1687814015584252.

Quirk, T. J., & Palmer-Schuyler, J. (2016). Excel 2010 for Human Resource Management Statistics. Springer.

Rafiee, K., Rabbani, M., Rafiei, H., & Rahimi-Vahed, A. (2011). A new approach towards integrated cell formation and inventory lot sizing in an unreliable cellular manufacturing system. Applied Mathematical Modelling, 35(4), 1810-1819.

Rafiei, H., and Ghodsi, R. (2013). A bi-objective mathematical model toward dynamic cell formation considering labor utilization. *Applied Mathematical Modelling*, Vol.37No.4, pp.2308-2316.

Rafiei, H., Rabbani, M., Nazaridoust, B., & Ramiyani, S. S. (2015). Multi-objective cell formation problem considering work-in-process minimization. The International Journal of Advanced Manufacturing Technology, 76(9-12), 1947-1955.

Raja, S., & Anbumalar, V. (2016). An effective methodology for cell formation and intra-cell machine layout design in cellular manufacturing system using parts visit data and operation sequence data. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 38(3), 869-882.

Rajput, R. K. (2007). A textbook of manufacturing technology: Manufacturing processes. Firewall Media.

Raman, D., Nagalingam, S. V., & Lin, G. C. (2009). Towards measuring the effectiveness of a facilities layout. Robotics and Computer-Integrated Manufacturing, 25(1), 191-203.

Raminfar, R., Zulkifli, N., & Vasili, M. (2013). A mathematical programming model for cell formation problem with machine replication. Journal of Applied Mathematics, 2013.

Rao, P. N. (2004). CAD/CAM: principles and applications. Tata McGraw-Hill Education.

Raworth, K. (2004). Trading away our rights: Women working in global supply chains. Oxfam Policy and Practice: Private Sector, 1(1), 1-52.

Reginato, G., Anzanello, M. J., & Kahmann, A. (2016). Mixed assembly line balancing method in scenarios with different mix of products. Gestão & Produção, v. 23, n. 2, p. 294-307.

Renna, P., & Ambrico, M. (2015). Design and reconfiguration models for dynamic cellular manufacturing to handle market changes. International Journal of Computer Integrated Manufacturing, 28(2), 170-186.

Rezazadeh, H., Mahini, R., & Zarei, M. (2011). Solving a dynamic virtual cell formation problem by linear programming embedded particle swarm optimization algorithm. Applied Soft Computing, 11(3), 3160-3169.

Roberts, G. W. (1994). Quality Planning, Control, and Improvement in Research and Development (Vol. 44). CRC Press.

Rodriguez Leon, J., Quiroga Mendez, J. E., & Ortiz Pimiento, N. R. (2013). Performance comparison between a classic particle swarm optimization and a genetic algorithm in manufacturing cell design. Dyna, 80(178), 29-36.

Roger, A. & Ruwanpura, K.N. (2016). Living wages: recurring problems of ethical fashion in Sri Lanka?. Retrieved from: http://discoversociety.org/2016/07/05/living-wages-recurring-problems-of-ethical-fashion-in-sri-lanka/

Roslin, E. N., Seang, O. G., & Dawal, S. Z. M. (2008). A Study on Facility Layout in Manufacturing Production Line Using WITNESS. In Proceedings of The 9th Asia Pasific Inductrial Engineering & Management System Conference (pp. 412-421).

Rothenberg, J. (1997). A Discussion of Data Quality for Verification, Validation, and Certification (VV&C) of Data to be used in Modeling. Rand Project Memorandum PM-709-DMSO, 24-61.

Roy, N., & Komma, V. R. (2014). Cellular manufacturing through composite part formation: a genetic algorithm approach. In International Conference on Industrial Engineering and Operations Management, Bali, Indonesia, January (pp. 7-9).

Rudolph, S., Gottlob, G., Ian, H., & Van Harmelen, F. (Eds.). (2013). Reasoning Web. Semantic Technologies for Intelligent Data Access: 9th International Summer School 2013, Mannheim, Germany, July 30--August 2, 2013. Proceedings (Vol. 8067). Springer.

Sabet, E., Yazdani, B., & De Leeuw, S. (2016). Supply chain integration strategies in fast evolving industries. International Journal of Logistics Management, 28(1), 29-46.

Saidi-Mehrabad, M., & Mirnezami-ziabari, S. M. (2011). Developing a Multi-objective Mathematical Model for Dynamic Cellular Manufacturing Systems. Journal of Optimization in Industrial Engineering, 1-9.

Sakhaii, M., Tavakkoli-Moghaddam, R., Bagheri, M., & Vatani, B. (2016). A robust optimization approach for an integrated dynamic cellular manufacturing system and production planning with unreliable machines. Applied Mathematical Modelling, 40(1), 169-191.

Salvendy, G. (Ed.). (2001). Handbook of industrial engineering: technology and operations management. John Wiley & Sons.

Sarcar, M. M. M., Rao, K. M., & Narayan, K. L. (2008). Computer aided design and manufacturing. PHI Learning Pvt. Ltd.

Sarkar, P. (2015) Garment Manufacturing Processes, Practices and Technology. OCS Publications.

Sauro, J., & Kindlund, E. (2005, April). A method to standardize usability metrics into a single score. In Proceedings of the SIGCHI conference on Human factors in computing systems (pp. 401-409). ACM.

Scheller, H. P. (1995). Dimensions of flexibility in apparel production.

Schmenner, R. W. (2012). Getting and staying productive: applying swift, even flow to practice. Cambridge University Press.

Schmenner, R.W. (2012) *Getting and Staying Productive: Applying Swift, Even Flow to Practice*, Cambridge University Press, pp 27-151

Scholz, D., Jaehn, F. and Junker, A. 2010. Extensions to STaTS for practical applications of the facility layout problem. European Journal of Operational Research, 204, pp. 463-472.

Selim, H. M., Askin, R. G., & Vakharia, A. J. (1998). Cell formation in group technology: review, evaluation and directions for future research. Computers & Industrial Engineering, 34(1), 3-20.

Shabani, M. K., Kalami, S., Farahani, S. M., & Rasekhi, N. (2013). Hybrid Approach of Genetic Algorithm in Case of Planning a Cellular Manufacturing System. Journal of American Science, 9(4s).

Shafigh, F., Defersha, F. M., & Moussa, S. E. (2017). A linear programming embedded simulated annealing in the design of distributed layout with production planning and systems reconfiguration. The International Journal of Advanced Manufacturing Technology, 88(1-4), 1119-1140.

Shahnazari-Shahrezaei, P., Tavakkoli-Moghaddam, R., & Kazemipoor, H. (2013). Solving a multi-objective multi-skilled manpower scheduling model by a fuzzy goal programming approach. Applied Mathematical Modelling, 37(7), 5424-5443.

Sharma, P., Phanden, R. K., & Singhal, S. (2013). A Comparative Analysis of Facility Layout Design and Optimization Techniques. In Proceedings of the 2nd national conference on Advancement in the Era of Multi Disciplinary Systems (pp. 1-6).

Sharma, P., Thakar, G., & Gupta, R. C. (2014). Evaluation of multi criteria assembly line balancing by MCDM approaches: a conceptual review. International Journal for Quality Research, 8(1).

Shen, B. (2014). Sustainable fashion supply chain: Lessons from H&M. Sustainability, 6(9), 6236-6249.

Shih, Y. C., & Goncalves Filho, E. V. (2014). A design procedure for improving the effectiveness of fractal layouts formation. AI EDAM, 28(1), 1-26.

Shiyas, C. R., & Pillai, V. M. (2014). A mathematical programming model for manufacturing cell formation to develop multiple configurations. Journal of Manufacturing Systems, 33(1), 149-158.

ShopperTrak (2015). *Fashion Conversion Benchmarking Report: 2015*. Retrieved from: http://uk.shoppertrak.com/wp-content/uploads/2016/03/Fashion-Conversion-Benchmarking-Report-2015.pdf.

Shumon, M. R. H., Arif-Uz-Zaman, K., Rahman, A., & Khulna, B. (2010, January). Productivity Improvement through Line Balancing in Apparel Industries. In Proceedings of the 2010 International Conference on Industrial Engineering and Operations Management.

Silva, A. L. (2010). Critical analysis of layout concepts: functional layout, cell layout, product layout, modular layout, fractal layout, small factory layout. In Challenges and Maturity of Production Engineering: Competitiveness of Enterprises, Working Conditions, Environment. Proceedings of the XVI International Conference on Industrial Engineering and Operations Management, São Carlos, Brazil (pp. 1-13).

Silva, S. C., & Alves, A. C. (2006). Detailed design of product oriented manufacturing systems.

Singh, K. (2007). Quantitative social research methods. Sage.

Singh, L. P. (2016). Work Study and Ergonomics. Cambridge University Press.

Singh, N., & Rajamani, D. (2012). Cellular manufacturing systems: design, planning and control. Springer Science & Business Media.

Sirovetnukul, R., & Chutima, P. (2010). The impact of walking time on U-shaped assembly line worker allocation problems. Engineering Journal, 14(2), 53-78.

Siti Farah Nadiah, T. (2007). Design of an Improved Production Layout for a Shoe Making Factory: A Case Study Of A Company.

Sly, D. P. (1997, January). Before dynamic simulation: Systematic layout design from scratch. In Winter Simulation Conference: Proceedings of the 29 th conference on Winter simulation (Vol. 7, No. 10, pp. 645-648).

Smithers, R. (2017). UK households binned 300,000 tonnes of clothing in 2016. Retrieved from: https://www.theguardian.com/environment/2017/jul/11/uk-households-binned-300000-tonnes-of-clothing-in-2016

So, K. (2013). *Fast fashion: Manufacturers embrace new production processes*. Retrieved from: http://www.just-style.com/management-briefing/manufacturers-embrace-newproduction-processes_id119206.aspx?d=1

Soimart, P., & Pongcharoen, P. (2011). Multi-row machine layout design using aritificial bee colony. In 2011 international conference on economics and business information (Vol. 9, pp. 103-108).

Solimanpur, M., Vrat, P., & Shankar, R. (2005). An ant algorithm for the single row layout problem in flexible manufacturing systems. Computers & Operations Research, 32(3), 583-598.

Sri Lanka Export Development Board (2017). *Apparel Export Performance*. Retrieved from: http://www.srilankabusiness.com/apparel/apparel-export-performance.html

Srivastava, N. A., & Chatterjii, A. (2014). Skills requirement analysis at the production floor in ready made garment industry. Asian journal of management sciences & education, 3(1), 23-34.

Stevenson, W. J., & Sum, C. C. (2002). Operations management (Vol. 8). New York, NY: McGraw-Hill/Irwin.

Streiner, D. L., Norman, G. R., & Cairney, J. (2015). Health measurement scales: a practical guide to their development and use. Oxford University Press, USA.

Sudarshan, B., & Rao, D. N. (2014) Productivity improvement through modular line in garment industries. 5th International & 26th All India Manufacturing Technology, Design and Research Conference (AIMTDR 2014), Guwahati, Assam, India

Suer, G.A., Huang, J. and Maddisetty, S., (2010). Design of dedicated, shared and remainder cells in a probabilistic demand environment. *International journal of production research*, Vol.48No.19, pp.5613-5646.

Sun, J. (2013, November). Empirical Research on the Influences of Different Layout Designs of HR Management on the Motivation of Employees Based on Fuzzy Comprehensive Evaluation. In 2nd International Conference on Management Science and Industrial Engineering (MSIE 2013). Atlantis Press.

Sundar, R., Balaji, A. N., & Kumar, R. S. (2014). A review on lean manufacturing implementation techniques. Procedia Engineering, 97, 1875-1885.

Suo, X. (2012). Facility layout. In Manufacturing system. InTech.

Suresh, N. C., & Kay, J. M. (Eds.). (2012). Group technology and cellular manufacturing: a state-of-the-art synthesis of research and practice. Springer Science & Business Media.

Suresh, N. C., & Kay, J. M. (Eds.). (2012). Group technology and cellular manufacturing: a state-of-the-art synthesis of research and practice. Springer Science & Business Media.

Syberfeldt, A., & Lidberg, S. (2012, December). Real-world simulation-based manufacturing optimization using cuckoo search. In Proceedings of the Winter Simulation Conference (p. 256). Winter Simulation Conference.

Tanchoco, J. M. A. (Ed.). (1994). Material flow systems in manufacturing. Chapman & Hall.

Tempelmeier, H., & Kuhn, H. (1993). Flexible manufacturing systems: decision support for design and operation (Vol. 12). John Wiley & Sons.

Tilindis, J., & Kleiza, V. (2014). The effect of learning factors due to low volume order fluctuations in the automotive wiring harness production. Procedia CIRP, 19, 129-134.

Tubaileh, A., & Siam, J. (2017). Single and multi-row layout design for flexible manufacturing systems. International Journal of Computer Integrated Manufacturing, 1-15.

Tunnukij, T., & Hicks, C. (2009). An Enhanced Grouping Genetic Algorithm for solving the cell formation problem. International Journal of Production Research, 47(7), 1989-2007.

Turker, D., & Altuntas, C. (2014). Sustainable supply chain management in the fast fashion industry: An analysis of corporate reports. European Management Journal, 32(5), 837-849.

Udomsakdigool, A., & Bangsaranthip, S. (2010). Combining ant colony optimization and dynamic programming for solving a dynamic facility layout problem. World Academy of Science, Engineering and Technology, 64, 523-527.

Ulutas, B., & Islier, A. A. (2015). Dynamic facility layout problem in footwear industry. Journal of Manufacturing Systems, 36, 55-61.

UNCTAD (2014). *Recent Trends in International Trade: Implications for Sri Lanka*.

Vallabhaneni, S. R. (2013). Wiley CIA exam review 2013, internal audit knowledge elements. John Wiley & Sons.

Vecchi, A., & Buckley, C. (2016). *Handbook of Research on Global Fashion Management and Merchandising*, IGI Global

Wadhawa, S., & Rao, K. S. (2003). Flexibility and agility for enterprise synchronization: knowledge and innovation management towards flexagility. Studies in Informatics and Control, 12(2), 111-128.

Wang, J., & Kusiak, A. (Eds.). (2000). Computational intelligence in manufacturing handbook. CRC Press.

Wang, M. J., Hu, M. H., & Ku, M. H. (2005). A solution to the unequal area facilities layout problem by genetic algorithm. Computers in Industry, 56(2), 207–220.

Wang, S., Zuo, X., Liu, X., Zhao, X., & Li, J. (2015). Solving dynamic double row layout problem via combining simulated annealing and mathematical programming. Applied Soft Computing, 37, 303-310.

Weinberg, S. (Ed.). (2007). Good laboratory practice regulations. CRC Press.

Wemmerlov, U. and Johnson, D.J. (2000), “Empirical findings on manufacturing cell design”,

Xambre, A. R., & Vilarinho, P. M. (2007). Virtual manufacturing cell formation problem (vmcfp) in a distributed layout. In ICPR19-19th International Conference on Production Research, Valparaiso, Chile.

Xu, J., Xu, X., & Xie, S. Q. (2011). Recent developments in Dual Resource Constrained (DRC) system research. European Journal of Operational Research, 215(2), 309-318.

Y. Zhao and S. Wallace (2014). “Integrated facility layout design and flow assignment problem under uncertainty.” INFORMS Journal on Computing 26(4), 798–808.

Yan, X. T., Jiang, C., & Eynard, B. (Eds.). (2008). Advanced design and manufacture to gain a competitive edge. Springer.

Yang, T., & Peters, B.A., (1998) Flexible machine layout design for dynamic and uncertain production environments, *European Journal of Operational Research 108, 49-64,* Elsevier Science B.V.

Zarea Fazlelahi, F., Pournader, M., Gharakhani, M., & Sadjadi, S. J. (2016). A robust approach to design a single facility layout plan in dynamic manufacturing environments using a permutation-based genetic algorithm. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 230(12), 2264-2274.

Zbicinski, I. (2006). Product design and life cycle assessment (Vol. 3). Baltic University Press.

Zhao, L. & Yang, J. (2011) Clothing workshop production line analysis and improvement research based on IE, *Advanced Material Research*, Vol. 291-294, pp 3147-3151, Trans Tech Publications, Switzerland

Zhenxiang, W., & Lijie, Z. (2011). Case study of online retailing fast fashion industry. International Journal of e-Education, e-Business, e-Management and e-Learning, 1(3), 195.

Zuo, X., Murray, C. C., & Smith, A. E. (2014). Solving an extended double row layout problem using multiobjective tabu search and linear programming. IEEE Transactions on automation science and engineering, 11(4), 1122-1132.

APPENDIX A: Summary of the literature review on CMS

Assumptions	Authors
Assumptions related with machine data	
Each machine type can perform one or more operations of different products	Niakan et al. (2016), Kia et al. (2014)
Each operation can be performed in different types of machines and possibly with different processing times.	Bayram & Sahin (2016), Dalfard (2013), Niakan et al. (2016), Kia et al. (2014)
Each machine has a limited capacity and several duplicates of the machines are allowed. Machine capacities are expressed in time units (e.g. h, days).	Hamedi et al. (2012), Bayram & Sahin (2016), Dalfard (2013), Niakan et al. (2016)
Time capacity of each machine is definite and fixed in all programming horizon.	Dalfard (2013)
Bounds and quantity of machines in each cell need to be specified in advance and they remain constant over time.	Bayram & Sahin (2016), Asgharpour & Javadian (2004)
All machines have the same dimension. Therefore any machine can be assigned to any location. However, only one machine can be assigned to a location.	Bayram & Sahin (2016)
Time of setting machinery and their failure probability are excluded.	Dalfard (2013), Bayram & Sahin (2016), Asgharpour & Javadian (2004), Sirovetnukul & Chutima (2010)
All machines are of rectangular shape	Dalfard (2013), Srinivas, Reddy, Ramji & Naveend (2014)
All machines are operated in the centre of that space	Srinivas et al. (2014)
The available surface for Machine layout is rectangular in shape	Srinivas, Reddy, Ramji & Naveen (2014)
Machines are not in the same size.	Allahyari & Azab (2015)
The sizes of all machines are equal with the dimensions of 1×1.	Golmohammadi, A. M., Tavakkoli-Moghaddam, Jolai & Golmohammadi, A. H. (2014)
The factory floor is divided into equal grids, and machines are assumed equal space in such a way that each machine just occupies one grid.	Hamedi et al. (2012)
Machines must be located within a given area.	Allahyari & Azab (2015)
In determining machine size and dimensions, the workspace required for operator usage and that needed to enforce between the different machines have been taken into account.	Allahyari & Azab (2015)

A U-line comprises inexpensive and small non-automated machines	Sirovetnukul & Chutima (2010)
Breakdown cost for each machine type is known.	Sakhaii et al. (2016)
The failure rate for each machine type is known.	Sakhaii et al. (2016)
If a machine is purchased in a period, it must stay on the shop floor in the following periods. Removal of machines from the shop floor is not assumed.	Bayram & Sahin (2016)
Since in the first period, there is no machine available to be utilized, it will be required to purchase some machines to meet part demands. In the next periods, if the present time capacity of machines is not enough to satisfy the part demands, some other machines will be purchased and added to the current utilized machines.	Kia et al. (2014)
In each period when there is surplus capacity, idle machines can be removed from the cells and transferred to the machine depot, where the idle machines are kept in order to decrease the machine overhead costs and provide empty locations incells to accommodate required machines. Whenever it will be necessary to increase the processing time capacity of the system because of high demand volume, those machines can be returned to the cells.	Kia et al. (2014)
Cell reconfiguration involves different situations that are: (1) transferring of the existing machines between different locations of a same cell or different cells, (2) purchasing and adding new machines to cells, and (3) transferring machines between cells and the machine depot because of changing capacity requirements in successive periods.	Kia et al. (2014)
The relocation cost of each machine type is known. All machine types can be moved to the machine depot or any location in the cells. This cost is paid for several situations: (1) to trans-fer and install a new purchased machine, (2) to relocate a machine between a cell and the machine depot, and (3) to relocate a machine between two different locations of a same cell or different cells. For the sake of simplicity, it is assumed that the unit cost of relocating a machine is the same for all three situations.	Kia et al. (2014)
Replacement cost of machines consists of installation and un-installation costs. When a machine is moved from one location to another, both installation and un-installation costs are incurred. Regardless of the purchase period,	Bayram & Sahin (2016)

installation cost is incurred for every new machine. Both installation and un-installation costs are expressed in terms of money per each relocation.	
The machine relocation cost during the periods is constant and known for a PER machine. This cost includes opening, transferring and resetting the machine.	Golmohammadi et al. (2014)
Cost of investment or purchase of any machine is independent of the work load allocated to it.	Dalfard (2013)
The time value of money is not considered in the CMS model	Asgharpour & Javadian (2004)
Assumptions related with part data	
Demand for each product type is varying in subsequent periods and the demand is known deterministically prior to the design.	Hamedi et al. (2012), Bayram & Sahin (2016), Dalfard (2013)
Demand must be satisfied in a given period hence backorders are not allowed.	Golmohammadi et al. (2014), Bayram & Sahin (2016)
Demand for each product is expressed in number units.	Hamedi et al. (2012), Bayram & Sahin (2016), Dalfard (2013), Golmohammadi et al. (2014)
The operating times for all part type operations on different machine types are known.	Dalfard (2013), Asgharpour & Javadian (2004)
The demand density function for each part type in each period is known.	Dalfard (2013), Asgharpour & Javadian (2004)
Processing capabilities are 100% reliable (i.e. no rework / scrap).	Dalfard (2013), Asgharpour & Javadian (2004)
No inventory is considered.	Golmohammadi et al. (2014), Dalfard (2013),
No queuing in production is allowed.	Dalfard (2013), Asgharpour & Javadian (2004)
Batch size is constant for all products and all periods.	Dalfard (2013), Asgharpour & Javadian (2004)
There is an operation sequence for each product.	Bayram & Sahin (2016), Dalfard (2013), Deep & Singh (2015), Kia et al. (2014), Sirovetnukul & Chutima (2010), Niakan et al. (2016)
In case of subcontracting a certain part, all the operations of that part are made by one supplier; however, different parts can be made by different suppliers.	Mohammadi & Forghani (2016)
The processing routings of parts and the operation sequences in each routing are pre-specified.	Mohammadi & Forghani (2016)

