Study of Restructuring Decisions and Complexity of Lean Manufacturing Systems

THESIS

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VARINDER SINGH

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Dr. P. M. Singru

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BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE
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CERTIFICATE

This is to certify that the thesis entitled **"Study of Restructuring Decisions and Complexity of Lean Manufacturing Systems"** and submitted by **Varinder Singh** ID No **2004PHXF450G** for award of Ph. D. Degree of the Institute embodies original work done by him under my supervision.

Signature in full of the Supervisor: ______________________

Name in capital block letters: **DR. P.M. SINGRU**

Designation: **Associate Professor**

Date:

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ABSTRACT

In order to meet the challenge of increasingly competitive global business environment characterized by the tough customer requirements, shorter product life cycles, rapid introduction and adjustments in the product lines, it is imperative that the competitiveness of manufacturing organizations be enhanced by appropriately using different practices of lean philosophy such as just in time (JIT), total quality management (TQM), quality at source etc. The overall objective of the lean philosophy is to attain customer focus for everything that is carried out within the organization so that non-value adding activities are identified and eliminated. The organizations generally need a considerable restructuring to implement lean principles. One of the basic restructuring decisions needed is to make processes synchronous to achieve flow production. In situations where the continuous flow is not possible, just-in-time practice can help in achieving the flow production for increasing efficiency of production process. Standardization in performing each job ensures minimal manpower and effort, highest quality, highest safety at the workstation and it goes a long way in eliminating many sources of wasteful activities. The motivation mechanisms such as job security to ensure whole hearted involvement of the employees need to be put in place. A tool that can assist organizations to quantify the benefits that may be expected from restructuring for implementing lean manufacturing to their system at the planning and evaluation stage can aid the vital first step in the journey of the organization towards lean manufacturing. The present study discusses graph theoretic modeling for analysis of decisions related to restructuring of manufacturing systems in the process of developing and designing lean manufacturing systems. A case of restructuring in a steel plant and two cases of restructuring in a packaging equipment industry have been taken for this study for achieving lean manufacturing philosophy. The restructuring decisions in the steel plant are towards simplification in the scheduling system by implementing pull production system in major part of the organization. On the other hand, one of the restructuring decisions in the packaging equipment industry case study involved the improvement in the internal work flow by introducing the concept of error proofing in the movement of material within the organization using a kitting system. The other restructuring decision

involved major improvement in the material flow associated with external suppliers by implementing the concept of built-in quality at the source through an external quality inspection vendor. The two restructuring decisions in the packaging equipment industry have resulted in improvements in the on time delivery performance by 6.25 percent and 18.75 percent respectively.

The graph theoretic models have been developed for the industrial organizations and their restructured configurations for providing greater understanding and insights into decision making process. Such models offer a unique and useful way of analysis. Different sub-graphs containing all possible interaction cycles in the manufacturing system are identified systematically which represent different cyclic activities. The sub-graphs were classified into different groups and subgroups depending on the pattern of interaction cycles. The number of sub-graphs under groups and subgroups were used for unique characterization of the interaction structure within organizations. The study discusses different methods for quantitative comparison and analysis of restructured configurations of manufacturing systems with respect to their respective original configurations. Two such methods were the well developed tools of coefficients of dissimilarity (criterion-1 and criterion-2) in graph theoretic literatures which have their basis in the unique structural characterization of manufacturing systems given by graph theoretic models. It offered a useful way to understand the impact of restructuring decisions in some manufacturing systems. However, the results of case study on restructuring in steel plant indicated its limitations to effectively analyze the impact of restructuring decisions towards complexity reduction. The study also proposes new methods for more effective quantitative comparison and analysis of restructuring decisions in manufacturing systems as indices of complexity. The new methods are proposed based on the physical interpretation of the existing quantitative methods of coefficients of dissimilarity based on the results of graph theoretic models in a multi-dimensional Euclidian space. Out of the four new methods, two are based on Cartesian distances and the rest two on Euclidian distances in multi-dimensional Euclidian space. Two of the methods also have their name and concept based on a popular multi attribute decision making (MADM) technique of TOPSIS. The real performance indicators such as improvement in on-time delivery performance from packaging equipment industry case study indicate a strong correlation with the values of proposed quantitative measures based on graph theoretic modeling. Such correlations have been investigated mathematically using the coefficient of correlation and the modulus of the values of coefficient of correlation is found to be all above 0.95 which indicates a very strong correlation. Thus, the new methods of analysis can be considered for effective analysis of such restructuring decisions in manufacturing organizations. Such methods may guide manufacturing organizations in realizing their goals of achieving required levels of leanness in their manufacturing systems by way of assessing different alternative structures at the conceptual stage.