Only one routing must be selected for processing each part type.	Mohammadi & Forghani (2016)
Demand for each period is uncertain.	Mohammadi & Forghani (2016), Niakan et al. (2016)
Assumptions related with material movement	
The cost of carrying items between two locations is proportional to the number of carried products.	Niakan et al. (2016), Bayram & Sahin (2016)
Both inter-cell and intra-cell material handling costs are linearly proportional to the distance between the locations of the machines.	Kia et al. (2014), Golmohammadi et al. (2014)
Parts move inside and outside the cells. Cost of cumulative inter-cell movement is more than that of intra-cell movement.	Dalfard (2013)
The predetermined places (candidate places) are adopted with considering movement inside the cells. Number of the places indicates the maximum number of permissible machinery inside that cell. Dimensions of the cells are not necessarily equal.	Dalfard (2013)
Parts are moved between and inside of cells in batches. The inter-call and intra-cell material handling cost per batch between and inside of cells is known and constant (independent of quantity of cells)	Dalfard (2013), Golmohammadi et al. (2014)
Inter-cell and intra-cell handling costs are constant for all moves regardless of the distance traveled.	Asgharpour & Javadian (2004)
For each part type, the unit inter- and intra-cell material handling costs per unit distance as well as the unit production and outsourcing costs are known in advance.	Mohammadi & Forghani (2016)
Material handling devices moving the part between machines are assumed to carry only one part at a time	Allahyari & Azab (2015), Kia et al. (2014)
The distance between two machines is calculated through a rectilinear distance.	Kia et al. (2014), Golmohammadi et al. (2014)
There is no physical partitioning between cells and a location can be assigned to different cells in different periods.	Bayram & Sahin (2016)
Assumptions related with operators	
Trained homogeneous skilled workers have the same efficiency and multi- functional skills and are able to operate any processes or machines. They walk in a circle inside the U-line (also called the zone constraint – machines allocated to each worker must be adjacently located within a loop)	Sirovetnukul & Chutima (2010)
A worker is assigned to one station (or one loop) only	Sirovetnukul & Chutima (2010)
A task cannot be split between two or more workers	Sirovetnukul & Chutima

	(2010)
Each worker is able to produce any product in any cycle. Consequently, job sequence is regardless at any period	Sirovetnukul & Chutima (2010)
Learning effect has no consideration since it is assumed that worker performance runs into steady state already	Sirovetnukul & Chutima (2010)
The hiring cost of each operator type is known.	Sakhaii et al. (2016)
The required time for relocation and operator training is assumed to be zero.	Sakhaii et al. (2016)
If an operator is able to work with specific machine or is trained to work with it, this learning effect will be considered in succeeding periods.	Sakhaii et al. (2016)
The minimum and maximum numbers of workers, which can be placed in each cell, are predetermined.	Hamedi et al. (2012)
Only multi-skilled workers, who can handle more than one machine, are considered.	Hamedi et al. (2012)
Each worker has the different level of job skills (multi-level flexibility).	Hamedi et al. (2012)
Workers have a different level of proficiency at performing their assigned tasks (heterogeneous worker flexibility).	Hamedi et al. (2012)
The maximum number of virtual cells, which each worker can be assigned, is predefined.	Hamedi et al. (2012)
The total capacity of workforces can be changed by hiring and firing of workers.	Hamedi et al. (2012)
The cross-training, hiring, and firing costs can be different between workers.	Hamedi et al. (2012)
The cross-training cost will be equal to zero if the worker is currently capable of performing the function and a value of one if the worker is incapable of being cross-trained to perform the function.	Hamedi et al. (2012)
Assumptions related with CMS design	
The number of cells used must be specified in advance and it remains constant over time.	Golmohammadi et al. (2014), Asgharpour & Javadian (2004)
Machine relocation from one cell to another is performed between periods and it requires zero time.	Asgharpour & Javadian (2004)
The machine relocation cost of each machine type is known and it is independent of where machines are actually being relocation.	Dalfard (2013), Asgharpour & Javadian (2004)
The maximum number of cells and the minimum and the maximum number of machines in cells are assumed to be known in advance.	Niakan et al. (2016), Bayram & Sahin (2016)

Positions and shapes of the cells are not predetermined.	Bayram & Sahin (2016)
Splitting of lots is allowed. Namely, an operation of a product can be split between two machines of same or different types, in a given period.	Bayram & Sahin (2016)
Cell's dimensions and orientation are predetermined	Allahyari & Azab (2015)

Input parameters	Authors
Part data	
Production volume/demand quantity	Sakhaii et al. (2016), Mohammadi & Forghani (2016), Shafigh et al. (2015), Bayram & Sahin (2016), Mahdavi, Teymourian et al. (2013), Rafiee et al. (2011), Raminfar et al. (2013), Han, Wang & Lv (2014), Deep & Singh (2015), Dalfard (2013), Rafiei & Ghodsi (2013)
Lower and upper bound for number of parts in a cell	Mahdavi, Teymourian et al. (2013)
Transfer batch size/bundle size	Mahdavi, Teymourian et al. (2013), Dalfard (2013), Niakan et al. (2016), Rafiei & Ghodsi (2013)
Precedence constraints/ operation sequence	Sirovetnukul & Chutima (2010)
Number of planning periods in the planning horizon	Sakhaii et al. (2016), Niakan et al. (2016), Rafiei & Ghodsi (2013), Shafigh et al. (2015)
Length of planning period	Shafigh et al. (2015)
Mean arrival rate of parts	Esmailnezhad, Fattahi & Kheirkhah (2015)
Number of parts/product types to be produced	Sakhaii et al. (2016), Niakan et al. (2016), Bayram & Sahin (2016)
Total available time for part types	Hamedi et al. (2012)
Processing time of part operation on specified machine	Sakhaii et al. (2016), Mohammadi & Forghani (2016), Rafiee et al. (2011), Raminfar et al. (2013), Han et al. (2014), Deep & Singh (2015), Dalfard (2013), Bayram & Sahin (2016), Niakan et al. (2016), Sirovetnukul & Chutima (2010)
Number of operations for a part	Bayram & Sahin (2016), Niakan et al. (2016), Sirovetnukul & Chutima (2010)
Machine data	
Lower and upper bound for number of machines in a cell	Mahdavi, Teymourian et al. (2013), Chang, Wu, T. & Wu, C. (2013), Rafiee et al. (2011), Hamedi et al. (2012), Raminfar et al. (2013), Deep & Singh (2015)
Machine capacity in time units	Mohammadi & Forghani (2016), Sakhaii et al. (2016), Rafiee et al. (2011), Raminfar et al. (2013), Deep & Singh (2015), Han et al. (2014), Dalfard (2013), Rafiei & Ghodsi (2013), Bayram & Sahin (2016), Niakan et al. (2016)
Number of machines	Murray et al. (2012), Han et al. (2014), Chang, Wu, T.

	& Wu, C. (2013)
Mean service rate of machines	Esmailnezhad et al. (2015)
Mean time between failures	Esmailnezhad et al. (2015)
Mean time between repairs	Esmailnezhad et al. (2015)
Breakdown rate of one type machine in processing a part type	Rafiee et al. (2011)
Number of machine types	Bayram & Sahin (2016), Niakan et al. (2016)
Dimensional data	
Width of machine	Mohammadi & Forghani (2016)
Length of machine	Mohammadi & Forghani (2016)
Aisle distance between machines in a same cell	Murray et al. (2012)
Aisle distance between cells	Murray et al. (2012), Mohammadi & Forghani (2016)
Horizontal and vertical dimensions of plant floor	Allahyari & Azab (2015)
Number of candidate locations to be a cell/in plant floor	Sakhaii et al. (2016), Bayram & Sahin (2016)
Travelling distances between cells	Mahdavi, Teymourian et al. (2013)
Distance between two candidate cell locations	Sakhaii et al. (2016), Bayram & Sahin (2016), Dalfard (2013)
Maximum number of machines permissible in a cell	Han et al. (2014), Bayram & Sahin (2016), Mohammadi & Forghani (2016)
Minimum number of machines allowable in a cell	Niakan et al. (2016), Bayram & Sahin (2016), Han et al. (2014)
Maximum number of cells	Niakan et al. (2016), Bayram & Sahin (2016), Rafiei & Ghodsi (2013)
Operator related data	
Number of available operators	Sakhaii et al. (2016)
Training cost for individual operators to operate with different individual machines	Sakhaii et al. (2016)
Hiring cost per operator	Sakhaii et al. (2016)
Maximum and minimum number of workers allowed per cell	Hamedi et al. (2012)
Available time for operators	Rafiei & Ghodsi (2013)
Cost related data	
Cost of backtracking and forward movement of unit	Mahdavi, Teymourian et al. (2013)

distance	
Incremental cost of subcontracting	Mohammadi & Forghani (2016)
Production cost of part using defined route	Mohammadi & Forghani (2016)
Intra-cell material handling cost for transporting specific part from specified machines to another	Mohammadi & Forghani (2016)
Inter-cell material handling cost for transporting specific part from specified machines to another	Mohammadi & Forghani (2016)
Unit cost of in-house production	Shafigh et al. (2015)
Unit cost of subcontracting	Rafiee et al. (2011), Deep & Singh (2015), Shafigh et al. (2015)
Unit inventory holding cost	Han et al. (2014), Sakhaii et al. (2016), Shafigh et al. (2015)
Unit backorder cost	Sakhaii et al. (2016), Shafigh et al. (2015)
Material handling cost per unit distance for one unit of product	Bayram & Sahin (2016), Shafigh et al. (2015)
Relocation cost per unit distance for a machine	Shafigh et al. (2015)
Setup cost for processing a sub-lot of product	Shafigh et al. (2015)
Inter-cell part trip unit cost per batch	Sakhaii et al. (2016), Rafiee et al. (2011), Raminfar et al. (2013), Han et al. (2014), Deep & Singh (2015), Rafiei & Ghodsi (2013)
Intra-cell part trip unit cost per batch	Sakhaii et al. (2016), Rafiee et al. (2011), Raminfar et al. (2013), Han et al. (2014), Deep & Singh (2015), Rafiei & Ghodsi (2013)
Replacement cost of one defective item	Rafiee et al. (2011)
Procurement cost of individual machine types	Rafiee et al. (2011), Bayram & Sahin (2016), Deep & Singh (2015)
Installation cost of one type machine	Rafiee et al. (2011), Bayram & Sahin (2016), Deep & Singh (2015)
Removing cost of one type machine	Rafiee et al. (2011), Bayram & Sahin (2016), Deep & Singh (2015)
Operational cost per hour of one type machine	Raminfar et al. (2013), Han et al. (2014), Deep & Singh (2015)
Cost per time unit of corrective repair	Rafiee et al. (2011)
Total cost of preventive	Rafiee et al. (2011)

maintenance for one type machine	
Hiring cost per worker	Hamedi et al. (2012)
Firing cost per worker	Hamedi et al. (2012)
Overhead cost per machine type in each period	Bayram & Sahin (2016), Deep & Singh (2015), Niakan et al. (2016)
Setup cost of route for part in period	Han et al. (2014)
Salary cost per worker	Niakan et al. (2016)

Objective functions	**Authors**
Cost terms	
Inter-cell and Intra-cell movement cost	Murray et al. (2012), Sakhaii et al. (2016), Rafiee et al. (2011), Kia et al. (2014), Golmohammadi et al. (2014), Shafigh et al. (2015), Deep & Singh (2015), Dalfard (2013), Mohammadi & Forghani (2016), Niakan et al. (2016), Rafiei & Ghodsi (2013), Han et al. (2014), Mahdavi, Teymourian et al. (2013), Allahyari & Azab (2015), Raminfar et al. (2013)
Production cost	Shafigh et al. (2015), Mohammadi & Forghani (2016)
Subcontracting cost	Shafigh et al. (2015), Mohammadi & Forghani (2016), Rafiee et al. (2011), Deep & Singh (2015)
Machine relocation cost	Mohammadi & Forghani (2016), Shafigh et al. (2015), Sakhaii et al. (2016), Bayram & Sahin (2016), Niakan et al. (2016), Kia et al. (2014), Golmohammadi et al. (2014), Dalfard (2013), Rafiei & Ghodsi (2013)
Inventory holding cost	Shafigh et al. (2015), Sakhaii et al. (2016), Rafiee et al. (2011), Han et al. (2014)
Machine setup cost	Shafigh et al. (2015), Rafiee et al. (2011)
Machine breakdown cost	Chung, Wu & Chang (2011), Sakhaii et al. (2016)
Operator hiring cost	Sakhaii et al. (2016), Hamedi et al. (2012)
Operator training cost	Sakhaii et al. (2016), Hamedi et al. (2012)
Machine procurement cost	Sakhaii et al. (2016), Rafiee et al. (2011), Dalfard (2013), Bayram & Sahin (2016), Kia et al. (2014), Deep & Singh (2015), Niakan et al. (2016), Rafiei & Ghodsi (2013)
Machine operational cost	Bayram & Sahin (2016), Kia et al. (2014), Sakhaii et al. (2016), Rafiee et al. (2011), Dalfard (2013), Deep & Singh (2015), Han et al. (2014)
Corrective repair cost	Rafiee et al. (2011), Sakhaii et al. (2016)
Preventive maintenance cost	Rafiee et al. (2011), Sakhaii et al. (2016)
Operator firing cost	Hamedi et al. (2012)
Machine installation cost	Bayram & Sahin (2016)
Machine un-installation	Bayram & Sahin (2016)

cost	
Machine overhead cost	Bayram & Sahin (2016), Niakan et al. (2016)
Process routes setup cost	Han et al. (2014)
Salary cost	Niakan et al. (2016)
Revenue from machine selling	Niakan et al. (2016), Rafiei & Ghodsi (2013)
Overtime cost	Rafiei & Ghodsi (2013)
Cost of moving operators from one cell to another	Rafiei & Ghodsi (2013)
Other	
Minimize number of exceptional elements regarding the production volume of each part	Mahdavi, Teymourian et al. (2013)
Minimize area consumed by cells	Murray et al. (2012)
Minimize deviation of operation times of workers	Sirovetnukul & Chutima (2010)
Minimize walking time	Sirovetnukul & Chutima (2010)
Minimize total inter-cellular movement distance	Chang, Wu, T. & Wu, C. (2013)
Maximize average effective arrival rate	Esmailnezhad et al. (2015)
Minimize total number of voids and exceptional elements in part-machine-worker matrix	Mahdavi, Aalaei et al. (2012)

Constraints	**Authors**
Each operation of the part is assigned to one cell in each period	Nouri (2016), Deep & Singh (2015), Mohammadi & Forghani (2014), Egilmez, & Suer (2011), Deljoo et al. (2010)
Internal part operation processing is limited to available machine capacity	Nouri (2016), Deep & Singh (2015), Mohammadi & Forghani (2014), Dalfard (2013), Hamedi et al. (2012), Rezazadeh, Mahini, & Zarei (2011), Deljoo et al. (2010)
The required number of each machine type and worker type in each cell with machine or worker duplication is determined	Nouri (2016)
The cell size lies within the upper and lower limits in terms of the number of machines	Nouri (2016), Bayram & Sahin (2016), Khannan et al. (2016),

	Deep & Singh (2015), Mohammadi & Forghani (2014), Dalfard (2013), Mahdhavi, Aalaei et al. (2012), Deljoo et al. (2010)
Ensure that the number of machines/workers in the current period is equal to the number of machines/workers in the previous period, as well as the number of machines/workers transferred in, and minus the number of machines/workers transferred out.	Nouri (2016), Bayram & Sahin (2016), Khannan et al. (2016), Dalfard (2013), Deljoo et al. (2010)
Each part demand can be satisfied in time period through internal production or subcontracting part operation	Deep & Singh (2015), Rezazadeh et al. (2011)
All the consecutive operations of part type consist of equal production quantities, thus a part operation can be internally processed or subcontracted to satisfy the part demand.	Deep & Singh (2015)
Total number of machines of each type assigned to cells is less than or equal to the number of machines of the same type that are available	Khannan et al. (2016), Deep & Singh (2015), Dalfard (2013), Mahdhavi, Aalaei et al. (2012)
Assign each machine to one cell only to avoid machine sharing	Khannan et al. (2016), Bagheri & Bashiri (2014), Shiyas, & Pillai (2014), Dalfard (2013), Hamedi et al. (2012), Deljoo et al. (2010)
Allocates operations of parts to one of the machines capable to perform the operation	Dalfard (2013)
Each employee can be assigned to work at his/her real skill level or at any lower skill level in each shift	Shahnazari-Shahrezaei, Tavakkoli-Moghaddam, & Kazemipoor (2013)
Upper bound on the total number of daily hours worked by each employee	Shahnazari-Shahrezaei et al. (2013)
Lower and upper bound on the total number of hours worked by each employee during the planning period	Shahnazari-Shahrezaei et al. (2013)
Each employee cannot be assigned to work in two successive shifts	Shahnazari-Shahrezaei et al. (2013)
Each employee who is assigned to work in two non-successive shifts of a day should be off for the next day	Shahnazari-Shahrezaei et al. (2013)
Each employee can just be assigned to work at one skill level in each shift of any day	Shahnazari-Shahrezaei et al. (2013)
Employers tend to pay the minimum penalty for assigning the employees at lower skill levels than their real skill	Shahnazari-Shahrezaei et al. (2013)
Employees tend to work equal to working hours that they have specified at the beginning	Shahnazari-Shahrezaei et al. (2013)

of planning	
Ensures that only one routing is selected for each part type	Mohammadi & Forghani (2014)
Machines belonging to the same cell do not overlap in the x-axis and y-axis	Mohammadi & Forghani (2014)
Calculate the length and width of cell based on the dimensions of the machines assigned to it	Mohammadi & Forghani (2014)
Measure the width and length of each machine (in the x- and y-axis, respectively) based on its orientation	Mohammadi & Forghani (2014)
To balance the load among formed cells, the load of each cell should be higher than a percent of overall load of all cells	Hamedi et al. (2012), Rezazadeh et al. (2011)
Each worker will be assigned to only one Cell	Bagheri & Bashiri (2014), Mahdhavi, Aalaei et al. (2012)
Each part type is assigned to only one cell	Khannan et al. (2016), Mahdhavi, Aalaei et al. (2012)
If one part type is required to be processed by one machine type, more than one worker would be able to service this machine type	Mahdhavi, Aalaei et al. (2012)
Lower bound for the number of parts to be allocated to each cell	Mahdhavi, Aalaei et al. (2012)
Limit the minimum number of operators assigned to cell	Mahdhavi, Aalaei et al. (2012)
Ensures that the minimum numbers of operators are hired	Bagheri & Bashiri (2014)
That an operator can be assigned to a machine and a cell, respectively, if has been hired in that period	Bagheri & Bashiri (2014)
Minimum and maximum number of operators required by each machine is restricted	Egilmez et al. (2014), Bagheri & Bashiri (2014)
The maximum and Minimum number of machines that each operator can operate with is restricted	Bagheri & Bashiri (2014)
Trained operator in a period will not need to learn again to work with the same machine.	Bagheri & Bashiri (2014)
Each cell should be assigned to only one candidate location and a location can be opened only for one cell.	Bayram & Sahin (2016), Bagheri & Bashiri (2014)
Ensure that an operation of a given product type can only be processed in a given location if a machine, which is capable of this operation, is assigned to the location.	Bayram & Sahin (2016)
Total number of processed parts cannot exceed the demand for the product	Bayram & Sahin (2016)
Total processing time of the operations routed	Bayram & Sahin (2016), Khannan

to a machine cannot exceed its capacity, which is defined in terms of time	et al. (2016)
Ensure that the total number of incoming products from all other locations to a location for its next operation is equal to the number of products which receive their next operation in the given location	Bayram & Sahin (2016)
Assure that the number of operators assigned to each operation is large enough to achieve the maximum production rate with respect to the risk level	Egilmez et al. (2014)
Total number of product operations processed anywhere in the factory floor must be equal to the total product demand	Bayram & Sahin (2016)
Total number of operators assigned to all operations cannot exceed the total number of operators available for cells	Egilmez et al. (2014)
If a part has not been produced in a period, none of its operation should have been dedicated to a machine, and cell	
One operator is assigned to one machine only	Khannan et al. (2016)
Lower and upper bound for subcontracting quantity for each part in each period	Khannan et al. (2016)
Inventory and backorder level must be zero at the end of periods	Khannan et al. (2016)
Ensures that inventory and backorder cannot happen simultaneously	Khannan et al. (2016)
A task is processed on an equipment type at a workstation only if that equipment is assigned to that workstation	Jayaswal, & Agarwal (2014)

APPENDIX B: Questionnaire QE 1

Introduction

Questionnaire (QE 1) was distributed to obtain necessary data on research problem justification, selection of an appropriate layout type, and to select the product category for subsequent stages of the research. It was advised to answer the questions with respect to orders in quantity range of 50 to 4000 pieces per order.

Questionnaire (QE 1)

QE 1.1 Machine types used for operations in production department

☐Semi-automatic machines

☐Fully automatic machines

QE 1.2 Rate the problems that are contributing to increased changeover time in production department. Rating scale: 5 – Highly frequent, 1 – Least frequent

Problems	**Rating**				
	5	**3**	**4**	**2**	**1**
Increased machine movement between different locations					
Increased machine setting and adjustment					
Increased operator training time					
Increased defect rate					
Raw material delays					
Poor coordination with supporting departments					
Insufficient number of operators					
Machine breakdowns					
Other					

QE 1.3 Rate the factors to include in layout design for fast fashion orders.

Rating scale: 5 – Highly important, 1 – Least important

Factor	**Rating**				
	5	**4**	**3**	**2**	**1**
Reduce total machine setup time					
Minimize machine movements					
Reduce material handling complexity					
Reduce WIP					
Reduce material handling cost					
Increase the ease of supervision					
Other					

QE 1.4 Select the product category/categories with highest demand for fast fashion orders.

☐Intimate apparels

☐Casual wear

☐Active wear

☐Outer wear

☐Sleep wear

☐Children's wear

☐Work wear

Other (Please specify):

APPENDIX C: Questionnaire QE 2

Introduction

Summary of the selected design attributes based on the perspective of Factory 1 are used in questionnaire (QE 2). QE 2 was developed to identify the design attributes to include in the developed production layout planning system for fast fashion apparels. It was advised to select the relevant options based on orders in quantity range of 50 to 4000 pieces per order. Furthermore, it was advised to mention if a particular option is not available in current situation and factories consider it as essential to include in developed system. If the factory does not currently use cellular layouts, it was advised to select the options based on existing layout.

The percentages of responses received for each option is indicated.

Questionnaire (QE 2) and its results

QE 2.1 Input data: State the current availability and importance of considering following data in a layout design for fast fashion apparels

Input data	Percentage of responses			
	Currently available		Important	
	Yes	***No***	***Yes***	***No***
Length of planning horizon with confirmed order details	98.4	-	98.4	-
Planned number of pieces per day for each part type	99.5	-	99.5	-
Bundle size for part types	99.5	-	99.5	-
SMVs of each operation	99.5	-	99.5	-
Operation sequence	99.5	-	99.5	-
Average time taken to load and unload machines to/from the hand truck	78.1	-	98.3	-
Cost per standard minute value for part types	99.5	-	99.5	-
Production downtime data	84.6	-	99.5	-
Total working minutes per day	99.5	-	99.5	-
Total number of days available to produce each part type in production department	99.5	-	99.5	-
Expected daily production efficiency for each part type	99.5	-	99.5	-
Planned order schedule	99.5	-	99.5	-
Number of working days in considered planning horizon	99.5	-	99.5	-
Average number of turning motions (45 to 90 degrees) when moving materials between layouts				
Maximum number of layouts that can be simultaneously changed by mechanics				
Number of available machines in each machine type	99.5	-	99.5	-
Machine settings required for operations with respective times				
Required minimum distance between adjacent machine rows				
Coordinates of the machine set-up area				
Dimensions of the machines, input/output boxes, and usable area for layouts				
Other (Please mention any additional comments)				

QE 2.2 Assumptions: State the current applicability and importance of considering following assumptions in a layout design for fast fashion apparels

Assumption	**Percentage of responses**			
	Currently applicable		**Important**	
	Yes	***No***	***Yes***	***No***
Adequate number of machines and operators are available for each planning period.	75.1	24.9	88.3	11.7
Multi-skilled pool of operators and mechanics is available to cover up absenteeism.	62.5	37.5	82.7	17.3
SMVs for each operation and each machine setup activity are defined.	95.9	4.1	98.2	1.8
Fixed machine set-up area is provided for machine set-up activities and operator training during changeovers, and to store additional machines.	96.7	3.3	98.2	1.8
Details of the upcoming orders are known in advance.	96.7	3.3	98.2	1.8
Simultaneous processing of multiple part types in a single layout is prohibited.	98.2	1.8	98.2	1.8
All the operators are in stand-up position.	43.4	56.6	79.1	20.9
Machine sharing between operators is not allowed.	88.8	11.2	88.8	11.2
Layout reconfiguration (if any) includes machine setup activities and machine relocations between and/or within the cells. In addition, machines are moved from/to machine set-up area to/from cells.	96.7	3.3	96.7	3.3
Physical partitioning of the cells is prohibited. Furthermore, layout reconfiguration does not require modifications to the buildings. Therefore, other than the machine relocation costs, any physical reconfiguration costs (i.e. changes in lighting and ventilation systems) are not allowed.	98.2	1.8	98.2	1.8
Adequate lighting and environmental conditions required for the operations are provided. Additional light bulbs are attached to the machines when necessary.	87.2	12.8	98.2	1.8
Multiple duplicate machines of each type are available. Existing machines are utilized when developing the layouts.	98.2	1.8	98.2	1.8
Machine working time is reduced due to production downtimes.	98.2	1.8	98.2	1.8
Bundle size for material handling between the machines and/or cells is defined.	71.2	28.8	83.4	16.6
Other (Please mention any additional comments)				

QE 2.3 Cost terms: State the current applicability and importance of considering following cost terms in a layout design for fast fashion apparels

Cost terms	Percentage of responses			
	Currently applicable		Important	
	Yes	*No*	*Yes*	*No*
Inter-cell machine relocation cost	50.3	-	82.1	-
Intra-cell machine relocation cost	85.5	14.5	96.4	-
Machine set-up cost	79.9	-	96.4	-
Inter-cell material handling cost	51.1	-	82.1	-
Intra-cell material handling cost	85.5	14.5	96.4	-
Cost of deviation between target cycle time per bundle and workstation cycle times	72.3	-	96.4	-
Cost of cycle time deviation between bottleneck workstation and other workstations	72.3	-	96.4	-
Other (Please mention any additional comments)				

QE 2.4 Constraints: State the current applicability and importance of considering following constraints in a layout design for fast fashion apparels.

Constraint	Percentage of responses			
	Currently applicable		Important	
	Yes	***No***	***Yes***	***No***
Maximum number of layouts that can be simultaneously changed is limited	98.4	-	98.4	-
Balance the workload between cells	70.2	29.8	81.1	-
Prevent utilizing of machine by exceeding its capacity	95.6	4.4	98.4	-
Use only the available machines on plant floor	82.6	17.4	98.4	-
Ensure non-overlapping of machines, layouts, and gangways	81.1	-	98.4	-
Prevent the developed cells from exceeding available floor dimensions	95.6	-	98.4	-
Improve area utilization	81.8	-	98.4	-
Limit the part processing capability of all machine types based on total machine capacity available for individual machine types	83.6	-	95.6	-
Ensure that the resultant daily efficiency is greater than or equal to planned daily efficiency for each part type assembled in each cell	84.3	-	98.4	-
Ensure that each workstation cycle time is less than or equal to the target cycle time of defined bundle size	88.8	-	98.4	-
Theoretical number of operator/machines should be greater than or equal to resultant number of operators in developed cells	80.1	-	98.4	-
Ensure only one part type is assembled at a time in each cell	79.2	-	98.4	-
Prevent the assignment of a single machine to more than one cell	81.6	-	88.8	-
Assign each operator to a single workstation only	78.5	-	98.4	-
Assign one machine only to a single location		-	98.4	-
Limit the maximum allowable number of operations per operator	92.6	-	98.4	-
Other (Please mention any additional comments)				

APPENDIX D: Sample of the program code

Sample of the program code of the developed system is given.

```
MODEL:
SETS:
! Specify number jobs, families, machine types;
JOBS/1 .. 12/:JOBPRIORITY;
FAMILIES/1 .. 3/;
MTYPES/1 .. 5/:THETA,VMPLUS,VMMINUS;
CELLS/1 .. 3/:NOWORKERS;
!--------------------------------------------------------;
! required processing times;
JOBMTYP(JOBS,MTYPES):PROCTIME;
! required setup times;
FAMMTYPE(FAMILIES,MTYPES):MAJSET;
! job families;
JOBSFAM(JOBS,FAMILIES):SF;
!--------------------------------------------------------;
! decision variables;
JOBCELL(JOBS,CELLS):XIK;
MTYPCELL(MTYPES,CELLS):MK,NMK,TMK;
FAMCELLMTYPE(FAMILIES,CELLS,MTYPES):ZFKM;
JOBCELLMTYPE(JOBS,CELLS,MTYPES):YIKM;
ENDSETS
STIME>0;
!--------------------------------------------------------;
DATA:
! import the data from excel;
SF,MAJSET,THETA,PROCTIME,RL,L,MAXW,MINW,ALPHA,
JOBPRIORITY = @OLE('G:\all dirs\papers\wip\virtual
cells\data13.xls');
! export the data back to excel;
```

```
@OLE('G:\all dirs\papers\wip\virtual cells\data13.xls')=
NOWORKERS,XIK,YIKM,ZFKM,MK,NMK,TMK,VMPLUS,VMMINUS,STIME;
ENDDATA
!------------------------------------------------------------;
[OBJECTIVE]MAX=
100*(@SUM(JOBS(I):@SUM(CELLS(K):@SUM(MTYPES(M):PROCTIME(I,M)
* XIK(I,K)))))- 10 * (@SUM(MTYPES(M):VMPLUS(M)))+
@SUM(MTYPES(M):VMMINUS(M));
!------------------------------------------------------------;
STIME =
(@SUM(JOBS(I):@SUM(CELLS(K):@SUM(MTYPES(M):PROCTIME(I,M)
* XIK(I,K)))));
!------------------------------------------------------------;
@FOR(JOBS(I):
[CO2] @SUM(CELLS(K):XIK(I,K)) <= 1);
@FOR(JOBS(I)|JOBPRIORITY(I)#EQ#1:
[CO3]@SUM(CELLS(K):XIK(I,K)) = 1);
[CO4]@SUM(CELLS(K):NOWORKERS(K)) <= L;
@FOR(MTYPES(M):
[CO5]@SUM(CELLS(K):NMK(M,K))<=THETA(M));
@FOR(MTYPES(M):@FOR(CELLS(K):
[CO6]MK(M,K)>= NMK(M,K)));
@FOR(MTYPES(M):
[CO7]@SUM(CELLS(K):MK(M,K))<= THETA(M) +
VMPLUS(M) - VMMINUS(M));
@FOR(JOBS(I):@FOR(CELLS(K):@FOR(MTYPES(M):
[CO8] XIK(I,K)*PROCTIME(I,M)<= 10000 *
YIKM(I,K,M))));
@FOR(FAMILIES(F):@FOR(CELLS(K):@FOR(MTYPES(M):
[CO9] @SUM(JOBS(I)|SF(I,F)#EQ#1:YIKM(I,K,M))<=
10000 * ZFKM(F,K,M))));
@FOR(CELLS(K):
```

```
[C10] @SUM(JOBS(I):@SUM(MTYPES(M): PROCTIME(I,M) *
YIKM(I,K,M))) +
@SUM(FAMILIES(F):@SUM(MTYPES(M): (ZFKM(F,K,M)+ ALPHA*
(@SUM(JOBS(I)|SF(I,F)#EQ#1:YIKM(I,K,M))-
ZFKM(F,K,M)))*MAJSET(F,M)))<=NOWORKERS(K) *RL);
@FOR(CELLS(K):@FOR(MTYPES(M):
[C11]@SUM(JOBS(I): PROCTIME(I,M) * YIKM(I,K,M)) +
@SUM(FAMILIES(F): (ZFKM(F,K,M) + ALPHA *
(@SUM(JOBS(I)|SF(I,F)#EQ#1:YIKM(I,K,M))-
ZFKM(F,K,M))) *MAJSET(F,M))<=NMK(M,K) * RL));
@FOR(CELLS(K):@FOR(MTYPES(M):
[C12]TMK(M,K)= @SUM(JOBS(I):PROCTIME(I,M) * YIKM(I,K,M)) +
@SUM(FAMILIES(F): (ZFKM(F,K,M) + ALPHA *
(@SUM(JOBS(I)|SF(I,F)#EQ#1:YIKM(I,K,M))-ZFKM(F,K,M)))
*MAJSET(F,M))));
@FOR(CELLS(K):
[C13] NOWORKERS(K) <= MAXW);
@FOR(CELLS(K):
[C14] NOWORKERS(K) >= MINW);
@FOR(JOBCELL(I,K):
[C15]@BIN(XIK(I,K)));
@FOR(JOBCELLMTYPE(I,K,M):
[C16]@BIN(YIKM(I,K,M)));
@FOR(FAMCELLMTYPE(F,K,M):
[C17]@BIN(ZFKM(F,K,M)));
@FOR(MTYPCELL(M,K):
[C18]@GIN(MK(M,K)));
@FOR(MTYPES(M):
[C19]@GIN(VMPLUS(M)));
@FOR(MTYPES(M):
[C20]@GIN(VMMINUS(M)));
END
```

APPENDIX E: MTM data tables

MTM codes and respective TMU values relevant for walking are given.

Source: Mital et al. (2017) and Karger and Bahya (1987)

Motion	**MTM code**	**Distance**	**TMU**
Side step			
Case 1: Complete when leading leg contacts the floor	SSC1	Less than or equal to 30 cm	17.0
		Each additional 1 cm	0.2
Case 2: Lagging leg must contact floor before next motion can be made	SSC2	Less than or equal to 30 cm	34.1
		Each additional 1 cm	0.4
Turn body: 45 to 90 degrees			
Case 1: Complete when leading leg contacts the floor	TBC1		18.6
Case 2: Lagging leg must contact floor before next motion can be made	TBC2		37.2
Walk: Obstructed	W-PO	Per pace or per feet	17.0
Sit	SIT		34.7
Standing from seated position	STD		43.4

APPENDIX F: Input and output data of system evaluation

Input data used for Factory 1

Production volume and expected daily efficiency in Factory 1

t	τ		
	1	2	3
1	1001	1167	1334
2	948	1106	
3	1015	1184	1353
4	967	1128	1289
5	1046	1220	
6	844	985	1126
7	770	898	1027
8	841	981	1122
Efficiency ladder	30%	35%	40%

Machine types required for operations of part types in Factory 1

n	t							
	1	2	3	4	5	6	7	8
1	1	2	1	11	11	1	1	11
2	2	10	2	1	1	2	2	1
3	4	1	5	2	2	7	5	4
4	6	4	8	4	4	10	8	2
5	13	4	8	6	5	9	8	5
6	5	7	9	1	5	9	7	3
7	5	7	8	5	6	9	9	8
8	6	9	9	5	8	13	1	10
9	7	10	12	8	1	4	13	7
10	8	12	13	9	1	13	13	10
11	10	13	13	12	6	13	13	13
12	10	13		13	12			13
13	13			13	13			13
14	13				13			13

Machine settings required for operations of part types in Factory 1

n	t							
	1	2	3	4	5	6	7	8
1	6	6	1	11	11	2	5	11
2	4	2	9	4	7	6	1	6
3	9	2	3	7	5	9	5	2
4	2	4	9	2	2	4	2	5
5	13	2	2	7	6	2	1	2
6	4	3	2	7	2	2	9	5
7	1	9	3	5	8	5	3	1
8	9	6	5	7	3	9	1	4
9	9	6	12	9	5	2	13	4
10	7	12	13	3	7	13	13	4
11	8	13	13	12	9	13	13	13
12	4	13		13	12			5
13	13			13	13			13
14	13				13			13

SMVs of respective operations of part types in Factory 1

n	t							
	1	2	3	4	5	6	7	8
1	0.1582	0.3615	0.3284	0.4517	0.4602	0.3500	0.2749	0.2156
2	0.2340	0.2041	0.1282	0.3512	0.1149	0.4231	0.2780	0.1488
3	0.5666	0.4244	0.3924	0.1118	0.0131	0.1526	0.4572	0.5263
4	0.5559	0.3070	0.4419	0.3860	0.2507	0.2479	0.0225	0.0077
5	0.1962	0.0107	0.0481	0.3379	0.2459	0.3987	0.3682	0.4186
6	0.0504	0.3322	0.0396	0.0249	0.3984	0.1406	0.4549	0.2866
7	0.1752	0.1300	0.3077	0.3574	0.0914	0.3988	0.3217	0.1834
8	0.1297	0.3393	0.0823	0.3199	0.0399	0.1735	0.3802	0.0241
9	0.1545	0.2550	0.4607	0.2621	0.0865	0.2838	0.2796	0.5452
10	0.1363	0.1693	0.0241	0.0585	0.3420	0.2300	0.2095	0.0133
11	0.4398	0.2518	0.2447	0.2459	0.2528	0.2028	0.2437	0.2947
12	0.1038	0.1316		0.1734	0.2019			0.3999
13	0.1751			0.0185	0.2782			0.4663
14	0.1485				0.3085			0.3047

Machine setup times for respective settings on each machine type in Factory 1

i	l									
	1	2	3	4	5	6	7	8	9	10
1	1.17	1.07	1.08	3.05	1.73	2.10	0.72	1.98	1.87	
2	0.83	2.39	0.86	2.30	2.59	1.13	1.55	1.18	2.75	
3	1.05	3.02	0.94	2.94	0.95	1.54	1.76	1.21	2.20	
4	0.86	2.05	1.91	1.77	1.17	1.47	3.28	1.07	2.50	
5	1.03	1.88	1.28	0.05	1.35	2.32	1.69	0.51	1.04	
6	1.54	1.03	1.11	1.55	1.58	2.50	1.48	0.65	3.20	
7	1.45	2.00	1.05	0.42	2.69	1.28	3.12	2.06	3.27	
8	1.83	1.01	1.71	0.49	2.76	1.32	2.85	1.12	1.26	
9	0.04	2.16	1.73	1.50	1.26	2.30	0.70	0.81	1.80	
10	1.09	2.41	1.36	0.49	0.70	2.34	1.61	0.62	2.83	
11										0.68
12										0.68

Random numbers generated based on production downtimes in Factory 1

10.774	23.689	34.960	20.385	10.769	4.656	42.158	4.171	39.180
28.177	5.347	6.389	25.312	14.159	15.493	26.146	18.277	18.463
36.687	11.504	34.982	22.801	19.787	32.533	8.933	3.294	37.533
23.361	34.916	29.903	20.915	34.874	25.426	1.181	9.007	14.848
13.523	5.526	29.438	16.404	36.907	18.813	30.015	12.557	0.386
32.935	4.396	23.995	35.131	41.863	25.865	33.426	2.760	37.208
30.226	24.070	9.702	30.323	40.446	10.027	36.392	0.483	10.544
30.564	38.669	23.290	20.552	41.422	32.984	18.536	17.481	5.975
36.003	8.434	41.306	31.994	5.561	1.363	17.258	24.560	6.046
27.456	40.089	21.506	1.572	15.127	16.405	3.516	11.654	36.547
5.588	36.128	32.626	0.018	0.464	3.181	5.357	28.989	13.007
32.923	21.032	34.198	32.336	39.793	1.447	1.164	4.909	37.676
1.291	1.141	6.656	0.129	31.922	20.848	40.622	0.810	35.711
31.529	34.399	13.570	40.796	40.468	38.797	15.138	11.794	37.154
15.460	2.683	4.961	29.951	23.173	1.636	10.110	25.742	41.064
28.664	40.306	16.737	9.610	40.278	37.286	11.857	32.860	33.423
7.832	32.645	11.701	36.996	7.304	26.710	30.866	3.708	37.731
11.585	4.791	18.825	13.263	41.819	34.662	18.030	25.907	27.975
31.565	39.769	22.854	36.896	23.379	41.190	37.603	40.845	14.046

Number of available machines of each type in Factory 1

i	Total number of available machines
1	33
2	20
3	12
4	24
5	28
6	22
7	22
8	17
9	29
10	25
11	14
12	16
13	43

Order sequence in Factory 1: 1,2,3,4 to 5,6,7,8

Dimensional input data of Factory 1 (measured in meters)

Input data	**Factory 1**
L_{PF}	65.51
W_{PF}	48.62
$max\left\{L_{m_{ij}}, L_{oC_k}\right\}$	1.25
$max\left\{W_{m_{ij}}, W_{oC_k}\right\}$	1.06
W_β	1
x_D	95.3
y_D	90.35

Other input data used for Factory 1

Input data	**Factory 1**
$U_{m_{i,j}}$(min)	5.21
B_t(pieces)	5
γ_t($)	3.2
ξ(min)	960
ψ	2
λ	11

Output data of Factory 1

Part family groups in Factory 1

b	*t*	*k*
1	1,8	1, 8
2	2,3,6,7	2 ,3, 6, 7
3	4,5	4,5

Number of machines of each machine type in the dynamic cells in Factory 1

i	*k*							
	1	2	3	4	5	6	7	8
1	1	1	2	4	4	1	2	1
2	2	1	2	1	1	1	1	2
3	0	0	0	0	0	0	0	2
4	1	3	0	2	1	1	0	1
5	2	0	1	3	2	0	1	1
6	2	0	0	2	2	0	0	0
7	1	2	0	0	0	2	2	1
8	1	0	5	1	2	0	3	1
9	0	3	3	1	0	4	2	0
10	3	2	0	0	0	3	0	3
11	0	0	0	1	1	0	0	1
12	0	2	1	1	2	0	0	0
13	4	2	2	2	3	3	4	4

Operator assignment to operations in dynamic cells in Factory 1

n	*k*							
	1	2	3	4	5	6	7	8
1	1	1,2	1,2	1,2	1,2	1,2	1	1
2	2	3	3	3,4	3	3,4	2	2
3	3,4	4,5	4,5	5	3	5	3,4	3,4
4	5,6	6	6,7	5,6	4	6	4	4
5	7	7	8	7,8	5	7,8	5,6	5,6
6	7	7,8	8	8	6,7	9	7,8	7
7	8	9	9,10	9,10	7	10,11	9	8
8	9	10,11	10	10,11	8	12	10,11	8
9	10	12	11,12	12	8	13	12	9,10
10	11	13	13	12	8,9	14	13	10
11	12,13	14	14	13	10	15	14	11
12	14	15		14	11			12
13	14			14	12			13,14
14	15				13			15

Coordinates of dynamic cell locations in Factory 1

k	x	y
1	6.16	2.31
2	18.84	2.31
3	18.84	7.93
4	6.16	7.93
5	6.16	7.93
6	18.84	2.31
7	18.84	7.93
8	6.16	2.31

Machine type at each location in Factory 1

g	*k*							
	1	2	3	4	5	6	7	8
1	1	2	1	11	11	1	1	11
2	2	10	1	1	1	2	2	1
3	4	1	2	1	1	7	5	4
4	6	4	2	2	2	7	8	2
5	2	4	5	4	4	10	8	2
6	5	4	8	4	5	10	8	5
7	5	7	8	6	5	10	7	3
8	6	7	8	6	6	9	7	3
9	7	9	8	1	8	9	9	8
10	8	9	9	1	8	9	9	10
11	10	9	8	5	1	9	1	10
12	10	10	9	5	1	13	13	7
13	10	12	9	5	6	4	13	10
14	13	12	12	8	12	13	13	13
15	13	13	13	9	12	13	13	13
16	13	13	13	12	13			13
17	13			13	13			13
18				13	13			

x-coordinate values for machine locations in dynamic cells in Factory 1

g	*k*							
	1	2	3	4	5	6	7	8
1	1.88	15.19	15.19	1.88	1.88	15.19	15.19	1.88
2	3.13	16.44	16.44	3.13	3.13	16.44	16.44	3.13
3	4.38	17.69	17.69	4.38	4.38	17.69	17.69	4.38
4	5.63	18.94	18.94	5.63	5.63	18.94	18.94	5.63
5	6.88	20.19	20.19	6.88	6.88	20.19	20.19	6.88
6	8.13	21.44	21.44	8.13	8.13	21.44	21.44	8.13
7	9.38	22.69	22.69	9.38	9.38	22.69	22.69	9.38
8	10.63	23.84	23.84	10.63	10.63	23.84	23.84	10.63
9	11.78	23.84	23.84	11.78	11.78	23.84	23.84	11.78
10	11.78	22.69	22.69	11.78	11.78	22.69	22.69	11.78
11	10.63	21.44	21.44	10.63	10.63	21.44	21.44	10.63
12	9.38	20.19	20.19	9.38	9.38	20.19	20.19	9.38
13	8.13	18.94	18.94	8.13	8.13	18.94	18.94	8.13
14	6.88	17.69	17.69	6.88	6.88	17.69	17.69	6.88
15	5.63	16.44	16.44	5.63	5.63	16.44	16.44	5.63
16	4.38	15.19	15.19	4.38	4.38			4.38
17	3.13			3.13	3.13			3.13
18				1.88	1.88			

y-coordinate values for machine locations in dynamic cells in Factory 1

g	*k*							
	1	2	3	4	5	6	7	8
1	0.53	0.53	6.15	6.15	6.15	0.53	6.15	0.53
2	0.53	0.53	6.15	6.15	6.15	0.53	6.15	0.53
3	0.53	0.53	6.15	6.15	6.15	0.53	6.15	0.53
4	0.53	0.53	6.15	6.15	6.15	0.53	6.15	0.53
5	0.53	0.53	6.15	6.15	6.15	0.53	6.15	0.53
6	0.53	0.53	6.15	6.15	6.15	0.53	6.15	0.53
7	0.53	0.53	6.15	6.15	6.15	0.53	6.15	0.53
8	0.53	1.69	7.31	6.15	6.15	1.69	7.31	0.53
9	1.69	2.94	8.56	7.31	7.31	2.94	8.56	1.69
10	2.94	4.09	9.71	8.56	8.56	4.09	9.71	2.94
11	4.09	4.09	9.71	9.71	9.71	4.09	9.71	4.09
12	4.09	4.09	9.71	9.71	9.71	4.09	9.71	4.09
13	4.09	4.09	9.71	9.71	9.71	4.09	9.71	4.09
14	4.09	4.09	9.71	9.71	9.71	4.09	9.71	4.09
15	4.09	4.09	9.71	9.71	9.71	4.09	9.71	4.09
16	4.09	4.09	9.71	9.71	9.71			4.09
17	4.09			9.71	9.71			4.09
18				9.71	9.71			

APPENDIX G: Input data of system validation

Input data used for the system validation for Factory 2 to 6 are given.