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LIST OF SYMBOLS

A	Permanent matrix for the current state of the steel plant
$A^{'}$	Permanent matrix for the desired future state of the steel plant
C_{d-1}	Coefficient of dissimilarity between two manufacturing system configurations by criterion-1
C_{d-2}	Coefficient of dissimilarity between two manufacturing system configurations by criterion-2
e_{ij}	Influence/interaction of subsystem 'S_i' to Subsystem 'S_j'
J_k^x	The total number of sub-graphs in the k^{th} group if no subgroups are present in it for manufacturing system-x
J_{kl}^x	The total number of sub-graphs in the l^{th} subgroup of the k^{th} group in case subgroups are present for manufacturing system-x
LECO	Hypothetical least complex system in a domain of systems
MOCO	Hypothetical most complex system in a domain of systems
P	Permanent matrix for original configuration of packaging equipment industry
$P^{'}$	Permanent matrix for restructured configuration-1 of packaging equipment industry
$P^{''}$	Permanent matrix for restructured configuration-2 of packaging equipment industry
S_1	Customer Subsystem
S_2	Sales and marketing subsystem
S_3	Design Subsystem
S_4	Purchase Subsystem
S_5	Vendor Subsystem
S_6	Vendor Subsystem
S_7	Vendor Subsystem
S_8	Purchase quality subsystem
S_9	PPC Subsystem
S_{10}	Store Subsystem
S_{11}	Consumable vendor Subsystem

S_{12} Manufacturing Subsystem

S_{13} Quality control Subsystem

S_{14} Logistics subsystem

T_1 Supplier Subsystem

T_2 Business planning subsystem

T_3 Customer-1 Subsystem

T_4 Customer-2 Subsystem

T_5 Furnace Subsystem

T_6 Basic oxygen process (BOP) Subsystem

T_7 Degasser Subsystem

T_8 Ladle metallurgical facility (LMF) subsystem

T_9 Continuous caster Subsystem

T_{10} Hot strip mill (HSM) Subsystem

T_{11} Pickling Subsystem

T_{12} Cold reduction (CR) Subsystem

T_{13} Hydrogen batch annealing (HBA) Subsystem

T_{14} Open coil annealing (OCA) subsystem

T_{15} Continuous annealing Subsystem

T_{16} Temper mill Subsystem

T_{17} Shipping Subsystem

X^{x}_{G-k} The number of sub-graphs in the k^{th} group in case subgroups are not present in manufacturing system-x as a coordinate in the Euclidian space of groups-subgroups of the graph theoretic model

$X^{x}_{G-k(l)}$ The number of sub-graphs in the l^{th} subgroup of the k^{th} group in case subgroups are present in manufacturing system-x as a coordinate in the Euclidian space of groups-subgroups of the graph theoretic model

LIST OF ACRONYMS

BOP	Basic oxygen process
CA	Continuous annealing
CO	Changeover time
CR	Cold reduction
CT	Cycle time
DEA	Data envelopment analysis
EDI	Electronic Data Interchange
FMCG	Fast moving consumer good
FMECA	Failure-mode and effects criticality analysis
GT	Graph theory
HBA	Hydrogen batch annealing
HFFS	Horizontal-form-fill-seal machine
HSM	Hot strip mill
I	Inventory
ISSS	International Society for Systems Sciences
JIT	Just in time
LECO	Hypothetical least complex system in a domain of systems
LMF	Ladle metallurgical facility
MADM	Multi-attribute decision making
MOCO	Hypothetical most complex system in a domain of systems
MR	Machine reliability
OCA	Open coil annealing
PCKL	Pickling
PPC	Production planning and control
SMED	Single-minute exchange of die
TM	Temper mill
TOPSIS	Technique for order preference by similarity to ideal situation
TPM	Total productive maintenance
TQM	Total Quality Management
VFFS	Vertical-form-fill-seal machine
VSM	Value stream mapping

Chapter I

INTRODUCTION

Lean manufacturing is a popular philosophy based on the methods mainly developed by Toyota Motor Corporation in the post world war-II period. Major focus of lean manufacturing is on the reduction of the non-value adding activities within the industrial organizations. The present study involves the development of lean manufacturing systems through restructuring of the traditional manufacturing systems. The study presents the use of new quantitative measures for analyzing the effect of restructuring on leanness of manufacturing systems at the conceptual stage of its development. In this chapter, the basic elements of lean manufacturing and the restructuring decisions for achieving the important objective of lean manufacturing i.e. removal of non-value adding elements in the manufacturing organizations are discussed. The motivation for the present work and the organization of the thesis are also presented.