Input data used for Factory 2

Production volume and expected daily efficiency in Factory 2

t	τ					
	1	2	3	4	5	6
1	797	929	929	929		
2	874	1092				
3	735	857				
4	735	857	980			
5	407	475	543	611		
6	570	665	760			
7	500	584	667			
8	687	687	801	916	687	801
9	767	895	895			
10	530	530				
11	742	742	865	989		
12	777	933	933	1088		
Efficiency ladder	25%	30%	30%	35%	40%	40%

Machine types required for operations of part types in Factory 2

n	t											
	1	2	3	4	5	6	7	8	9	10	11	12
1	1	1	12	12	1	14	14	1	12	14	1	1
2	1	1	1	1	7	2	2	1	1	14	1	1
3	3	3	14	1	2	1	2	3	1	2	9	3
4	2	1	2	1	2	9	1	7	1	2	1	7
5	4	2	2	6	9	2	9	2	6	3	9	2
6	5	4	1	3	3	14	2	1	3	3	10	1
7	11	11	3	2	7	8	14	3	2	9	2	3
8	3	11	2	1	2	1	8	9	1	9	11	9
9	13	9	1	6	3	1	1	3	6	1	3	3
10	14	14	6	3	7	9	1	6	3	1	9	11
11	14	14	5	2	2	3	9	11	2	9	14	3
12		14	14	11	14	9	3	3	11	14	14	13
13			11	14	14	11	9	13	14	9		13
14			14	14	3	11	11	13	14	9		14
15			14		3	9	11	14		2		14
16			14		3	13	9	14		9		
17					11	14	13			9		
18					9	14	14			2		
19					3		14			3		
20					14					3		
21					14					9		
22										11		
23										9		
24										14		
25										14		

Machine settings required for operations of part types in Factory 2

n	t											
	1	2	3	4	5	6	7	8	9	10	11	12
1	4	6	12	12	2	14	14	3	12	14	7	7
2	1	7	5	6	3	4	5	6	3	14	1	2
3	1	2	14	7	1	7	4	2	8	7	5	3
4	7	6	3	2	5	8	4	3	3	2	5	1
5	5	4	3	1	5	4	2	5	6	5	4	5
6	1	9	1	12	5	14	6	8	6	1	1	6
7	2	3	2	4	2	1	14	8	3	1	1	7
8	6	1	6	5	1	7	4	5	1	2	1	8
9	12	8	2	3	1	1	2	1	1	1	3	11
10	14	14	5	2	3	4	5	3	2	1	4	8
11	14	14	12	8	7	2	5	5	6	2	14	9
12		14	14	11	14	1	3	1	1	14	14	12
13			11	14	14	2	6	13	14	3		12
14			14	14	4	2	2	13	14	3		14
15			14		1	2	3	14		2		14
16			14		1	12	10	14		4		
17					1	14	12			4		
18					5	14	14			7		
19					12		14			1		
20					14					1		
21					14					2		
22										2		
23										3		
24										14		
25										14		

SMVs of respective operations of part types in Factory 2

n	t											
	1	2	3	4	5	6	7	8	9	10	11	12
1	0.0696	0.2703	0.2400	0.2420	0.0673	0.2182	0.2182	0.0900	0.2420	0.2239	0.4719	0.0900
2	0.2425	0.7094	0.0673	0.0673	0.7328	0.1899	0.2734	0.2800	0.0673	0.2239	0.5071	0.2800
3	0.1904	0.2205	0.1210	0.2278	0.2428	0.2354	0.2030	0.2360	0.1527	0.1983	0.6563	0.2360
4	0.4080	0.2815	0.2847	0.5330	0.3560	0.3151	0.2354	0.4390	0.5330	0.1983	0.1545	0.4390
5	0.4925	0.2073	0.2329	0.6486	0.4232	0.1955	0.3151	0.3700	0.6947	0.1936	0.2194	0.4060
6	0.9930	0.1597	0.2840	0.1511	0.6405	0.2244	0.1966	0.3150	0.1511	0.1936	0.4039	0.3150
7	0.2145	0.2810	0.1973	0.1784	0.3625	0.7359	0.2244	0.1780	0.1674	0.4935	0.3919	0.1780
8	0.3492	0.1576	0.3962	0.2957	0.2370	0.4705	0.7359	0.3930	0.2957	0.5033	0.5174	0.3930
9	0.2014	0.1035	0.4377	0.3760	0.4017	0.3100	0.4602	0.2420	0.3760	0.1368	0.3492	0.2420
10	0.4046	0.4046	0.4159	0.2627	0.6457	0.2851	0.3100	0.4470	0.2627	0.3125	0.2310	0.2460
11	0.4095	0.3663	0.7700	0.1613	0.2044	0.2309	0.2851	0.2460	0.1502	0.3233	0.4046	0.1140
12		0.0529	0.1722	0.4167	0.0367	0.2310	0.2309	0.1140	0.4167	0.1156	0.4181	0.2640
13			0.2407	0.4046	0.1009	0.5209	0.2310	0.2640	0.4046	0.3846		0.2370
14			0.1620	0.2220	0.1775	0.1381	0.5209	0.2370	0.2220	0.3714		0.2100
15			0.4046		0.1695	0.1801	0.1381	0.4100		0.1835		0.2501
16			0.2220		0.3028	0.1907	0.1801	0.3500		0.3332		
17					0.2892	0.4046	0.1907			0.3085		
18					0.3837	0.3672	0.4046			0.1841		
19					0.2140		0.3672			0.2548		
20					0.4046					0.2309		
21					0.2220					0.2310		
22										0.4068		
23										0.1385		
24										0.4046		

25										0.1922		

Machine setup times for respective settings on each machine type in Factory 2

i	l											
	1	2	3	4	5	6	7	8	9	10	11	12
1	5.48	1.23	0.89	1.34	0.94	0.85	0.85					
2	6.16	1.74	1.01	1.34	0.94	0.85	0.85					
3	0.81	0.47	1.50	0.98	0.88	0.64		0.74	0.51	1.11	0.42	
4	5.46	1.42	1.02	1.21	0.82	0.65	1.98	0.98	1.78	1.45	0.42	
5	5.46	1.4	1.51	1.10	0.84	0.65	1.98	0.98	1.78	1.45	0.42	
6	5.46	1.38	1.32	0.97	0.86	0.65	1.98	0.98	1.78	1.45	0.42	
7	5.46	1.43	1.22	1.12	2.31	0.65	1.98	0.98	1.78	1.45	0.42	
8	0.81	0.47	1.08	1.02	0.88	0.64		0.88	0.51	1.21	0.42	
9	0.81	0.47	1.23	0.74	0.88	0.64		0.88	0.51	1.21	0.42	
10	9.12	1.88	1.05	1.00		0.58	2.31	1.06	2.73	4.32		
11	0.89	1.02	1.00	1.05							0.42	
12												0.82
13												0.56

Random numbers generated based on production downtimes in Factory 2

8.668	3.826	29.438	38.499	24.950	28.825	3.403	4.100	12.924
10.993	31.108	21.072	35.046	19.806	27.129	36.047	17.570	11.282
41.428	5.064	35.320	23.922	33.214	26.622	30.605	30.840	22.007
9.555	13.507	27.060	12.809	35.849	6.045	39.982	38.554	39.390
18.840	34.271	38.861	27.166	1.593	15.137	16.983	28.755	34.703
37.357	13.945	14.133	12.874	41.271	22.605	29.718	25.118	18.651
29.607	35.836	1.694	12.965	19.309	18.816	37.177	32.055	31.058
37.388	10.237	10.425	39.843	40.537	36.673	11.221	34.307	0.886
13.228	24.108	23.786	6.545	37.583	32.417	1.771	9.451	28.665
8.759	34.154	17.920	40.584	1.718	26.263	13.689	41.497	34.500
15.691	40.556	19.898	4.057	39.232	5.749	1.083	17.488	39.963
6.723	20.440	23.344	14.670	10.225	24.545	1.726	37.003	11.115
36.256	2.495	22.627	28.941	41.231	34.558	3.835	42.269	41.714
17.987	28.456	40.457	17.668	3.037	20.060	0.913	36.591	6.602
26.314	16.423	34.217	23.505	0.975	14.379	35.213	18.992	15.817
18.551	30.377	40.139	41.146	7.289	41.511	22.048	31.284	3.304
17.714	23.141	33.377	24.119	6.848	36.371	14.510	26.861	16.905
9.365	14.879	28.269	38.741	34.943	38.189	10.254	3.108	3.923
25.654	37.763	1.240	3.376	25.885	20.066	40.495	5.659	31.148

Number of available machines of each type in Factory 2

i	Total number of available machines
1	46
2	40
3	40
4	18
5	27
6	23
7	21
8	23
9	39
10	19
11	36
12	18
13	23
14	46

Input data used for Factory 3

Production volume and expected daily efficiency in Factory 3

t	τ					
	1	2	3	4	5	6
1	455	546	546	637	728	
2	523	627	627	732	836	
3	473	567	567	662		
4	597	716	716			
5	734	880	880	1027		
6	710	852	852	994		
7	571	685	685	799	914	
8	412	494	494	577	659	742
9	527	632	632	737	843	
10	637	764	764	891		
11	1275	1529				
12	373	447	447	522		
13	529	635	635	740		
14	375	450	450	525		
15	418	502	502	586	669	
16	604	724	724	845	966	
17	589	706	706	824	942	
18	620	744	744	868	992	
19	910	1091	1091			
20	779	935	935	1091		
21	546	656	656	765	874	
22	396	475	475	554	634	713
23	468	561	561	655	748	842
Efficiency ladder	25%	30%	30%	35%	40%	45%

Machine types required for operations of part types in Factory 3

n	t																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	13	7	1	13	11	1	15	8	13	15	13	3	13	2	13	9	1	3	13	11	3	11	14
2	2	3	14	15	14	8	6	15	6	10	4	4	3	12	2	15	1	3	15	15	1	13	15
3	5	3	15	4	3	3	4	7	3	6	15	14	9	4	7	14	5	5	2	1	4	7	12
4	6	13	3	1	9	10	10	13	15	3	5	10	2	3	4	9	9	9	7	7	13	3	10
5	9	9	1	8	13	4	8	3	9	11	2	12	8	13	4	8	9	14	10	3	7	8	7
6	10	4	6	9	15	5	3	3	11	10	10	12	9	1	15	1	3	4	15	6	12	12	4
7	4	14	8	7	3	9	15	9	11	15	11	1	4	15	1	7	7	4	5	6	6	11	13
8	6	13	13	5	4	5	5	8	7	14	15	13	6	14	10	2	4	11	12	3	6	7	1
9	11	13	3	10	15	1	9	14	5	1	15	9	15	9	10	6	9	8	11	2	1	14	9
10	12	15	9	11	15	1	3	15	12	7		10	10	4	11	13	9	2	11	15	14	10	3
11	12	10	1	15		9	11	3	12	15		9	12	6	11	15	10	15	6	15	10	10	9
12	15	7	11	15		10	14	12	9	15		9	8	1	8	15	14	7	14		8	6	9
13	3	15	11			14	15	4	11			11	14	9	8		15	3	15		12	15	15
14	2	15	4			15	15	5	11			14	15	8	9		15	14	15		12	15	9
15	3		3			15		2	12			9	15	12	10			15			15		15
16	9		8					3	14			11		14	14			15			15		14
17	15		11					6	15			9		14	15								5
18	15		12					15	15			13		9	15								1
19			15					15				15		15									15
20			15									15		15									15

Machine settings required for operations of part types in Factory 3

n	t																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	13	8	10	13	11	9	15	5	13	15	11	3	13	2	13	9	8	8	13	11	3	11	11
2	5	1	11	15	11	3	7	15	8	10	2	3	7	1	8	15	1	4	15	15	5	11	15
3	9	3	15	8	4	8	4	6	6	9	15	11	5	5	8	11	9	7	8	9	1	6	6
4	6	11	1	9	6	3	2	11	15	3	4	10	7	4	7	9	3	2	4	10	11	6	10
5	6	2	7	8	11	6	3	2	8	11	2	12	1	11	4	8	7	14	4	1	7	10	7
6	5	5	2	6	15	7	4	6	8	3	10	3	6	8	15	1	1	1	15	6	12	2	4
7	7	11	8	8	1	6	15	9	5	15	11	1	3	15	3	7	7	7	1	4	2	11	11
8	1	11	11	7	4	4	5	8	5	11	15	11	1	11	6	2	1	5	7	2	9	10	5
9	3	11	4	2	15	4	2	11	7	4	15	9	15	9	5	6	2	3	3	2	1	11	9
10	5	15	1	3	15	2	4	15	1	10		10	2	5	1	11	7	2	6	15	11	10	3
11	9	4	1	15		9	4	3	6	15		9	8	2	8	15	8	15	2	15	5	10	10
12	15	8	4	15		6	14	12	9	15		9	5	9	6	15	14	5	14		9	4	9
13	7	15	11			14	15	4	5			11	14	9	5		15	4	15		4	15	15
14	9	15	4			15	15	5	8			11	15	8	8		15	14	15		6	15	9
15	3		1			15		6	9			9	15	12	6			15			15		15
16	4		5					3	14			11		11	14			15			15		11
17	15		11					5	15			9		11	15								5
18	15		12					15	15			11		9	15								6
19			15					15				15		15									15
20			15									15		15									15

SMVs of respective operations of part types in Factory 3

n	t											
	1	2	3	4	5	6	7	8	9	10	11	12
1	0.1800	0.4981	0.1253	0.1443	0.4217	0.0228	0.6617	0.1918	0.1992	0.5728	0.4874	0.4544
2	0.5096	0.2339	0.1612	0.1746	0.4533	0.4932	0.3722	0.5254	0.1305	0.5984	0.0030	0.1535
3	0.4855	0.3466	0.4482	0.5998	0.3298	0.1821	0.1917	0.2952	0.3957	0.3982	0.3508	0.1861
4	0.3407	0.0052	0.2474	0.2437	0.4493	0.0314	0.4698	0.5369	0.6004	0.5768	0.4589	0.6828
5	0.1360	0.6328	0.3212	0.6601	0.4704	0.4695	0.0191	0.1668	0.3042	0.4557	0.3545	0.3116
6	0.4638	0.3730	0.0077	0.5535	0.4348	0.6634	0.4898	0.5432	0.5710	0.3986	0.2135	0.1063
7	0.6607	0.5625	0.4460	0.5545	0.3169	0.1670	0.3005	0.3576	0.4936	0.4837	0.1094	0.3230
8	0.4756	0.4261	0.3481	0.2688	0.0355	0.0364	0.1205	0.3225	0.1132	0.0285	0.2750	0.0628
9	0.2408	0.2303	0.5112	0.0368	0.5389	0.5051	0.2648	0.4632	0.3741	0.4025	0.0073	0.6128
10	0.2400	0.1503	0.0543	0.6157	0.4758	0.1493	0.6251	0.2941	0.0830	0.1144		0.3202
11	0.2042	0.6424	0.4549	0.6534		0.1722	0.5375	0.0519	0.0113	0.2628		0.0928
12	0.2484	0.2249	0.1791	0.3194		0.6190	0.3580	0.3640	0.1169	0.2308		0.1376
13	0.2387	0.5725	0.0519			0.2620	0.5129	0.2829	0.2482			0.3338
14	0.5485	0.6094	0.5445			0.2380	0.1202	0.4777	0.3625			0.4105
15	0.3185		0.2173			0.0429		0.4286	0.6647			0.6613
16	0.2220		0.6596					0.6184	0.1722			0.7450
17	0.4420		0.5595					0.4599	0.3549			0.6255
18	0.3755		0.1126					0.3709	0.2712			0.6768
19			0.0983					0.2410				0.1235
20			0.5476									0.7058

SMVs of respective operations of part types in Factory 3 continued

n	t										
1	13	14	15	16	17	18	19	20	21	22	23
2	0.4816	0.0850	0.6217	0.3278	0.4788	0.2102	0.2063	0.1254	0.1923	0.4734	0.3542
3	0.2703	0.1506	0.0612	0.6609	0.4177	0.6497	0.6013	0.3050	0.2404	0.2387	0.0566
4	0.3707	0.5350	0.6087	0.3516	0.2194	0.1479	0.1213	0.0693	0.1745	0.1568	0.5522
5	0.7260	0.6595	0.6237	0.4665	0.5730	0.7222	0.4782	0.1624	0.0114	0.7026	0.0372
6	0.1718	0.7406	0.0895	0.5969	0.0367	0.4194	0.0370	0.7083	0.2098	0.0892	0.2126
7	0.6394	0.2882	0.5127	0.2637	0.2319	0.5567	0.1233	0.3754	0.1532	0.4805	0.6076
8	0.6577	0.2608	0.7086	0.2208	0.3368	0.5900	0.0695	0.3366	0.0470	0.5556	0.5017
9	0.4037	0.0183	0.4843	0.6150	0.1121	0.4891	0.1286	0.1514	0.6105	0.3465	0.1598
10	0.4451	0.5851	0.0667	0.3366	0.2434	0.4994	0.5003	0.1492	0.1660	0.6012	0.1845
11	0.2025	0.4858	0.1870	0.2498	0.3547	0.1576	0.3884	0.6114	0.1301	0.4260	0.6868
12	0.2340	0.2513	0.1672	0.2496	0.1367	0.0058	0.7038	0.1721	0.2916	0.4272	0.4590
13	0.3870	0.6731	0.1066	0.4340	0.6483	0.0682	0.3478		0.0885	0.3572	0.1677
14	0.3016	0.4312	0.2637		0.6229	0.1593	0.6838		0.4803	0.3869	0.5728
15	0.0989	0.6355	0.0848		0.4809	0.3249	0.2582		0.6359	0.0315	0.4275
16	0.0564	0.7239	0.4044			0.6316			0.2145		0.5727
17		0.2123	0.5148			0.5282			0.0503		0.4700
18		0.5295	0.7459								0.1478
19		0.1545	0.6336								0.5907
20		0.0121									0.0076
21		0.2518									0.5022

Machine setup times for respective settings on each machine type in Factory 3

i	l										
	1	2	3	4	5	6	7	8	9	10	11
1	0.92	1.58	0.75	1.44	0.65	0.93	1.77	1.03	1.65	1.22	
2	0.84	1.01	0.85	2.86	0.93	0.85	5.34				
3	6.18	0.98	0.85	1.02		0.59	9.02				
4	5.46	1.33	0.59	1.08	0.99	1.40		0.43	0.90	0.98	
5	1.36	0.81	0.53	1.03	1.02	1.33		3.37	0.53	1.59	
6	0.72	0.95	0.48	1.02	1.01	0.92	0.98	1.78	0.48	1.48	
7	8.79	1.12	0.97		0.87	0.84	0.98	1.78	1.04	1.64	
8	1.40	0.76	0.88		0.98	1.02	0.98	1.78	0.65	1.66	
9	1.33	1.19	0.78	1.15	0.78	1.08	0.88	0.51	0.93	1.56	
10	0.83	1.13	1.03	1.03	0.59		0.88	0.51	1.21	1.32	
11	1.16	1.04	0.74	1.26	0.85		1.01	1.33	0.34	1.90	
12	0.41	0.93	0.85	1.03	0.98	1.04	0.93	1.03	1.02	1.85	
13	1.61	1.47	0.85	0.99	0.88	0.93		4.83	1.03	1.60	
14											0.63

Random numbers generated based on production downtimes in Factory 3

29.148	16.813	19.512	31.478	12.403	6.946	5.994	11.276	23.375
25.097	25.062	19.627	33.914	29.368	29.054	3.552	19.861	3.139
32.247	8.676	23.288	22.303	3.865	3.955	26.310	12.805	21.771
31.189	7.607	23.109	10.201	18.451	14.864	6.585	5.061	20.609
14.789	0.269	21.661	3.348	32.821	17.762	16.090	33.613	33.789
13.080	19.104	5.824	24.996	15.430	9.233	15.915	29.305	18.480
33.355	3.134	12.883	12.950	2.987	33.588	29.890	18.133	9.486
7.818	17.916	14.563	2.585	1.035	33.650	16.611	13.810	31.938
11.389	21.645	15.886	23.484	33.714	18.604	33.153	24.909	15.599
8.872	12.880	20.692	17.424	10.586	29.083	30.098	19.158	10.677
14.382	18.313	4.172	4.574	31.337	15.015	4.176	5.734	17.652
8.124	20.797	14.597	5.720	15.528	0.631	33.420	16.453	15.561
3.417	13.590	9.448	10.268	0.912	17.006	19.111	9.077	26.805
3.356	25.893	14.418	5.016	15.094	25.469	21.346	19.024	15.903
32.991	25.875	7.093	22.650	17.806	20.008	9.361	27.006	25.565
31.736	2.719	7.453	27.479	26.521	4.442	2.981	4.992	5.083
20.692	20.705	29.867	10.280	2.906	5.103	16.534	32.052	4.221
26.430	1.734	10.316	25.828	2.602	24.042	21.316	28.295	8.056
21.086	21.890	13.108	15.149	11.318	10.403	26.145	20.932	22.538
0.135	15.301	13.103	16.499	9.553	33.607	19.827	31.757	29.941
0.157	8.673	2.324	33.938	32.869	1.898	13.551	22.397	5.002
3.734	11.172	4.866	21.143	6.564	7.195	9.173	1.807	7.423
16.892	25.928	23.065	0.312	11.860	26.121	9.118	28.016	11.705
19.196	18.823	31.392	32.086	1.064	6.100	20.256	25.194	17.235
32.290	9.870	21.233	22.543	9.479	27.519	8.103	19.409	25.493

Number of available machines of each type in Factory 3

i	Total number of available machines
1	12
2	13
3	26
4	25
5	17
6	27
7	20
8	19
9	36
10	19
11	27
12	17
13	25
14	21
15	59

Input data used for Factory 4

Production volume and expected daily efficiency in Factory 4

t	τ			
	1	2	3	4
1	435	521	521	608
2	500	600	600	700
3	543	651	651	760
4	583	699	699	816
5	897	1077		
6	434	521	521	608
7	721	865		
8	696	835	835	
9	711	853	853	
10	501	601	601	
11	598	718	718	
12	596	716	716	835
13	639	767	767	
14	581	697	697	813
15	826	991	991	1156
16	674	809	809	944
17	866	1039	1039	
18	1209	1451		
19	762	915		
20	662	794	794	926
21	1070	1284	1284	
22	869	1043	1043	
23	1003	1204	1204	
24	732	878	878	1024
25	786	944	944	1101
26	804	965	965	1125
27	895	1074	1074	
28	1034	1240	1240	
Efficiency ladder	25%	30%	30%	35%

Machine types required for operations of part types in Factory 4

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

Machine settings required for operations of part types in Factory 4

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

SMVs of respective operations of part types in Factory 4

n	t													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.6736	0.2064	0.7267	0.6066	0.1069	0.5124	0.2268	0.4451	0.5800	0.2369	0.4796	0.0209	0.2127	0.3420
2	0.7669	0.0423	0.5907	0.1962	0.3841	0.7008	0.7584	0.3476	0.4150	0.3404	0.6990	0.2407	0.4987	0.6826
3	0.5592	0.4821	0.1574	0.1884	0.2527	0.5420	0.7440	0.3537	0.4583	0.0004	0.2483	0.5219	0.0101	0.3390
4	0.4916	0.1829	0.4370	0.3221	0.5050	0.2750	0.0613	0.2409	0.6108	0.4796	0.6962	0.4455	0.7625	0.6146
5	0.2010	0.3288	0.2529	0.2096	0.3041	0.2560	0.0097	0.1328	0.2049	0.0866	0.6516	0.2655	0.5099	0.3034
6	0.5880	0.6751	0.6144	0.5646	0.2553	0.1312	0.6605	0.5119	0.1589	0.4903	0.3893	0.2876	0.7484	0.3463
7	0.5769	0.3716	0.5185	0.1731	0.2574	0.3030	0.0671	0.0302	0.1014	0.7143	0.5779	0.3556	0.3989	0.0439
8	0.0393	0.3887	0.4033	0.6174	0.0942	0.5416	0.6605	0.6522	0.3477	0.0653	0.4551	0.1424	0.1104	0.6623
9	0.6834	0.1486	0.2278	0.0447	0.0062	0.2762	0.5399	0.2886	0.2110	0.3227	0.4758	0.7013	0.5778	0.0579
10	0.1085	0.7328	0.4836	0.4096	0.1560	0.2660		0.4098	0.6959	0.2298	0.2823	0.2827	0.6784	0.4719
11	0.6325	0.4695	0.5411	0.6040	0.6737	0.3771		0.2569			0.0378	0.4926		0.3435
12	0.1059	0.1799		0.6293		0.1984		0.1940			0.3714	0.4840		
13	0.7578	0.3651		0.0461		0.6750						0.2524		
14		0.7462				0.4205								
15		0.0521				0.7139								

SMVs of respective operations of part types in Factory 4 continued

n	t													
	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1	0.3482	0.0832	0.4396	0.1999	0.1217	0.2200	0.2074	0.0780	0.2470	0.0936	0.4522	0.0972	0.2941	0.0249
2	0.1293	0.2929	0.0561	0.1563	0.1379	0.3421	0.2389	0.1656	0.4554	0.0516	0.0577	0.2557	0.1529	0.0191
3	0.2869	0.1979	0.2746	0.2607	0.2674	0.0046	0.0102	0.3978	0.0882	0.0716	0.2274	0.3858	0.0154	0.0505
4	0.0373	0.2848	0.0128	0.3406	0.3862	0.3004	0.1507	0.4289	0.0843	0.3165	0.3255	0.4152	0.4367	0.0761
5	0.4314	0.3646	0.4486	0.1633	0.4524	0.4131	0.4041	0.1707	0.3323	0.2063	0.0149	0.2799	0.3404	0.2169
6	0.1585	0.4386	0.3910	0.1305	0.1958	0.3463	0.1902	0.3978	0.0070	0.2098	0.3377	0.0301	0.0097	0.1500
7	0.3787	0.3438	0.1182	0.3405	0.3393	0.4199	0.2031	0.1153	0.2746	0.2656	0.1362	0.0450	0.2888	0.4433
8	0.3611	0.2041	0.0208	0.2387	0.0494	0.1577	0.0937	0.1181	0.3905	0.3628	0.2210	0.0312	0.1460	0.1085
9	0.3830	0.2493	0.2864	0.0687	0.3879	0.2928	0.0665	0.1533	0.1831	0.3486	0.3870	0.3148	0.4080	0.3310
10	0.0951	0.3300	0.1627	0.0581	0.1078	0.3804	0.2799	0.2713	0.1851	0.4097	0.2768	0.4522	0.3279	0.4140
11	0.1643	0.1285	0.0751	0.0643	0.1309	0.0117	0.2809	0.0060	0.0269	0.3188	0.3363	0.2118	0.1585	0.2121
12	0.1893	0.2599	0.3748	0.1820	0.4461	0.3701	0.0282	0.1671	0.0872	0.1775	0.1574	0.3346	0.1513	0.0545
13	0.0590	0.3651		0.0168		0.2866		0.3403	0.0019	0.4309		0.2524	0.1040	0.3708
14		0.3651		0.0029		0.3526		0.2840	0.3167	0.4101			0.1701	0.1295
15		0.3651				0.4538								

Machine setup times for respective settings on each machine type in Factory 4

i	*l*									
	1	2	3	4	5	6	7	8	9	10
1	0.48	1.08	1.40	1.01	3.37	1.36	5.34	1.05	0.83	
2	0.97	1.03	1.33	0.98	1.78	0.72	9.02			
3	7.08	1.02	0.92	1.33		0.59	9.02			
4	5.46	1.33	0.59	1.08	0.99	1.40		0.43	0.90	
5	1.03	1.02	1.40	1.03	1.78	1.33		3.37	0.53	
6	0.85	1.08	1.33	1.02	1.78	0.92		1.78	0.48	
7	0.59	1.03	0.97		0.87	0.84		1.78	1.04	
8	1.40	0.76	0.88		0.98	1.02	0.98	1.78	0.65	
9	1.03	1.19	0.78	1.15	0.78	1.08	0.88	0.51	0.93	
10										0.63
11										0.62

Random numbers generated based on production downtimes in Factory 4

18.112	21.958	3.983	2.166	6.183	9.577	18.182	13.557	12.959
21.726	17.866	19.823	18.773	16.029	3.114	10.805	14.061	4.055
16.896	12.317	21.316	19.613	5.199	1.961	6.462	1.793	12.440
4.155	10.852	14.667	15.797	12.414	1.270	19.947	2.016	15.609
8.294	14.048	18.126	0.856	2.049	23.797	23.086	20.726	11.714
16.976	2.144	15.415	24.943	3.784	8.307	17.816	5.901	12.553
4.988	22.489	9.596	10.069	23.136	17.736	13.388	9.623	15.147
12.812	16.747	20.590	0.488	11.877	1.678	8.752	17.099	16.598
7.370	0.423	7.497	14.181	7.276	6.768	3.244	11.561	20.300
19.562	5.462	9.784	6.563	8.395	14.014	18.438	10.943	24.056
14.379	5.404	21.355	15.893	25.395	16.279	16.638	7.605	1.643
4.067	9.002	17.772	21.227	0.080	10.232	23.724	12.172	13.921
7.958	15.464	0.830	0.232	4.486	20.830	3.141	23.770	3.309
9.941	16.760	1.919	17.817	7.587	14.082	12.630	8.215	1.111
23.446	8.010	18.975	0.113	4.853	14.573	6.260	19.649	25.570
3.815	24.172	16.877	11.968	14.698	19.022	17.997	15.878	24.401
14.011	0.686	1.096	22.638	3.351	8.350	16.001	0.703	4.024
2.578	16.558	18.928	2.266	4.138	8.259	9.746	15.065	5.950
10.951	15.159	19.658	13.135	8.274	11.185	17.302	6.159	13.134

Number of available machines of each type in Factory 4

i	Total number of available machines
1	18
2	32
3	29
4	24
5	27
6	22
7	24
8	23
9	21
10	20
11	23
12	57

Input data used for Factory 5

Production volume and expected daily efficiency in Factory 5

t	τ			
	1	2	3	4
1	523	628	733	
2	993	1191		
3	988	1186		
4	857	1028	1199	
5	712	855	997	
6	885	1062		
7	710	851	993	
8	692	830	968	
9	710	852	994	1136
10	637	764	891	
11	735	882	1029	1176
12	867	1040	1214	
13	1264	1516		
14	957	1148	1339	
15	1011	1214	1416	
16	884	1061	1238	
17	1362	1634		
18	870	1044	1218	
19	1038	1245		
20	870	1044	1218	
21	933	1119	1306	
Efficiency ladder	25%	30%	35%	40%

Machine types required for operations of part types in Factory 5

n	t																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	11	5	1	9	1	13	10	6	15	14	10	5	13	15	1	8	12	6	2	3	7
2	11	7	7	9	15	2	6	8	13	10	3	6	9	1	10	11	6	14	6	4	11
3	11	10	2	2	8	7	10	9	8	6	7	13	10	6	7	2	8	5	7	8	5
4	8	3	11	1	6	8	10	13	8	13	3	4	8	1	15	1	1	4	12	10	7
5	14	4	11	11	8	3	10	7	8	1	15	11	13	13	6	2	4	3	1	6	4
6	11	14	14	12	12	3	11	1	1	14	11	1	13	13	13	12	11	7	12	8	6
7	15	10	5	7	4	2	8	12	10	8	1	10	15	15	8	4	7	14	2	4	14
8	15	1	2	9	11	11	12	13	9	11	5	3	14	5	15	12	12	14	15	3	14
9	7	15	15	6	12	5	11	12	5	5	14	3	10	8	2	13	9	2	13	9	5
10	13	15	15	15	13	15	2	3	9	15	9	13	9	9	5	7	7	9	5	15	5
11	2			15	2	15	3	9	10	15	15	13	15	15	15	11	15	7	15	13	15
12	15				13		15	5	9		15	15	15	15	15	7	15	15	10	12	15
13	15				7		15	11	15			15				15		15	15	15	
14					12			15	1							15			15	15	
15					15			15	15												
16					9				15												
17					15																
18					15																

Machine settings required for operations of part types in Factory 5

n	t																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	2	8	7	2	7	11	2	3	10	11	8	9	7	15	2	7	9	3	5	9	2
2	3	3	7	7	9	9	6	1	11	8	6	3	9	1	3	10	4	7	8	7	10
3	10	8	7	10	4	9	3	4	8	7	4	1	4	4	9	4	7	2	8	4	9
4	9	8	9	3	2	2	3	11	8	1	2	4	4	3	7	5	10	1	8	3	9
5	11	4	5	8	5	10	1	7	8	1	5	10	6	3	2	8	7	8	7	3	8
6	11	11	11	8	12	4	8	1	1	8	10	6	6	3	1	8	6	1	2	5	8
7	15	2	7	5	3	8	8	12	10	8	7	9	15	15	4	4	7	10	2	4	10
8	15	9	10	8	3	3	4	11	9	2	9	6	10	8	15	4	12	10	15	3	10
9	2	15	15	3	3	4	1	10	9	3	11	7	8	10	7	2	1	7	1	8	9
10	11	15	15	15	11	15	5	4	10	3	9	1	4	4	4	2	10	5	1	15	1
11	2			15	2	15	5	4	5	6	15	7	15	15	15	9	15	4	15	13	15
12	15				13		15	7	3		15	15	15	15	15	6	15	15	10	8	15
13	15				7		15	11	15			15				15		15	15	15	
14					12			15	4												
15					15			15	15												
16					9				15												
17					15																
18					15																

SMVs of respective operations of part types in Factory 5

n	t													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.2630	0.3140	0.0973	0.5202	0.3338	0.4996	0.5499	0.4539	0.4884	0.3573	0.5573	0.1578	0.0850	0.0685
2	0.5068	0.0905	0.3589	0.4870	0.3952	0.3980	0.1071	0.0694	0.3907	0.5664	0.1504	0.2381	0.2993	0.2541
3	0.5565	0.4795	0.4957	0.5196	0.2082	0.2318	0.2417	0.2460	0.0340	0.4986	0.1009	0.3212	0.1021	0.2424
4	0.4878	0.1922	0.3840	0.2242	0.2870	0.5479	0.1949	0.3765	0.4350	0.1379	0.0243	0.3322	0.1390	0.1581
5	0.5340	0.3782	0.1342	0.5129	0.5254	0.1331	0.3309	0.2312	0.1002	0.2843	0.4456	0.0181	0.1356	0.2092
6	0.2471	0.0281	0.1087	0.2996	0.1971	0.0345	0.1251	0.1783	0.2872	0.4062	0.2355	0.3109	0.1896	0.2058
7	0.2893	0.4883	0.0041	0.1315	0.0139	0.2303	0.0665	0.3647	0.5619	0.3219	0.3583	0.1887	0.2461	0.1675
8	0.4925	0.2756	0.4365	0.2855	0.5011	0.3173	0.1362	0.0987	0.1170	0.4419	0.1760	0.1715	0.0422	0.2358
9	0.4748	0.5161	0.4837	0.0924	0.0882	0.2318	0.1047	0.2520	0.0078	0.3410	0.5628	0.1821	0.2640	0.0423
10	0.4599	0.1380	0.4117	0.0801	0.2658	0.4928	0.4675	0.2141	0.1835	0.1769	0.5541	0.3260	0.1134	0.2686
11	0.5608			0.2090	0.0158	0.1381	0.4621	0.2020	0.3494	0.5255	0.2829	0.0452	0.1045	0.2049
12	0.1238				0.0441		0.1115	0.5398	0.2035		0.4708	0.0785	0.1027	0.3516
13	0.5089				0.2578		0.5157	0.4468	0.2175			0.5089		
14					0.0576			0.0783	0.3577					
15					0.2409			0.3076	0.2457					
16					0.2422				0.1857					
17					0.1508									
18					0.2187									

SMVs of respective operations of part types in Factory 5 continued

n	t						
	15	16	17	18	19	20	21
1	0.1404	0.3300	0.2883	0.2501	0.1122	0.1424	0.2066
2	0.1290	0.3165	0.1550	0.0474	0.1370	0.2289	0.1619
3	0.1983	0.1436	0.0219	0.1201	0.1907	0.2956	0.2708
4	0.2541	0.1012	0.2172	0.1481	0.2617	0.2886	0.1948
5	0.0191	0.3501	0.0841	0.0997	0.0590	0.1315	0.3129
6	0.1183	0.1358	0.2622	0.0412	0.0412	0.1440	0.2207
7	0.2843	0.2621	0.0349	0.2679	0.2395	0.2899	0.1220
8	0.1269	0.2481	0.2768	0.3216	0.2226	0.1607	0.2357
9	0.3049	0.1929	0.0000	0.3378	0.3248	0.1663	0.0569
10	0.3558	0.1764	0.0039	0.1326	0.1030	0.0030	0.3250
11	0.0726	0.3143	0.2191	0.2926	0.3343	0.3299	0.3354
12	0.2747	0.1547	0.1283	0.2945	0.0399	0.3343	0.0273
13		0.2578		0.5157	0.4468	0.2175	
14		0.0576			0.0783	0.3577	

Machine setup times for respective settings on each machine type in Factory 5

i	l										
	1	2	3	4	5	6	7	8	9	10	11
1	0.40	0.65	0.48	1.00	1.02	1.63	0.99	0.58	1.35	0.98	
2	1.55	1.92	0.57	1.68	0.95	1.61	0.87	0.67	0.55	0.96	
3	1.42	1.16	0.34	1.11	1.21	1.53	0.51	0.65	0.51	0.51	
4	5.84	0.66	0.64	1.46	0.97	1.02	0.75	0.78	0.53	1.54	
5	6.22	0.97	0.81	2.03	1.59	2.11	0.99	0.98	0.92	0.95	
6	1.39	0.67	0.73	1.36	1.64	1.06	0.41	0.76	0.46	0.95	
7	1.72	1.91	0.44	2.00	0.99	1.20	0.43	0.75	0.54	0.76	
8	1.37	0.41	0.43	2.10	1.92	1.90	0.58	0.79	0.74	1.82	
9	0.83	1.02	0.59	1.34	1.01	1.20	0.63	1.11	0.72	1.69	
10	2.05	1.20	0.61	1.60	1.12	1.46	0.89	0.75	0.82	0.66	
11	0.98	1.21	0.57	1.68	1.01	1.40	0.41	0.92	0.87	0.85	
12	1.55	0.41	0.61	1.33	1.18	1.06	0.41	0.32	0.85	0.91	
13	1.55	0.41	0.61	1.33	1.18	1.06	0.41	0.32	0.85		
14											0.71

Random numbers generated based on production downtimes in Factory 5

12.459	35.025	19.796	27.340	10.276	42.837	31.938	40.272	12.413
13.681	14.108	39.737	34.017	23.645	2.452	40.456	18.841	10.870
5.057	11.111	14.478	19.787	33.323	30.288	30.367	32.428	36.315
12.522	20.886	20.714	29.138	30.935	24.373	15.962	0.274	1.099
14.938	35.574	18.704	19.718	42.751	29.152	28.572	1.163	12.211
7.552	42.049	21.171	7.097	30.262	31.860	34.359	17.869	29.733
41.924	40.185	23.109	35.591	2.608	18.452	0.845	21.035	26.986
38.811	27.307	9.255	3.008	4.930	20.851	6.304	17.051	1.545
7.707	17.178	26.424	40.276	14.560	26.340	38.877	21.883	8.142
7.770	2.147	0.471	22.873	39.635	8.021	22.468	16.150	39.957
19.551	35.693	33.180	15.259	20.189	0.932	0.537	40.790	26.560
13.315	39.354	15.060	11.884	42.228	7.643	28.502	33.429	17.464
36.474	40.060	13.088	11.087	6.268	19.909	6.815	20.603	8.041
13.783	22.848	4.097	22.769	6.225	9.221	38.480	35.856	4.506
6.986	14.514	17.910	29.068	33.579	1.280	8.475	16.871	14.933
41.905	26.294	12.907	14.659	38.133	33.797	24.483	24.924	31.593
41.717	12.951	33.541	29.550	31.592	21.576	40.342	17.297	42.458
9.545	24.080	1.553	42.439	11.977	26.482	15.289	16.808	27.774
20.659	8.709	0.795	34.597	38.335	24.184	19.081	20.810	13.613

Number of available machines of each type in Factory 5

i	Total number of available machines
1	17
2	25
3	21
4	16
5	20
6	19
7	15
8	18
9	26
10	31
11	32
12	21
13	24
14	17
15	45

Input data used for Factory 6

Production volume and expected daily efficiency in Factory 6

t	τ				
	1	2	3	4	5
1	465	558	651	744	
2	666	799	932		
3	531	638	744	850	
4	618	742			
5	508	609	711		
6	583	700	817	933	
7	662	794	927	1059	
8	732	878	1024		
9	862	1034	1206		
10	666	799	932		
11	479	575	670	766	862
12	969	1163			
13	989	1187	1385		
14	1077	1292			
15	818	981	1145		
16	925	1110	1295		
17	1101	1322			
18	1067	1280	1493		
19	975	1170	1365		
20	1247	1497			
21	997	1196	1395		
Efficiency ladder	25%	30%	35%	40%	45%

Machine types required for operations of part types in Factory 6

n	t																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1	14	14	2	3	14	14	16	10	4	14	12	1	13	7	13	12	1	11	16	1
2	2	10	5	5	5	6	3	6	5	15	6	4	14	5	3	4	5	15	15	4	8
3	5	9	2	5	2	6	1	3	15	6	4	6	9	6	8	13	7	16	7	15	14
4	7	4	3	7	10	2	8	10	16	12	9	14	11	1	11	11	2	15	9	14	7
5	11	7	4	4	8	13	7	7	9	9	11	6	15	12	1	10	7	2	3	9	4
6	6	14	8	4	16	5	1	6	14	13	16	8	8	15	7	1	13	4	10	7	3
7	12	7	10	16	16	10	11	6	4	5	12	9	10	6	15	5	2	12	6	10	12
8	16	11	2	11	9	5	7	6	5	16	11	12	15	1	3	14	1	8	13	7	2
9	16	4	11	11	1	1	8	12	9	1	11	3	3	16	12	2	12	10	5	4	2
10	3	5	9	12	11	3	16	1	13	4	10	10	7	12	5	10	6	8	10	15	8
11	4	16	13	9	4	4	16	1	16	4	5	13	14	16	15	4	9	16	11	7	2
12	10	15	1	6	12	4		5	16	8	7	16	4	3	6	4	6	4	16	4	16
13	3	16	15	3	11	11		16		16	10	16	12	14	4	16	12	1	16	16	16
14	15	16	16	10	13	12		16		16	16		1	16	16	3	13	7		16	
15	16		16	16	16	16					16		16	16	16	16	16	16			
16	16			16	16	16							16			16	16	16			