1.1 Elements of lean manufacturing

Lean manufacturing is a comprehensive philosophy for structuring, operating, controlling, managing and continuously improving industrial production systems. The mass production philosophy (i.e. more and faster production means cheaper production) does not yield appropriate results in many of the modern challenging environments characterized by customization in most of the products because it ignores different indirect costs. Lean manufacturing links final customer to all manufacturing processes up to the raw material, resulting in the smooth flow and thus shorter lead time, higher quality and lower cost. One of the major objectives of implementing this philosophy in manufacturing organizations is to achieve better competitive position by achieving more with lesser resources. Some of the typical means of quantitatively analyzing the effect of implementing lean principles are in terms of reduction in lead time and inventory levels while satisfying the same production requirements. The key to reduce lead time and inventory level is the identification and elimination of the wasteful activities in the organization. In fact, to achieve the objectives of lean philosophy, one needs to do more than just eliminate the obvious waste and find out the root causes of waste. Basically, a smooth work flow in manufacturing organization go a long way in eliminating the root cause of waste and results in shorter lead time, highest quality and lowest cost. Overproduction, which may result from ambiguous goals, is one of the other important root causes of waste and it causes not just excess inventory or money tied up in that inventory but all other kinds of waste also e.g. overproduction may cause shortage of certain items as the processes are busy in producing things not immediately required. Many authors (Womack et al., 1990; Womack and Jones, 1996; Dove, 2001; Pavnaskar et al., 2003; Dennis, 2007) have contended that only the 5 % of the activities within the traditional manufacturing systems, for which the customer is willing to pay, constitute the value adding activities and the rest around 95 % of the activities can be classified as waste. A typical spread of such wasteful activities is shown in the Fig. 1.1 below.

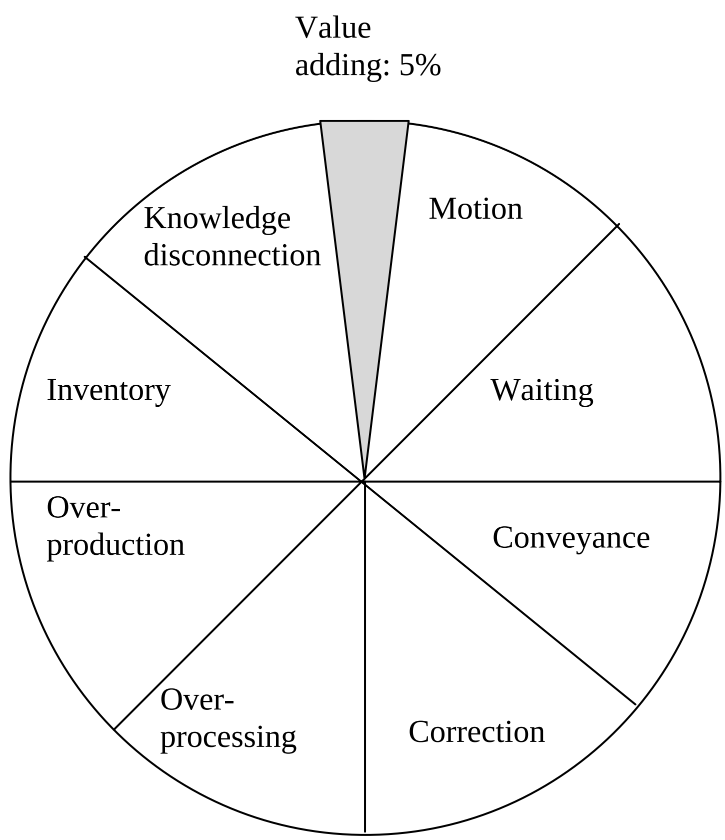


Fig. 1.1 Typical spread of value adding and non-value adding activities in traditional organizations (Dennis, 2007)

The segments in the above figure point to different sources of possible waste and may be attributed to the wasteful activities due to inefficiencies in work flow, e.g. the possibility of cycles of activities to fulfill a particular objective. Key tools of the lean philosophy that may help in reducing such sources of inefficiency in work flow are listed below.

- Level production
- Just in time (JIT)
- Quality at the source
- Standardized work/Production procedure simplification
- Visual Control
- Process stability
- Single minute exchange of die (SMED) principle i.e. short set-up time
- Production stop policy/Employee empowerment
- Continuous improvement

The overall objective of the lean philosophy is to attain customer focus for everything that is carried out within the organization so that non-value adding activities are identified and eliminated. The process stability as well as standardization in procedures is considered as the base for the lean philosophy as depicted in the Fig. 1.2.