Machine settings required for operations of part types in Factory 6

n	t																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	3	10	14	6	5	14	10	16	6	6	14	7	2	11	9	10	5	5	6	16	1
2	9	7	6	6	5	1	9	9	7	10	9	4	14	2	8	12	11	15	15	4	8
3	3	1	9	1	9	16	8	9	10	5	9	2	4	12	3	12	1	16	2	15	14
4	8	1	2	1	6	1	8	7	16	3	8	10	8	6	1	1	8	15	3	14	1
5	6	9	1	2	7	5	5	5	9	5	8	8	15	8	3	4	9	4	11	9	2
6	8	10	3	1	4	1	1	9	10	8	16	4	11	15	4	3	10	1	9	12	8
7	1	1	2	16	16	8	5	5	6	7	4	9	6	10	15	5	6	11	12	12	12
8	16	9	6	6	6	9	4	5	7	16	3	7	15	3	8	14	5	2	7	7	10
9	16	2	3	6	2	9	9	8	4	3	8	4	2	16	5	11	3	8	9	4	8
10	1	3	2	8	2	5	16	5	4	7	6	7	12	12	11	12	5	4	8	15	2
11	9	16	7	3	5	3	16	4	16	7	5	6	14	16	3	8	6	16	10	6	3
12	2	10	1	5	2	7		2	16	3	8	16	6	11	10	11	1	1	16	5	16
13	8	16	15	2	7	3		16		16	7	16	12	14	8	16	5	1	16	16	16
14	15	16	16	9	6	7		16		16	16		3	16	16	3	10	9		16	
15	16		16	16	16	16					16		16	16	16	16	16	16			
16	16			16	16	16							16			16	16	16			

SMVs of respective operations of part types in Factory 6

n	t													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.2832	0.4640	0.4246	0.5370	0.0389	0.1314	0.4574	0.0013	0.1988	0.3520	0.5167	0.4520	0.1570	0.2601
2	0.3057	0.6500	0.6052	0.0575	0.6030	0.4458	0.6083	0.5172	0.0049	0.1098	0.4684	0.3109	0.2205	0.3140
3	0.5231	0.4679	0.4561	0.4875	0.1795	0.2725	0.4095	0.1039	0.4295	0.4535	0.5164	0.0416	0.2787	0.3099
4	0.5826	0.1393	0.2214	0.1400	0.4880	0.6415	0.1767	0.0264	0.2440	0.3034	0.5963	0.0750	0.2426	0.2382
5	0.1847	0.2846	0.3413	0.3823	0.5506	0.5482	0.5893	0.0576	0.5674	0.4121	0.4530	0.1364	0.2170	0.0458
6	0.0727	0.3685	0.0711	0.0488	0.6101	0.0475	0.6166	0.2666	0.2234	0.4579	0.3820	0.1698	0.0498	0.1482
7	0.4066	0.5039	0.5717	0.4513	0.5385	0.0267	0.0481	0.4653	0.1660	0.2271	0.6118	0.2840	0.1963	0.0152
8	0.4816	0.1362	0.2996	0.0190	0.2630	0.1989	0.6274	0.2983	0.5360	0.4868	0.4263	0.3739	0.2880	0.2401
9	0.3342	0.4994	0.5851	0.0089	0.5151	0.2762	0.4149	0.4764	0.0338	0.3561	0.4513	0.3003	0.0562	0.0372
10	0.5831	0.0703	0.0451	0.1888	0.4050	0.1245	0.0603	0.4777	0.5818	0.0234	0.1361	0.3610	0.2667	0.1260
11	0.5942	0.0891	0.2778	0.5562	0.3067	0.0412	0.3421	0.1389	0.2001	0.2434	0.0691	0.2663	0.2172	0.0178
12	0.4741	0.1371	0.6155	0.2122	0.1323	0.5615		0.1424	0.1574	0.6466	0.3555	0.0378	0.2048	0.2746
13	0.3999	0.5093	0.2341	0.1250	0.4781	0.6266		0.5624		0.0299	0.3715	0.1620	0.0188	0.2660
14	0.1112	0.0044	0.3255	0.6245	0.3761	0.1332		0.4012		0.2218	0.2430		0.1583	0.0896
15	0.4232		0.3483	0.2815	0.0311	0.5983					0.4185		0.3025	0.2924
16	0.4306			0.5393	0.1555	0.2641							0.2320	

SMVs of respective operations of part types in Factory 6 continued

n	t						
	15	16	17	18	19	20	21
1	0.3392	0.2157	0.2471	0.1465	0.3145	0.0704	0.1949
2	0.1542	0.3108	0.3019	0.3329	0.2350	0.2886	0.2224
3	0.0919	0.2089	0.0787	0.2810	0.1917	0.0661	0.2912
4	0.2032	0.3427	0.2722	0.0484	0.2842	0.1136	0.2463
5	0.1637	0.1051	0.2275	0.2288	0.0950	0.2075	0.2200
6	0.2139	0.0875	0.3428	0.2579	0.0680	0.1001	0.1407
7	0.2635	0.3201	0.1179	0.2040	0.0581	0.3439	0.2323
8	0.3093	0.1581	0.1894	0.3474	0.3095	0.0676	0.3532
9	0.1148	0.2799	0.2595	0.2720	0.2563	0.1792	0.0385
10	0.0595	0.1596	0.1198	0.0420	0.1492	0.0794	0.0063
11	0.3454	0.0700	0.2102	0.0571	0.1549	0.3001	0.0989
12	0.3440	0.2005	0.1214	0.2888	0.1482	0.0761	0.2664
13	0.3409	0.1785	0.0617	0.0368	0.2962	0.0652	0.1932
14	0.2376	0.1952	0.0139	0.0941		0.1971	
15	0.3422	0.1850	0.1146	0.1333			
16		0.3021	0.1106	0.1087			

Machine setup times for respective settings on each machine type in Factory 6

i	l									
	1	2	3	4	5	6	7	8	9	10
1	2.17	1.07	0.85	3.13	2.73	2.10	0.72	1.98	1.87	
2	0.83	3.39	0.86	2.30	2.59	1.13	1.55	1.18	2.75	
3	2.05	3.02	0.94	2.94	0.95	2.54	2.76	1.21	2.20	
4	0.86	3.05	1.91	1.77	1.17	1.47	3.28	1.07	2.50	
5	1.38	1.88	3.28	0.05	3.35	2.32	1.69	0.51	1.04	
6	1.54	1.03	1.11	1.55	1.58	2.50	1.48	0.65	3.20	
7	2.45	2.00	1.85	0.42	2.69	1.28	3.12	2.06	3.27	
8	1.83	1.01	1.71	0.49	2.76	1.32	2.85	1.12	1.26	
9	0.04	2.16	1.73	1.50	1.26	2.30	0.70	0.81	1.80	
10	1.99	3.41	1.36	0.49	0.70	2.34	1.61	0.62	2.83	
11	3.38	3.09	0.86	1.74	1.11	2.52	1.41	0.65	2.16	
12	2.69	2.27	2.32	0.13	3.08	3.20	1.04	3.41	2.30	
13	1.99	3.41	1.03	1.11	0.94	2.94	2.76	1.21	2.20	
14										0.68
15										0.68

Random numbers generated based on production downtimes in Factory 6

21.572	42.435	39.542	17.204	4.222	21.486	15.604	13.208	15.485
12.323	4.454	34.661	13.944	26.809	20.364	33.406	23.318	34.843
37.078	38.560	8.068	12.455	13.137	9.516	2.071	2.770	25.021
21.914	16.754	27.198	22.336	18.690	12.863	3.133	36.474	0.941
15.515	8.624	24.240	8.653	12.517	36.422	40.468	30.392	12.725
21.838	15.436	23.799	15.351	1.406	42.629	0.315	13.807	7.939
42.417	10.851	18.674	1.745	8.816	21.120	32.921	10.205	21.046
41.260	28.287	33.217	3.474	41.578	27.857	34.867	41.191	41.305
11.142	31.365	12.768	9.825	19.347	19.962	33.339	27.124	1.770
10.783	15.785	38.225	14.803	21.788	42.113	33.219	34.651	38.024
24.946	9.601	1.019	9.330	9.947	10.426	40.948	21.592	37.675
10.952	12.046	18.784	11.561	13.880	19.096	10.652	38.470	4.265
34.661	17.457	2.080	40.778	21.122	28.449	29.075	31.059	25.970
31.934	2.930	42.728	25.443	0.551	17.729	42.727	23.944	29.708
20.237	29.543	18.470	33.090	31.353	28.517	26.398	42.802	39.781
34.806	11.394	16.666	18.709	38.872	4.595	36.839	39.819	2.617
13.833	28.209	7.153	3.011	2.058	37.895	30.989	15.628	4.055
34.340	10.677	11.102	23.067	23.201	11.799	4.541	13.807	20.528
35.546	10.650	3.419	22.467	31.338	35.795	23.258	3.724	8.665

Number of available machines of each type in Factory 6

i	Total number of available machines
1	18
2	22
3	20
4	20
5	27
6	24
7	17
8	17
9	21
10	16
11	22
12	17
13	20
14	26
15	24
16	46

Order sequence data of Factory 2 to 6

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

Dimensional input data of Factory 2 to 6 (measured in meters)

Input data	Factory 2	Factory 3	Factory 4	Factory 5	Factory 6
L_{PF}	65.51	88.6	95.92	68.54	70.25
W_{PF}	48.62	53.8	58.98	40.38	58.72
$max\left\{L_{m_{ij}}, L_{oC_k}\right\}$	1.22	1.2	1.26	1.18	1.25
$max\left\{W_{m_{ij}}, W_{oC_k}\right\}$	1.06	1.1	1.14	1.16	1
W_{β}	0.89	1.5	1	1	1
x_D	95.3	118.51	110.81	75.69	109.03
y_D	70.35	142.74	68.43	84.26	63.97

Other input data used for Factory 2 to 6

Input data	Factory 2	Factory 3	Factory 4	Factory 5	Factory 6
$U_{m_{i,j}}$(min)	3.21	3.15	2.17	2.82	3.38
B_t(pieces)	8	5	10	10	12
γ_t($)	4.2	3.6	3.8	4.5	4.1
ξ(min)	960	900	960	960	900
ψ	4	4	6	5	6
λ	12	12	14	10	18

APPENDIX H: Output data of system validation

Output data of the system validation for Factory 3 to 6 are given hereafter.

Part family groups and respective cells of Factory 3 to 6

Factory	*b*	*t*	*k*
3	1	1,4,6,7,9	1,4,6,7,9
	2	13,15,17,18,19	13,15,17,18,19
	3	2,3,5,8,10	2,3,5,8,10
	4	11,12,14,21,23	11,12,14,21,23
	5	16,20	16,20
	6	22	22
4	1	1,7,8,9,11,12,13,14	1,7,8,9,11,12,13,14
	2	3,2,6,10	3,2,6,10
	3	4,5	4,5
	4	19,21	19,21
	5	16,17,18	16,17,18
	6	20,22,26	20,22,26
	7	15,23,24	15,23,24
	8	25,27,28	25,27,28
5	1	1,10	1,10
	2	2,3,4,6	2,3,4,6
	3	5	5
	4	7,8	7,8
	5	9,11	9,11
	6	14,21	14,21
	7	13,18	13,18
	8	12,15,16,17,19,20	12,15,16,17,19,20
6	1	1,3,4,5,6,11	1,3,4,5,6,11
	2	2,8,10,12	2,8,10,12
	3	7,9	7,9
	4	13,15,16,21	13,15,16,21
	5	14,17,18,19	14,17,18,19
	6	20	20

Output data of Factory 3

Number of machines of each machine type in the dynamic cells in Factory 3

i	k																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0	0	3	2	0	3	0	0	0	2	0	1	0	2	1	1	3	0	0	1	2	0	2
2	2	0	0	0	0	0	0	1	0	0	3	0	1	1	1	1	0	1	1	1	0	0	0
3	2	2	3	0	4	1	2	4	1	2	0	1	2	1	0	0	2	3	0	4	1	2	1
4	1	1	1	1	1	2	2	1	0	0	1	1	1	2	2	0	1	2	0	0	1	0	1
5	1	0	0	1	0	4	1	1	1	0	3	0	0	0	0	0	2	1	2	0	0	0	1
6	1	0	1	0	0	0	1	1	1	2	0	0	1	1	0	1	0	0	1	3	3	1	0
7	0	2	0	2	0	0	0	1	1	1	0	0	0	0	1	2	1	1	1	1	1	2	1
8	0	0	2	2	0	1	2	2	0	0	0	0	2	1	2	1	0	2	0	0	1	1	0
9	2	2	1	1	2	2	1	1	2	0	0	5	3	3	1	3	4	1	0	0	0	0	4
10	1	2	0	3	0	2	1	0	0	4	2	2	1	0	3	0	2	0	1	0	1	2	1
11	1	0	3	1	2	0	2	0	4	2	1	2	0	0	2	0	0	1	4	1	0	2	0
12	2	0	1	0	0	0	0	1	2	0	0	2	1	2	0	0	0	0	1	0	5	1	1
13	1	3	1	1	2	0	0	1	1	0	4	2	1	1	1	1	0	0	1	0	1	1	1
14	0	2	1	0	2	1	1	1	2	1	0	2	1	3	1	2	1	2	2	0	1	1	2
15	4	5	3	4	6	2	5	4	3	6	6	2	4	3	3	4	2	3	4	5	2	2	5

Operator assignment to operations in dynamic cells in Factory 3

n	k																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1	1	1	1	1,2	1	1,2	1	1	1,2	1,2,3,4	1	1	1	1	1	1	1
2	2	2	1	1	3,4	1,2	3	1	1	3,4	4	2	2	1	2	2,3	2	2
3	3	3	2	2,3	5,6	3	4	2	2	5,6	5,6,7	2	3	2	3	4	3	3
4	4	3	2	4	7,8	3	5	2	3	7,8	8,9,10	3	4,5	3	4	5	4,5	4,5
5	4	4,5	3	5,6	9,10	4	5	3	4	9,10	11,12,13	4	6	4	5	6,7	5	6
6	5	6	3	7,8	11,12	5,6	6	3	5	11,12	14,15	4	7,8	5	6	8	6	7
7	6	7,8	4	9,10	13,14	7	7	4	6	13,14	16	5	9,10	5	7	9	7	8
8	7	9	4	11	15	7	8	4	7	14	17	5	11	5	8	10,11	8	9
9	8	10	5	11	16,17	8,9	8	5	7	15,16	17	6	11	6	2	12	8	10
10	8	10	6	12,13	18,19	10	9,10	5	8	17		7	12	7	9	13	9	11
11	9	11,12	6	14,15		10	11,12	5	8	18		7	12	8	9	14	10	11
12	9	13	7	16		11,12	13	6	8	19		8						
13	10	14,15	7			13	14,15	6	9			8						
14	11	16,17	8			14	16	7	9			9						
15	12		8			15		8	10			10						
16	12		9					9	11			11						
17	13		10					10	11			12						
18	14		11					11	12			13						
19			11					11				14						
20			11									15						

Operator assignment to operations in dynamic cells in Factory 3 continued

n	*k*				
	19	20	21	22	23
1	1	1	1	1	1
2	2,3	2	2	2	1
3	4	3	3	2	2
4	5	3	3	3,4	3
5	6	4,5,6	4	5	3
6	6	7,8	5	6	4
7	6	9	5	7	5
8	7	10	6,7	8	6
9	8,9	11	8	9	6
10	10	12,13,14	8	10	7
11	11,12	15	9	11	8
12	13		10	12	9
13	14,15		11,12	13	10
14	4		13,14	5	9
15			15		11
16			15		12
17					12
18					13
19					14
20					14

Coordinates of dynamic cell locations in Factory 3

k	x	y	*k*	x	y
1	5.95	3.50	13	5.95	3.50
2	18.75	3.50	14	18.75	20.50
3	18.75	12.00	15	5.95	12.00
4	5.95	12.00	16	18.75	46.00
5	18.75	20.50	17	5.95	20.50
6	5.95	20.50	18	5.95	29.00
7	5.95	29.00	19	5.95	37.50
8	18.75	29.00	20	18.75	46.00
9	5.95	37.50	21	18.75	29.00
10	18.75	37.50	22	18.75	54.50
11	18.75	3.50	23	18.75	37.50
12	18.75	12.00			

Machine type at each location in Factory 3

g	*k*																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	13	7	1	13	11	1	15	8	13	15	13	3	13	2	13	9	1	3	13	11	3	11	14
2	2	3	14	15	11	8	6	15	6	15	13	4	3	12	2	15	1	3	15	15	1	13	15
3	5	3	15	4	14	3	4	7	3	10	13	14	9	4	7	15	1	5	2	1	4	7	12
4	6	13	3	1	14	10	4	13	15	10	13	10	9	3	4	14	5	9	7	7	13	3	10
5	9	9	1	1	3	4	10	3	9	6	4	12	2	13	4	14	5	14	10	3	7	3	7
6	10	9	6	8	3	4	8	3	11	6	15	12	8	1	15	9	9	4	15	3	12	8	4
7	4	4	8	8	9	5	8	9	11	3	15	1	9	15	1	9	9	4	5	3	6	12	13
8	6	14	13	9	9	5	3	8	7	3	15	13	4	14	10	8	3	11	5	6	6	11	1
9	11	14	3	7	13	9	15	14	5	11	5	9	6	9	10	1	3	8	12	6	6	7	9
10	12	13	9	7	13	5	15	15	12	11	5	10	3	4	11	7	7	8	11	6	1	14	3
11	12	13	1	5	15	5	5	3	12	10	5	9	15	6	11	7	4	2	11	3	14	10	9
12	15	15	11	10	15	1	9	12	9	10	2	9	15	1	8	2	9	15	11	2	10	10	9
13	3	10	11	10	3	1	3	4	11	15	2	11	10	9	8	6	9	7	11	15	8	6	15
14	2	10	4	10	3	9	11	5	11	15	2	14	12	8	9	13	10	3	6	15	12	15	9
15	3	7	3	11	4	10	11	2	12	14	10	9	8	12	10	15	10	14	14	15	12	15	15
16	9	15	8	15	15	14	14	3	14	1	10	11	14	14	14	15	14	15	14	15	12		14
17	15	15	11	15	15	15	15	6	15	1	11	9	15	14	15		15	15	15		12		5
18	15	15	12	15	15	15	15	15	15	7	15	13	15	9	15		15		15		15		1
19		15	15		15			15		15	15	15		15							15		15
20			15							15	15	15		15									15

x-coordinate values for machine locations in dynamic cells in Factory 3

g	*k*															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0.20	14.00	14.00	0.20	14.00	0.20	0.20	14.00	0.20	14.00	14.00	14.00	0.20	14.00	0.20	14.00
2	1.40	15.20	15.20	1.40	15.20	1.40	1.40	15.20	1.40	15.20	15.20	15.20	1.40	15.20	1.40	15.20
3	2.60	16.40	16.40	2.60	16.40	2.60	2.60	16.40	2.60	16.40	16.40	16.40	2.60	16.40	2.60	16.40
4	3.80	17.60	17.60	3.80	17.60	3.80	3.80	17.60	3.80	17.60	17.60	17.60	3.80	17.60	3.80	17.60
5	5.00	18.80	18.80	5.00	18.80	5.00	5.00	18.80	5.00	18.80	18.80	18.80	5.00	18.80	5.00	18.80
6	6.20	20.00	20.00	6.20	20.00	6.20	6.20	20.00	6.20	20.00	20.00	20.00	6.20	20.00	6.20	20.00
7	7.40	21.20	21.20	7.40	21.20	7.40	7.40	21.20	7.40	21.20	21.20	21.20	7.40	21.20	7.40	21.20
8	11.35	22.40	22.40	11.35	22.40	11.35	11.35	22.40	11.35	22.40	22.40	22.40	11.35	22.40	11.35	11.00
9	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.00
10	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	21.20
11	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	11.35	20.00
12	7.40	11.35	11.35	7.40	11.35	7.40	7.40	11.35	7.40	11.35	11.35	11.35	7.40	11.35	7.40	18.80
13	6.20	22.40	22.40	6.20	22.40	6.20	6.20	22.40	6.20	22.40	22.40	22.40	6.20	22.40	6.20	17.60
14	5.00	21.20	21.20	5.00	21.20	5.00	5.00	21.20	5.00	21.20	21.20	21.20	5.00	21.20	5.00	16.40
15	3.80	20.00	20.00	3.80	20.00	3.80	3.80	20.00	3.80	20.00	20.00	20.00	3.80	20.00	3.80	15.20
16	2.60	18.80	18.80	2.60	18.80	2.60	2.60	18.80	2.60	18.80	18.80	18.80	2.60	18.80	2.60	14.00
17	1.40	17.60	17.60	1.40	17.60	1.40	1.40	17.60	1.40	17.60	17.60	17.60	1.40	17.60	1.40	
18	0.20	16.40	16.40	0.20	16.40	0.20	0.20	16.40	0.20	16.40	16.40	16.40	0.20	16.40	0.20	
19		15.20	15.20		15.20			15.20		15.20	15.20	15.20		15.20		
20			14.00							14.00	14.00	14.00		14.00		

x-coordinate values for machine locations in dynamic cells in Factory 3 continued

g	*k*						
	17	18	19	20	21	22	23
1	0.20	0.20	0.20	14.00	14.00	14.00	14.00
2	1.40	1.40	1.40	15.20	15.20	15.20	15.20
3	2.60	2.60	2.60	16.40	16.40	16.40	16.40
4	3.80	3.80	3.80	17.60	17.60	17.60	17.60
5	5.00	5.00	5.00	18.80	18.80	18.80	18.80
6	6.20	6.20	6.20	20.00	20.00	20.00	20.00
7	7.40	7.40	7.40	21.20	21.20	21.20	21.20
8	11.35	11.35	11.35	11.00	22.40	11.00	22.40
9	11.35	11.35	11.35	11.00	11.35	11.00	11.35
10	11.35	11.35	11.35	21.20	11.35	21.20	11.35
11	11.35	11.35	11.35	20.00	11.35	20.00	11.35
12	7.40	7.40	7.40	18.80	11.35	18.80	11.35
13	6.20	6.20	6.20	17.60	22.40	17.60	22.40
14	5.00	5.00	5.00	16.40	21.20	16.40	21.20
15	3.80	3.80	3.80	15.20	20.00	15.20	20.00
16	2.60	2.60	2.60	14.00	18.80		18.80
17	1.40	1.40	1.40		17.60		17.60
18	0.20	0.20	0.20		16.40		16.40
19					15.20		15.20
20							14.00

y-coordinate values for machine locations in dynamic cells in Factory 3

g	*k*															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0.55	0.55	9.05	9.05	17.55	17.55	26.05	26.05	34.55	34.55	0.55	9.05	0.55	17.55	9.05	43.05
2	0.55	0.55	9.05	9.05	17.55	17.55	26.05	26.05	34.55	34.55	0.55	9.05	0.55	17.55	9.05	43.05
3	0.55	0.55	9.05	9.05	17.55	17.55	26.05	26.05	34.55	34.55	0.55	9.05	0.55	17.55	9.05	43.05
4	0.55	0.55	9.05	9.05	17.55	17.55	26.05	26.05	34.55	34.55	0.55	9.05	0.55	17.55	9.05	43.05
5	0.55	0.55	9.05	9.05	17.55	17.55	26.05	26.05	34.55	34.55	0.55	9.05	0.55	17.55	9.05	43.05
6	0.55	0.55	9.05	9.05	17.55	17.55	26.05	26.05	34.55	34.55	0.55	9.05	0.55	17.55	9.05	43.05
7	0.55	0.55	9.05	9.05	17.55	17.55	26.05	26.05	34.55	34.55	0.55	9.05	0.55	17.55	9.05	43.05
8	1.70	0.55	9.05	10.20	17.55	18.70	27.20	26.05	35.70	34.55	0.55	9.05	1.70	17.55	10.20	44.20
9	2.90	1.70	10.20	11.40	18.70	19.90	28.40	27.20	36.90	35.70	1.70	10.20	2.90	18.70	11.40	45.40
10	4.10	2.90	11.40	12.60	19.90	21.10	29.60	28.40	38.10	36.90	2.90	11.40	4.10	19.90	12.60	46.55
11	5.30	4.10	12.60	13.80	21.10	22.30	30.80	29.60	39.30	38.10	4.10	12.60	5.30	21.10	13.80	46.55
12	6.45	5.30	13.80	14.95	22.30	23.45	31.95	30.80	40.45	39.30	5.30	13.80	6.45	22.30	14.95	46.55
13	6.45	6.45	14.95	14.95	23.45	23.45	31.95	31.95	40.45	40.45	6.45	14.95	6.45	23.45	14.95	46.55
14	6.45	6.45	14.95	14.95	23.45	23.45	31.95	31.95	40.45	40.45	6.45	14.95	6.45	23.45	14.95	46.55
15	6.45	6.45	14.95	14.95	23.45	23.45	31.95	31.95	40.45	40.45	6.45	14.95	6.45	23.45	14.95	46.55
16	6.45	6.45	14.95	14.95	23.45	23.45	31.95	31.95	40.45	40.45	6.45	14.95	6.45	23.45	14.95	46.55
17	6.45	6.45	14.95	14.95	23.45	23.45	31.95	31.95	40.45	40.45	6.45	14.95	6.45	23.45	14.95	
18	6.45	6.45	14.95	14.95	23.45	23.45	31.95	31.95	40.45	40.45	6.45	14.95	6.45	23.45	14.95	
19		6.45	14.95		23.45			31.95		40.45	6.45	14.95		23.45		
20			14.95							40.45	6.45	14.95		23.45		

y-coordinate values for machine locations in dynamic cells in Factory 3 continued

g	*k*						
	17	18	19	20	21	22	23
1	17.55	26.05	34.55	43.05	26.05	49.15	34.55
2	17.55	26.05	34.55	43.05	26.05	49.15	34.55
3	17.55	26.05	34.55	43.05	26.05	49.15	34.55
4	17.55	26.05	34.55	43.05	26.05	49.15	34.55
5	17.55	26.05	34.55	43.05	26.05	49.15	34.55
6	17.55	26.05	34.55	43.05	26.05	49.15	34.55
7	17.55	26.05	34.55	43.05	26.05	49.15	34.55
8	18.70	27.20	35.70	44.20	26.05	50.30	34.55
9	19.90	28.40	36.90	45.40	27.20	51.50	35.70
10	21.10	29.60	38.10	46.55	28.40	52.65	36.90
11	22.30	30.80	39.30	46.55	29.60	52.65	38.10
12	23.45	31.95	40.45	46.55	30.80	52.65	39.30
13	23.45	31.95	40.45	46.55	31.95	52.65	40.45
14	23.45	31.95	40.45	46.55	31.95	52.65	40.45
15	23.45	31.95	40.45	46.55	31.95	52.65	40.45
16	23.45	31.95	40.45	46.55	31.95		40.45
17	23.45	31.95	40.45		31.95		40.45
18	23.45		40.45		31.95		40.45
19					31.95		40.45
20							40.45

Output data of Factory 4

Number of machines of each machine type in the dynamic cells in Factory 4

i	*k*																											
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1	0	0	0	1	0	0	3	1	2	0	1	2	1	2	0	1	0	5	1	0	0	3	2	1	1	0	2	0
2	1	3	3	0	5	2	0	0	1	3	1	0	1	2	1	0	2	1	1	0	3	0	2	1	2	1	0	2
3	1	0	4	1	1	2	2	0	1	0	3	1	0	0	1	0	1	1	0	2	0	2	1	1	0	2	1	1
4	1	0	1	3	3	0	0	1	0	0	0	0	1	0	1	2	0	1	0	0	0	0	1	0	0	1	0	1
5	4	1	0	3	1	0	0	0	0	1	1	2	0	1	1	1	0	1	1	0	0	0	4	1	0	2	2	0
6	2	4	1	0	0	0	2	1	2	0	1	2	1	0	0	4	1	0	0	0	2	1	0	1	2	3	0	0
7	0	3	1	1	0	1	0	2	0	3	2	0	0	1	2	1	2	0	1	3	2	2	0	0	1	0	0	1
8	2	0	0	0	0	0	1	1	3	1	0	1	3	3	2	0	1	1	1	1	0	0	1	2	1	0	4	1
9	0	2	1	0	2	1	0	2	0	3	0	2	0	1	0	0	2	1	2	1	0	3	0	1	1	1	1	1
10	0	0	1	2	0	4	0	1	0	0	0	0	2	0	0	2	0	1	0	3	1	1	0	1	2	2	0	3
11	1	1	2	1	2	2	1	2	0	1	1	2	0	0	2	1	3	1	3	1	0	1	1	2	1	0	1	0
12	2	4	2	6	4	4	5	3	5	2	4	2	5	4	4	3	3	2	2	4	5	2	2	3	2	3	3	4

Operator assignment to operations in dynamic cells in Factory 4

n	k																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1	1	1,2	1,2	1	1	1	1	1,2	1	1	1	1	1	1	1	1,2	1	1	1
2	2,3	1	2,3	3	1,2	2	2,3	2	3	2	2,3	1	2	2,3	2	1	3	2	1	2
3	4	2	4	3	3	3	4,5	3	4,5	2	4	2	2	4	3	2	4	3	2	2
4	5	3	5	4	4,5	4	5	4	6,7	3,4	5,6	3	3,4	5,6	4	3	4	4,5	3	3
5	6	3	6	5	6,7	5	5	4	8	4	7	4	5	7	5,6	4	5,6	6	4	4
6	7	4,5	7,8	5,6	8	5	6,7	5,6	9	5,6	8	5	6,7	8	7	5	7,8	7	5	5
7	8	6	8,9	7	9	6	7	6	9	7,8,9	9	6	8	9	8	6	9	8,9	6	6
8	8	7	10	7,8	10	7	8,9	7,8	10	9	10	7	8	9,10	9	7	9	10	7	7
9	9	8	4	9	10	8	10,11	9	11	10	11	7,8	9,10	10	10	8	10	11	8	8
10	6	8,9	11	9	10	8		10	12,13	11	12	9	11,12	11	4	9	11	11	9	9
11	10	10	12	10,11	11,12	9		11			12	10		12	11	10	11	11	9	9
12	10	11		12,13		9		12			13	11			12	10		12		10
13	11	11		13		10						12			12	11		12		11
14		12,13				11										12				12
15		13				12										13				13

Operator assignment to operations in dynamic cells in Factory 4 continued

n	k							
	21	22	23	24	25	26	27	28
1	1	1	1	1	1,2	1	1	1
2	2	1	2,3	1	3	2	2	1
3	3	2,3	4	1	3	3	2	1
4	3	4,5	4	2	4	4,5	3,4	2
5	4,5	6	5,6	3	4	6	5	3
6	6	7,8	6	4	5	7	5	4
7	7	9	7	5	6	7	6	5,6
8	8	9	8,9	6	7	7	7	2
9	8	10	10	7	8	8	8,9	7,8
10		11	11	8	9	9,10	10	9,10
11		11			10	11		11
12		12			11	12		
13						13		
14								
15								

Coordinates of dynamic cell locations in Factory 4

k	x	y	k	x	y
1	4.62	2.4	15	40.94	2.4
2	15.43	9.34	16	29.98	3.03
3	15.43	2.4	17	29.98	10.09
4	16	16.85	18	29.98	17.15
5	16	14.57	19	29.35	23.58
6	15.43	2.4	20	29.98	3.03
7	4.62	8.2	21	40.94	19.8
8	4.62	14	22	29.98	10.09
9	4.62	19.8	23	40.94	8.2
10	15.43	8.2	24	40.94	14
11	4.62	8.2	25	40.94	2.4
12	4.62	14	26	29.98	17.15
13	4.62	19.8	27	40.94	8.2
14	4.62	8.2	28	40.94	14

Machine type at each location in Factory 4

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

x-coordinate values for machine locations in dynamic cells in Factory 4

g	*k*													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.57	10.18	10.18	10.18	10.18	10.18	0.57	0.57	0.57	10.18	0.57	0.57	0.57	0.57
2	1.71	11.32	11.32	11.32	11.32	11.32	1.71	1.71	1.71	11.32	1.71	1.71	1.71	1.71
3	2.85	12.46	12.46	12.46	12.46	12.46	2.85	2.85	2.85	12.46	2.85	2.85	2.85	2.85
4	3.99	13.6	13.6	13.6	13.6	13.6	3.99	3.99	3.99	13.6	3.99	3.99	3.99	3.99
5	5.13	14.74	14.74	14.74	14.74	14.74	5.13	5.13	5.13	14.74	5.13	5.13	5.13	5.13
6	6.27	15.88	15.88	15.88	15.88	15.88	6.27	6.27	6.27	15.88	6.27	6.27	6.27	6.27
7	7.47	17.02	17.02	17.02	17.02	17.02	7.47	7.47	7.47	17.02	7.47	7.47	7.47	7.47
8	7.47	19.36	19.36	18.16	18.16	19.36	7.47	7.47	7.47	19.36	7.47	7.47	7.47	7.47
9	6.27	19.36	19.36	10.89	10.89	19.36	6.27	6.27	6.27	19.36	6.27	6.27	6.27	6.27
10	5.13	19.36	17.02	10.89	10.89	17.02	5.13	5.13	5.13	17.02	5.13	5.13	5.13	5.13
11	3.99	19.36	15.88	10.89	10.89	15.88	3.99	3.99	3.99	15.88	3.99	3.99	3.99	3.99
12	2.85	17.02	14.74	18.16	18.16	14.74	2.85	2.85	2.85	14.74	2.85	2.85	2.85	2.85
13	1.71	15.88	13.6	17.02	17.02	13.6	1.71	1.71	1.71	13.6	1.71	1.71	1.71	1.71
14	0.57	14.74	12.46	15.88	15.88	12.46	0.57	0.57	0.57	12.46	0.57	0.57	0.57	0.57
15		13.6	11.32	14.74	14.74	11.32				11.32				
16		12.46	10.18	13.6	13.6	10.18				10.18				
17		11.32		12.46	12.46									
18		10.18		11.32	11.32									

x-coordinate values for machine locations in dynamic cells in Factory 4 continued

g	*k*													
	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1	36.59	25.63	25.63	25.63	25.63	25.63	36.59	25.63	36.59	36.59	36.59	25.63	36.59	36.59
2	37.85	26.89	26.89	26.89	26.89	26.89	37.85	26.89	37.85	37.85	37.85	26.89	37.85	37.85
3	39.11	28.15	28.15	28.15	28.15	28.15	39.11	28.15	39.11	39.11	39.11	28.15	39.11	39.11
4	40.37	29.41	29.41	29.41	29.41	29.41	40.37	29.41	40.37	40.37	40.37	29.41	40.37	40.37
5	41.63	30.67	30.67	30.67	30.67	30.67	41.63	30.67	41.63	41.63	41.63	30.67	41.63	41.63
6	42.89	31.93	31.93	31.93	33.13	31.93	42.89	31.93	42.89	42.89	42.89	31.93	42.89	42.89
7	45.35	8.13	8.13	8.13	33.13	8.13	45.35	8.13	45.35	45.35	45.35	8.13	45.35	45.35
8	45.35	8.13	8.13	8.13	30.67	8.13	45.35	8.13	45.35	45.35	45.35	8.13	45.35	45.35
9	42.89	8.13	8.13	8.13	29.41	8.13	42.89	8.13	42.89	42.89	42.89	8.13	42.89	42.89
10	41.63	31.93	31.93	31.93	28.15	31.93	41.63	31.93	41.63	41.63	41.63	31.93	41.63	41.63
11	40.37	30.67	30.67	30.67	26.89	30.67	40.37	30.67	40.37	40.37	40.37	30.67	40.37	40.37
12	39.11	29.41	29.41	29.41	25.63	29.41	39.11	29.41	39.11	39.11	39.11	29.41	39.11	39.11
13	37.85	28.15	28.15	28.15		28.15	37.85	28.15	37.85	37.85	37.85	28.15	37.85	37.85
14	36.59	26.89	26.89	26.89		26.89	36.59	26.89	36.59	36.59		26.89	36.59	36.59
15		25.63	25.63	25.63		25.63		25.63				25.63		

y-coordinate values for machine locations in dynamic cells in Factory 4

g	*k*													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.57	8.08	0.57	14.33	14.33	0.57	5.11	12.23	18.03	5.11	12.23	5.11	0.57	18.03
2	0.57	8.08	0.57	14.33	14.33	0.57	5.11	12.23	18.03	5.11	12.23	5.11	0.57	18.03
3	0.57	8.08	0.57	14.33	14.33	0.57	5.11	12.23	18.03	5.11	12.23	5.11	0.57	18.03
4	0.57	8.08	0.57	14.33	14.33	0.57	5.11	12.23	18.03	5.11	12.23	5.11	0.57	18.03
5	0.57	8.08	0.57	14.33	14.33	0.57	5.11	12.23	18.03	5.11	12.23	5.11	0.57	18.03
6	0.57	8.08	0.57	14.33	14.33	0.57	5.11	12.23	18.03	5.11	12.23	5.11	0.57	18.03
7	1.83	8.08	0.57	14.33	14.33	0.57	6.37	13.43	19.23	5.11	13.43	6.37	1.83	19.23
8	2.97	9.28	1.83	14.33	14.33	1.83	7.51	14.57	20.37	6.37	14.57	7.51	2.97	20.37
9	4.11	10.42	2.97	15.53	15.53	2.97	8.71	16.4	22.2	7.51	16.4	8.71	4.11	22.2
10	4.11	11.56	4.11	16.67	16.67	4.11	8.71	16.4	22.2	8.71	16.4	8.71	4.11	22.2
11	4.11	12.7	4.11	17.81	17.81	4.11	8.71	16.4	22.2	8.71	16.4	8.71	4.11	22.2
12	4.11	13.9	4.11	19.01	19.01	4.11	8.71	16.4	22.2	8.71	16.4	8.71	4.11	22.2
13	4.11	13.9	4.11	19.01	19.01	4.11	8.71	16.4	22.2	8.71	16.4	8.71	4.11	22.2
14	4.11	13.9	4.11	19.01	19.01	4.11	8.71	16.4	22.2	8.71	16.4	8.71	4.11	22.2
15		13.9	4.11	19.01	19.01	4.11				8.71				
16		13.9	4.11	19.01	19.01	4.11				8.71				
17		13.9		19.01	19.01									
18		13.9		19.01	19.01									

y-coordinate values for machine locations in dynamic cells in Factory 4 continued

g	*k*													
	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1	0.57	0.57	7.63	14.69	22.37	0.57	17.97	7.63	6.37	12.17	0.57	14.69	6.37	12.17
2	0.57	0.57	7.63	14.69	22.37	0.57	17.97	7.63	6.37	12.17	0.57	14.69	6.37	12.17
3	0.57	0.57	7.63	14.69	22.37	0.57	17.97	7.63	6.37	12.17	0.57	14.69	6.37	12.17
4	0.57	0.57	7.63	14.69	22.37	0.57	17.97	7.63	6.37	12.17	0.57	14.69	6.37	12.17
5	0.57	0.57	7.63	14.69	22.37	0.57	17.97	7.63	6.37	12.17	0.57	14.69	6.37	12.17
6	0.57	0.57	7.63	14.69	23.57	0.57	17.97	7.63	6.37	12.17	0.57	14.69	6.37	12.17
7	1.77	1.77	8.83	15.89	24.83	1.77	19.17	8.83	7.57	13.37	1.77	15.89	7.57	13.37
8	3.03	3.03	10.09	17.15	27.29	3.03	20.43	10.09	8.83	14.63	3.03	17.15	8.83	14.63
9	4.23	4.29	11.35	18.41	27.29	4.29	22.89	11.35	10.03	15.83	4.23	18.41	10.03	15.83
10	4.23	5.49	12.55	19.61	27.29	5.49	22.89	12.55	10.03	15.83	4.23	19.61	10.03	15.83
11	4.23	5.49	12.55	19.61	27.29	5.49	22.89	12.55	10.03	15.83	4.23	19.61	10.03	15.83
12	4.23	5.49	12.55	19.61	27.29	5.49	22.89	12.55	10.03	15.83	4.23	19.61	10.03	15.83
13	4.23	5.49	12.55	19.61		5.49	22.89	12.55	10.03	15.83	4.23	19.61	10.03	15.83
14	4.23	5.49	12.55	19.61		5.49	22.89	12.55	10.03	15.83		19.61	10.03	15.83
15		5.49	12.55	19.61		5.49		12.55				19.61		

Output data of Factory 5

Number of machines of each machine type in the dynamic cells in Factory 5

i	*k*																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0	1	1	1	1	0	0	1	2	1	1	2	0	2	1	1	2	0	1	0	0
2	1	0	4	2	1	3	2	0	0	0	0	0	0	0	2	3	0	2	2	0	0
3	0	1	0	0	0	2	2	1	0	0	2	2	0	0	0	0	0	1	0	2	0
4	0	2	0	0	1	0	0	0	0	0	0	2	0	0	0	1	1	1	0	2	1
5	0	2	1	0	0	1	0	2	1	1	1	1	0	1	2	0	0	1	1	0	4
6	0	0	0	1	1	0	1	2	0	2	0	1	0	1	1	0	1	1	1	1	2
7	1	1	2	1	1	1	0	1	0	0	1	0	0	0	1	2	3	2	1	0	1
8	1	0	0	0	3	2	1	1	3	1	0	0	1	1	2	2	1	0	0	2	0
9	0	0	0	5	1	0	0	2	3	0	2	0	3	2	0	0	1	1	0	1	0
10	0	4	0	0	0	0	5	0	3	2	2	1	3	0	1	0	0	0	1	1	0
11	4	0	3	2	2	1	2	1	0	1	1	1	0	0	0	2	2	0	0	0	1
12	0	0	0	1	3	0	1	2	0	0	0	0	0	0	0	3	4	0	2	2	0
13	1	0	0	0	2	2	0	2	1	1	0	4	4	2	1	1	0	0	2	2	0
14	1	1	1	0	0	0	0	0	0	2	2	0	1	2	0	0	0	4	0	0	3
15	4	3	4	2	4	3	3	2	5	3	5	3	5	5	7	2	2	3	6	4	3

Operator assignment to operations in dynamic cells in Factory 5

n	k															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1	1,2	1	1,2	1	1,2	1,2	1,2	1,2	1	1,2	1	1	1	1	1,2
2	2	2	1,2	3,4	2	3,4	2	3	3	2,3	3	2	2,3	2	2	3
3	3	3,4	3,4	5,6	3	5	3	3	3	4,5	3	3,4	4	3	3	4
4	4	5	5,6	7	4	6,7	4	4	4	6	3	5,6	5	4	4,5	4
5	5	6,7	7	8,9	5,6	8	5	5	5	7	4,5	7	6	5	6	5,6
6	6	7	8	10	7	8	6	6	5	8	6	8,9	7	6	7	7
7	7	8,9	9	11	7	9	6	7	6,7	9	7	10	8,9	7	8,9	8
8	8	10	10,11	12	8,9	10	7	8	8	10	8	11	10	8	10	9,10
9	9	11,12	12,13	13	9	11	7	8	8	11	9,10	12	11,12	9	11,12	11
10	10	12	14,15	13	10	12,13	8,9	9	8	6	11,12	13,14	12	10,11	13,14	12
11	11			14	10	13	10,11	10	9	12,13	13	15	13	12	15	13
12	11				10		12	11,12	10		14	16	14	13,14	16,17	14
13	12				11		12,13	13	11			17,18				15
14					11			14	12							16
15					12			14	13							
16					13				14							
17					14											
18					14											

Operator assignment to operations in dynamic cells in Factory 5 continued

n	k				
	17	18	19	20	21
1	1,2	1	1	1	1
2	3	2	2	2	2
3	4	2	3	3	3,4
4	5,6	3	4	4	5
5	7	4	5	5	6,7
6	8,9	4	5	6	8
7	10	5	6	7	9
8	11,12	6,7	7	8	10
9	12	8,9	8,9	9	11
10	13	10	10	9	12,13
11	13	11	11,12	10,11	14,15
12	14	12	13	12,13	15
13		13,14	14,15	14	
14			13	15,16	