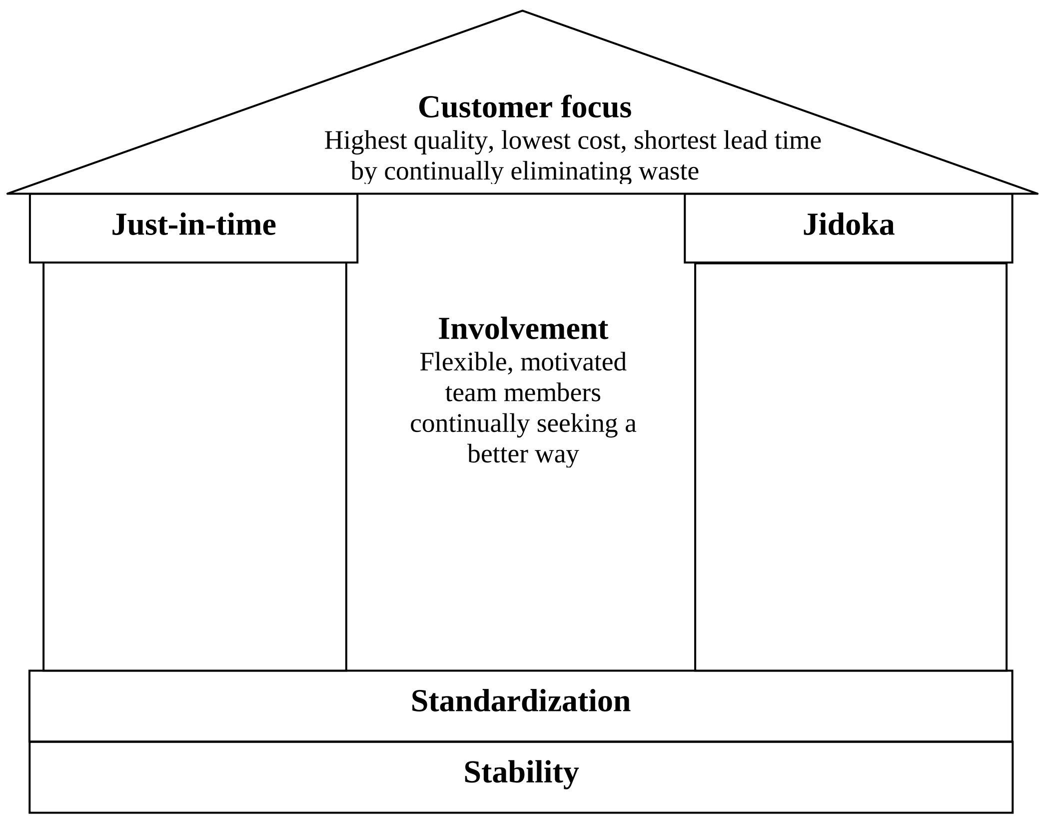


Fig. 1.2 Bases and pillars of lean manufacturing philosophy for achieving its overall objective of customer focus (Dennis, 2007)

One of the other most important elements of lean manufacturing is JIT which acts as a pillar to support the overall objective of lean philosophy i.e. the customer focus. The rest of the elements listed above may be classified under Jidoka which means automation with a human mind that acts as another pillar of the lean philosophy. The heart of the lean philosophy is the involvement of employees who participate in a motivated manner in the team work required to achieve higher competitiveness. In general, a number of restructuring decisions are involved in transforming traditional manufacturing systems into lean manufacturing systems as discussed in the next section.

1.2 The restructuring decisions for implementing the elements of lean philosophy

The major objective of the lean manufacturing philosophy as discussed in the previous section is to eliminate all sources of wasteful activities by using the bases of standardization as well as stabilization in different business processes within the organization. Some of the necessary structural changes or restructuring decisions that are required for transforming the traditional manufacturing systems into lean manufacturing systems are discussed below:

1. One of the basic restructuring decisions needed for elimination of waste within manufacturing organization is to make processes synchronous. An important lean element that helps to avoid this waste is continuous flow, which means each item immediately passes from one process step to the next process without any stagnation in between. The synchronous work flow makes in the overall system efficient.
2. In situations where the continuous flow is not possible, just-in-time (JIT**)** practice can help in achieving the flow production for increasing efficiency of production process. In the JIT system, rather than centrally scheduling the processes, pull from up-steam process is used. The schedule is considered merely an estimate of what the next process will actually need. The planned schedule is sent to the pace maker process step only. Some of the examples of situations where JIT is beneficial are when a process need to serve for multiple product families or when a distant supplier who can ship a product when requested. Mixed-model sequenced production scheduling is highly benefited by employing this technique.