Coordinates of dynamic cell locations in Factory 5

k	x	y	k	x	y
1	15.72	9.02	12	15.72	2.93
2	4.71	2.34	13	4.71	25.61
3	4.71	8.02	14	4.71	19.34
4	4.71	2.34	15	15.72	26.79
5	5.3	13.88	16	15.72	33.65
6	4.71	8.02	17	15.72	2.93
7	15.72	8.02	18	4.71	33.06
8	15.72	8.02	19	15.72	26.79
9	15.72	2.34	20	15.72	33.65
10	15.72	9.02	21	4.71	19.34
11	15.72	2.34			

Machine type at each location in Factory 5

g	*k*																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	11	5	1	9	1	13	10	6	15	14	10	5	13	15	1	8	12	6	2	3	7
2	11	5	7	9	15	13	10	6	15	10	10	6	9	1	10	8	12	14	6	4	11
3	11	7	7	9	8	2	6	8	13	10	3	13	9	6	7	11	6	5	7	8	5
4	8	10	2	9	6	2	10	9	8	6	7	13	10	1	15	2	8	4	12	10	5
5	14	10	2	2	8	7	10	13	8	6	3	4	8	13	15	1	1	3	1	6	4
6	11	3	11	2	8	8	10	7	8	13	15	4	13	13	6	2	1	7	12	8	6
7	15	4	11	1	12	8	11	1	1	1	15	11	13	15	13	2	4	14	2	4	6
8	15	4	11	11	4	3	8	12	10	14	11	1	15	5	8	12	11	14	15	3	14
9	7	14	14	11	11	3	12	13	10	8	1	1	15	8	8	4	11	14	13	9	14
10	13	10	5	12	11	2	11	12	9	11	5	10	14	9	15	12	7	2	13	15	5
11	2	10	2	7	12	11	2	3	5	5	14	3	10	9	2	12	12	2	5	13	5
12	15	1	2	9	13	5	2	9	9	15	14	3	10	15	2	13	12	9	15	13	15
13	15	15	15	6	2	15	3	5	10	15	9	13	9	15	5	7	9	7	15	12	15
14		15	15	15	13	15	3	5	9	15	9	13	15	15	5	11	7	15	10	12	15
15		15	15	15	7	15	15	11	15		15	13	15		15	7	7	15	15	15	
16			15		12		15	15	1		15	15			15	15	15	15	15	15	
17					15		15	15	15		15	15			15	15	15		15	15	
18					9				15			15									
19					15																
20					15																

x-coordinate values for machine locations in dynamic cells in Factory 5

g	*k*										
	1	2	3	4	5	6	7	8	9	10	11
1	12.19	0.59	0.59	0.59	0.59	0.59	11.01	11.01	11.01	12.19	11.01
2	13.37	1.77	1.77	1.77	1.77	1.77	12.19	12.19	12.19	13.37	12.19
3	14.55	2.95	2.95	2.95	2.95	2.95	13.37	13.37	13.37	14.55	13.37
4	15.73	4.13	4.13	4.13	4.13	4.13	14.55	14.55	14.55	15.73	14.55
5	16.91	5.31	5.31	5.31	5.31	5.31	15.73	15.73	15.73	16.91	15.73
6	18.09	6.49	6.49	6.49	6.49	6.49	16.91	16.91	16.91	18.09	16.91
7	20.44	7.67	7.67	7.67	7.67	7.67	18.09	18.09	18.09	20.44	18.09
8	20.44	10.02	10.02	10.02	8.85	10.02	19.27	19.27	19.27	20.44	19.27
9	18.09	10.02	10.02	10.02	11.2	10.02	11.20	11.20	11.20	18.09	11.20
10	16.91	7.67	7.67	7.67	11.2	7.67	11.20	11.20	11.20	16.91	11.20
11	15.73	6.49	6.49	6.49	11.2	6.49	19.27	19.27	19.27	15.73	19.27
12	14.55	5.31	5.31	5.31	11.2	5.31	18.09	18.09	18.09	14.55	18.09
13	13.37	4.13	4.13	4.13	8.85	4.13	16.91	16.91	16.91	13.37	16.91
14		2.95	2.95	2.95	7.67	2.95	15.73	15.73	15.73	12.19	15.73
15		1.77	1.77	1.77	6.49	1.77	14.55	14.55	14.55		14.55
16			1.77		5.31		13.37	13.37	13.37		13.37
17					4.13		12.19	12.19	12.19		12.19
18					2.95				11		
19					1.77						
20					0.59						

x-coordinate values for machine locations in dynamic cells in Factory 5 continued

g	*k*									
	12	13	14	15	16	17	18	19	20	21
1	11.01	0.59	0.59	11.01	11.01	11.01	0.59	11.01	11.01	0.59
2	12.19	1.77	1.77	12.19	12.19	12.19	1.77	12.19	12.19	1.77
3	13.37	2.95	2.95	13.37	13.37	13.37	2.95	13.37	13.37	2.95
4	14.55	4.13	4.13	14.55	14.55	14.55	4.13	14.55	14.55	4.13
5	15.73	5.31	5.31	15.73	15.73	15.73	5.31	15.73	15.73	5.31
6	16.91	6.49	6.49	16.91	16.91	16.91	6.49	16.91	16.91	6.49
7	18.09	8.84	8.84	18.09	18.09	18.09	8.84	18.09	18.09	8.84
8	20.44	8.84	8.84	20.44	20.44	20.44	8.84	20.44	20.44	8.84
9	20.44	8.84	6.49	20.44	20.44	20.44	8.84	20.44	20.44	6.49
10	20.44	8.84	5.31	20.44	20.44	20.44	8.84	20.44	20.44	5.31
11	18.09	6.49	4.13	18.09	18.09	18.09	8.84	18.09	18.09	4.13
12	16.91	5.31	2.95	16.91	16.91	16.91	8.84	16.91	16.91	2.95
13	15.73	4.13	1.77	15.73	15.73	15.73	6.49	15.73	15.73	1.77
14	14.55	2.95	0.59	14.55	14.55	14.55	5.31	14.55	14.55	0.59
15	13.37	1.77		13.37	13.37	13.37	4.13	13.37	13.37	
16	12.19			12.19	12.19	12.19	2.95	12.19	12.19	
17	11.01			11.01	11.01	11.01		11.01	11.01	

y-coordinate values for machine locations in dynamic cells in Factory 5

g	*k*										
	1	2	3	4	5	6	7	8	9	10	11
1	11.94	0.58	6.26	0.58	11.94	6.26	6.26	6.26	0.58	11.94	0.58
2	11.94	0.58	6.26	0.58	11.94	6.26	6.26	6.26	0.58	11.94	0.58
3	11.94	0.58	6.26	0.58	11.94	6.26	6.26	6.26	0.58	11.94	0.58
4	11.94	0.58	6.26	0.58	11.94	6.26	6.26	6.26	0.58	11.94	0.58
5	11.94	0.58	6.26	0.58	11.94	6.26	6.26	6.26	0.58	11.94	0.58
6	11.94	0.58	6.26	0.58	11.94	6.26	6.26	6.26	0.58	11.94	0.58
7	13.11	0.58	6.26	0.58	11.94	6.26	6.26	6.26	0.58	13.11	0.58
8	14.29	1.75	7.43	1.75	11.94	7.43	6.26	6.26	0.58	14.29	0.58
9	15.46	2.93	8.61	2.93	13.1	8.61	7.43	7.43	1.75	15.46	1.75
10	15.46	4.10	9.78	4.10	14.3	9.78	8.61	8.61	2.93	15.46	2.93
11	15.46	4.10	9.78	4.10	15.5	9.78	9.78	9.78	4.10	15.46	4.10
12	15.46	4.10	9.78	4.10	16.7	9.78	9.78	9.78	4.10	15.46	4.10
13	15.46	4.10	9.78	4.10	15.46	9.78	9.78	9.78	4.10	15.46	4.10
14		4.10	9.78	4.10	15.46	9.78	9.78	9.78	4.10	15.46	4.10
15		4.10	9.78	4.10	15.46	9.78	9.78	9.78	4.10		4.10
16			9.78		15.46		9.78	9.78	4.10		4.10
17					15.46		9.78	9.78	4.10		4.10
18					15.46				4.10		
19					15.46						
20					15.46						

y-coordinate values for machine locations in dynamic cells in Factory 5 continued

g	*k*									
	12	13	14	15	16	17	18	19	20	21
1	17.58	23.25	17.58	24.26	31.30	17.58	30.12	24.26	31.30	17.58
2	17.58	23.25	17.58	24.26	31.30	17.58	30.12	24.26	31.30	17.58
3	17.58	23.25	17.58	24.26	31.30	17.58	30.12	24.26	31.30	17.58
4	17.58	23.25	17.58	24.26	31.30	17.58	30.12	24.26	31.30	17.58
5	17.58	23.25	17.58	24.26	31.30	17.58	30.12	24.26	31.30	17.58
6	17.58	23.25	17.58	24.26	31.30	17.58	30.12	24.26	31.30	17.58
7	17.58	24.43	18.75	24.26	31.30	17.58	31.29	24.26	31.30	18.75
8	18.75	25.61	19.93	25.43	32.47	18.75	32.47	25.43	32.47	19.93
9	19.93	26.79	21.10	26.61	33.65	19.93	33.65	26.61	33.65	21.10
10	21.11	27.96	21.10	27.79	34.83	21.11	34.83	27.79	34.83	21.10
11	22.28	27.96	21.10	28.96	36.00	22.28	36.00	28.96	36.00	21.10
12	22.28	27.96	21.10	28.96	36.00	22.28	36.00	28.96	36.00	21.10
13	22.28	27.96	21.10	28.96	36.00	22.28	36.00	28.96	36.00	21.10
14	22.28	27.96	21.10	28.96	36.00	22.28	36.00	28.96	36.00	21.10
15	22.28	27.96		28.96	36.00	22.28	36.00	28.96	36.00	
16	22.28			28.96	36.00	22.28	36.00	28.96	36.00	
17	22.28			28.96	36.00	22.28		28.96	36.00	

Output data of Factory 6

Number of machines of each machine type in the dynamic cells in Factory 6

i	*k*																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1	0	1	0	1	1	2	2	0	1	0	0	2	2	1	1	1	2	0	0	1
2	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	2	1	0	0	4
3	2	0	2	1	1	1	1	1	0	0	0	1	1	1	2	1	0	0	1	0	1
4	1	2	1	2	1	2	0	0	1	3	1	1	1	0	1	3	0	2	0	4	1
5	1	1	1	2	1	2	0	1	2	1	1	0	0	2	1	1	1	0	1	0	0
6	1	0	0	1	0	2	0	4	0	1	1	2	0	3	1	0	2	0	1	0	0
7	1	2	0	1	0	0	3	1	0	0	1	0	1	0	2	0	2	1	1	4	1
8	0	0	1	0	1	0	2	1	0	1	0	1	1	0	1	0	0	3	0	0	2
9	0	1	1	1	1	0	0	0	3	1	2	1	1	0	0	0	1	0	2	1	0
10	1	1	1	1	1	1	0	1	1	1	2	1	1	0	0	2	0	1	2	2	0
11	1	1	1	2	2	1	1	0	0	0	3	0	1	0	1	1	0	0	3	0	0
12	1	0	0	1	1	1	0	1	0	1	1	3	1	2	1	0	2	1	0	0	1
13	0	0	1	0	1	1	0	0	1	1	0	1	1	1	0	2	4	0	2	0	0
14	0	2	1	0	0	1	1	0	1	0	1	1	2	2	0	1	0	0	0	1	2
15	1	1	1	0	0	0	0	0	1	1	0	0	2	1	3	0	0	3	1	2	0
16	3	3	2	3	4	2	2	2	3	3	3	2	2	4	2	4	2	3	3	3	2

Operator assignment to operations in dynamic cells in Factory 6

n	k																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1,2	1	1
2	1	2	2	1	1	1	1	1	1	1	1	1	2	2,3	2	2	2	2,3	3	2,3	2
3	2	3	3	2	1	1	2	1	1	1	1	1	3	4,5	2	3	3	4	4	4	3,4
4	3	4	3	2	3	2	2	2	2	2	2	2	4	6	3	4	4	5	5,6	5	5
5	4	4	4	3	4	3	3	2	2	2	2	2	5	7	4	5	5	6	7	6	6
6	4	5	4	3	5	3	4	2	3	3	3	2	5	7	5	5	6,7	7	7	7	7
7	5	6	5	4	6	3	4	3	3	3	3	3	5	7	6	6	8	8	8	8,9	8
8	6	7	5	4	6	4	5	3	3	3	4	3	6	8	7	7	9	9,10	9,10	10	9,10
9	7	8	6	4	7	4	5	4	4	4	4	4	7	9	8	8	10	11	11	11	11
10	8	7	6	5	7	4	6	4	4	4	4	4	8	9	8	9	11	5	12	12	11
11	9	7	7	5	8	5	6	5	4	4	5	5	9	9	9	9	12	12	13	13,14	11
12	10	9	7	6	8	5		5	5	5	5	5	10	10	10	10	13	13	14	15	12
13	11	10	8	6	9	6		5		5	5	5	10	11	11	11	13	14	15,16	15	13
14	11	10	8	6	9	6		6		5	6		7	12	12	12	14	14		16	
15	12		9	7	10	7					6		11	13	13	13	14	15			
16	13			7	10	7															

Coordinates of dynamic cell locations in Factory 6

k	x	y	*k*	x	y
1	5.5	2.25	12	16.88	7.75
2	16.88	2.25	13	17.5	17.25
3	5.5	7.75	14	2.2	17.875
4	5.5	13.25	15	17.5	24.75
5	5.5	7.75	16	17.5	17.25
6	5.5	2.25	17	2.2	24.625
7	16.25	13.25	18	2.2	17.875
8	16.88	7.75	19	2.2	24.625
9	16.25	13.25	20	2.2	31.375
10	16.88	2.25	21	17.5	24.75

Machine type at each location in Factory 6

g	*k*																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1	14	14	2	3	14	14	6	10	4	14	12	1	13	7	13	12	1	11	16	1
2	2	10	5	5	5	6	3	3	5	15	6	4	14	5	3	4	5	15	11	4	8
3	2	9	2	5	2	6	1	10	15	6	4	6	9	5	8	13	7	15	15	4	14
4	5	4	3	7	10	2	8	7	16	12	9	14	11	6	11	11	2	16	7	15	14
5	7	7	3	4	8	13	7	6	9	9	9	6	15	6	1	10	7	15	9	14	7
6	11	14	4	4	16	5	1	6	14	13	11	8	8	1	7	1	13	2	9	9	4
7	6	7	8	16	16	10	11	6	4	5	16	9	10	12	15	5	13	4	3	7	3
8	12	11	10	11	9	5	7	12	5	16	12	12	15	15	3	14	2	12	10	10	12
9	16	4	2	11	1	1	8	1	9	1	11	3	3	6	12	2	1	8	6	10	2
10	3	5	11	12	11	3	16	1	13	4	11	10	7	1	5	10	13	8	13	7	2
11	3	16	9	9	4	4	16	5	16	4	10	13	14	16	15	4	6	10	13	4	2
12	4	15	13	6	12	4		16	16	8	10	16	4	12	6	4	9	8	5	15	8
13	10	16	1	3	11	11		16		16	5	16	12	16	4	16	6	16	10	7	2
14	15	16	16	10	13	12				16	7		1	3	16	3	12	4	11	7	16
15	16		16	16	16	16					16		16	14	16	16	13	1	16	4	16
16	16			16	16	16							16	16		16	16	7	16	16	
17														16			16	16	16	16	
18																		16			

x-coordinate values for machine locations in dynamic cells in Factory 6

g	*k*											
	1	2	3	4	5	6	7	8	9	10	11	12
1	0.63	12.63	0.63	0.63	0.63	0.63	12.63	12.63	12.63	12.63	0.63	12.63
2	1.88	13.88	1.88	1.88	1.88	1.88	13.88	13.88	13.88	13.88	1.88	13.88
3	3.13	15.13	3.13	3.13	3.13	3.13	15.13	15.13	15.13	15.13	3.13	15.13
4	4.38	16.38	4.38	4.38	4.38	4.38	16.38	16.38	16.38	16.38	4.38	16.38
5	5.63	17.63	5.63	5.63	5.63	5.63	17.63	17.63	17.63	17.63	5.63	17.63
6	6.88	18.88	6.88	6.88	6.88	6.88	20.00	18.88	20.00	18.88	6.88	18.88
7	8.13	20.00	8.13	8.13	8.13	8.13	20.00	20.00	20.00	20.00	8.13	20.00
8	10.50	20.00	10.50	10.50	10.50	10.50	17.63	20.00	17.63	20.00	10.50	20.00
9	10.50	18.88	10.50	10.50	10.50	10.50	16.38	18.88	16.38	18.88	10.50	18.88
10	8.13	17.63	8.13	8.13	8.13	8.13	15.13	17.63	15.13	17.63	8.13	17.63
11	6.88	16.38	6.88	6.88	6.88	6.88	13.88	16.38	13.88	16.38	6.88	16.38
12	5.63	15.13	5.63	5.63	5.63	5.63		15.13	12.63	15.13	5.63	15.13
13	4.38	13.88	4.38	4.38	4.38	4.38		13.88		13.88	4.38	13.88
14	3.13	12.63	3.13	3.13	3.13	3.13				12.63	3.13	
15	1.88		1.88	1.88	1.88	1.88					1.88	
16	0.63			0.63	0.63	0.63						

x-coordinate values for machine locations in dynamic cells in Factory 6 continued

g	*k*								
	13	14	15	16	17	18	19	20	21
1	12.63	0.63	12.63	12.63	0.63	0.63	0.63	0.63	12.63
2	13.88	1.88	13.88	13.88	1.88	1.88	1.88	1.88	13.88
3	15.13	3.13	15.13	15.13	3.13	3.13	3.13	3.13	15.13
4	16.38	4.38	16.38	16.38	4.38	4.38	4.38	4.38	16.38
5	17.63	5.63	17.63	17.63	5.63	5.63	5.63	5.63	17.63
6	18.88	6.88	18.88	18.88	6.88	6.88	6.88	6.88	18.88
7	20.13	8.13	20.13	20.13	8.13	8.13	8.13	8.13	20.13
8	22.50	10.50	22.50	22.50	10.50	10.50	10.50	10.50	22.50
9	22.50	10.50	22.50	22.50	10.50	10.50	10.50	10.50	22.50
10	20.13	10.50	20.13	20.13	10.50	10.50	10.50	10.50	20.13
11	18.88	8.13	18.88	18.88	8.13	8.13	8.13	8.13	18.88
12	17.63	6.88	17.63	17.63	6.88	6.88	6.88	6.88	17.63
13	16.38	5.63	16.38	16.38	5.63	5.63	5.63	5.63	16.38
14	15.13	4.38	15.13	15.13	4.38	4.38	4.38	4.38	15.13
15	13.88	3.13	13.88	13.88	3.13	3.13	3.13	3.13	13.88
16	12.63	1.88		12.63	1.88	1.88	1.88	1.88	
17		0.63			0.63	0.63	0.63	0.63	

y-coordinate values for machine locations in dynamic cells in Factory 6

g	*k*											
	1	2	3	4	5	6	7	8	9	10	11	12
1	0.50	0.50	6.00	11.50	6.00	0.50	11.50	6.00	11.50	0.50	11.50	6.00
2	0.50	0.50	6.00	11.50	6.00	0.50	11.50	6.00	11.50	0.50	11.50	6.00
3	0.50	0.50	6.00	11.50	6.00	0.50	11.50	6.00	11.50	0.50	11.50	6.00
4	0.50	0.50	6.00	11.50	6.00	0.50	11.50	6.00	11.50	0.50	11.50	6.00
5	0.50	0.50	6.00	11.50	6.00	0.50	11.50	6.00	11.50	0.50	11.50	6.00
6	0.50	0.50	6.00	11.50	6.00	0.50	12.63	6.00	12.63	0.50	11.50	6.00
7	0.50	1.63	6.00	11.50	6.00	0.50	13.87	9.50	13.87	1.63	11.50	9.50
8	1.63	2.88	9.50	12.63	9.50	1.63	15.00	10.75	15.00	2.88	12.63	10.75
9	2.88	4.00	10.75	13.88	10.75	2.88	15.00	9.50	15.00	4.00	13.88	9.50
10	4.00	4.00	9.50	15.00	9.50	4.00	15.00	9.50	15.00	4.00	15.00	9.50
11	4.00	4.00	9.50	15.00	9.50	4.00	15.00	9.50	15.00	4.00	15.00	9.50
12	4.00	4.00	9.50	15.00	9.50	4.00		9.50	15.00	4.00	15.00	9.50
13	4.00	4.00	9.50	15.00	9.50	4.00		9.50		4.00	15.00	9.50
14	4.00	4.00	9.50	15.00	9.50	4.00				4.00	15.00	
15	4.00		9.50	15.00	9.50	4.00					15.00	
16	4.00			15.00	6.00	4.00					15.00	

y-coordinate values for machine locations in dynamic cells in Factory 6 continued

g	*k*								
	13	14	15	16	17	18	19	20	21
1	15.63	15.50	21.13	15.63	22.38	15.50	22.38	29.13	21.13
2	15.63	15.50	21.13	15.63	22.38	15.50	22.38	29.13	21.13
3	15.63	15.50	21.13	15.63	22.38	15.50	22.38	29.13	21.13
4	15.63	15.50	21.13	15.63	22.38	15.50	22.38	29.13	21.13
5	15.63	15.50	21.13	15.63	22.38	15.50	22.38	29.13	21.13
6	15.63	15.50	21.13	15.63	22.38	15.50	22.38	29.13	21.13
7	15.63	15.50	21.13	15.63	22.38	15.50	22.38	29.13	21.13
8	16.63	16.63	22.13	16.63	23.38	16.63	23.38	30.13	22.13
9	17.88	17.88	23.38	17.88	24.63	17.88	24.63	31.38	23.38
10	19.00	19.13	23.50	19.00	25.88	19.13	25.88	32.63	23.50
11	19.00	20.25	23.50	19.00	27.00	20.25	27.00	33.75	23.50
12	19.00	20.25	23.50	19.00	27.00	20.25	27.00	33.75	23.50
13	19.00	20.25	23.50	19.00	27.00	20.25	27.00	33.75	23.50
14	19.00	20.25	23.50	19.00	27.00	20.25	27.00	33.75	23.50
15	19.00	20.25	23.50	19.00	27.00	20.25	27.00	33.75	23.50
16	19.00	20.25		19.00	27.00	20.25	27.00	33.75	
17		20.25			27.00	20.25	27.00	33.75	