3. Quality must be built into the processes rather than relying on excessive inspection. This is achieved through systems that identify and resolve quality problems at their source. Inspection systems that provide immediate feedback (e.g. self-and-successor-inspection strategies), monitoring and control of factors that cause quality problems, and error-proofing (kitting systems) mechanisms are widely employed techniques.
4. The visual controls rather than planned schedules should display the operational status of the production system and help in identification and working on the priority jobs for efficiently dealing with real customer requirements. Techniques such as 5S and inventory displays (supermarket concept) are required to be utilized
5. Standardization in performing each job ensures minimal manpower and effort, highest quality, highest safety at the workstation and it goes a long way in eliminating many sources of wasteful activities. However, in the lean philosophy, the shop floor workers are encouraged to continually exceed the standards thus making it possible to constantly improve the standards. The necessary structural change is to put in place the motivation mechanisms such as job security to ensure whole hearted involvement of the employees.
6. High standards in equipment reliability, raw material and purchased parts quality, employee knowledge and skills, and production quality control and rapid machine set-ups/changeover and flexible, multi-machine manning strategies are required as a pre-requisite for attaining process stability, capacity balance and synchronization of all production operations. The production cycle time can be controlled as per customer's acceptable waiting time for order receipt so as to enable demand-based scheduling.

1.3 Motivation for the present work

As noted in the previous sections, there are substantial differences between the traditional manufacturing systems and the lean manufacturing systems. Such differences are prominent in the areas of employee management, plant layouts, material and information flow systems, and production scheduling/control methods. Thus, implementation of lean manufacturing requires extensive restructuring of the existing work procedures which is generally considered quite disruptive for a production industry. These differences make it difficult for organizations that have relied on traditional manufacturing methods over the years, to readily accept the new systems without first getting convincing evidence on the possible benefits of implementing lean principles. It many time forms one of the reasons for the reluctance of the top managements to go ahead with lean philosophy in their organizations. Another reason for apprehension of organizations to implement lean philosophy is that in spite of great success stories available in literature (McKone et al., 2001; Alvarez et al., 2009) discussing the implementation of lean manufacturing concept, there are many instances of failures also (Chen and Meng, 2010) while implementing the lean principles. However, this must not be allowed as a hindrance in implementing the lean manufacturing as almost all the reported cases of failures in different organizations have been attributed to incomplete or half hearted implementation of lean principles rather than due to a fault in the lean principles.

Thus, a tool that can assist organizations to quantify the benefits that may be expected from restructuring for implementing lean manufacturing to their system at the planning and evaluation stage can aid the vital first step in the journey of the organization towards lean manufacturing. This information would enable management to assess the performance of the lean system relative to the existing system. Performance improvements like reduction in inventory levels, lead times and other forms of waste from applying the lean manufacturing principles of continuous flow, just-in-time inventory management, quality at the source, and level production scheduling have been modeled in the past by several researchers (Carlson and Yao, 1992; Galbraith and Standridge, 1994; Welgama and Mills, 1995; Lummus, 1995; McDonald et al., 2002; Hsu and Sha, 2007; Ramesh et al., 2008) using techniques such as simulation, knowledge based models, network models such as visual stream mapping etc. However, such models need extensive data for construction and many times are not able to completely satisfy the need for a comprehensive and quantitative analysis of the overall improvement due to implementation of lean concept at the conceptual stage. The restructuring exercise for attaining lean manufacturing can be completed more effectively if applied strategically after thorough analysis at the conceptual stage before actual implementation. Thus, there is ample motivation for researchers to propose such aids which can help in better informed decision making process for implementation of lean manufacturing concepts.

1.4 Outline of the Thesis

To present the thesis work in a logical order, it is divided into chapters as follows:

- In chapter I, the basic elements of lean manufacturing are discussed and importance of restructuring decisions for achieving the important objective of lean manufacturing i.e. removal of non-value added elements in the manufacturing organizations is described. The motivation for the present work and the outline of the thesis are spelt out.
- In chapter II, the literature on the previous work on lean manufacturing is reviewed. Different methods of quantitative modeling of leanness reported in the literature have been discussed. Different methods of restructuring in the manufacturing organizations reported in the literature have been reviewed e.g. conceptual methods, simulation based methods, object oriented models, knowledge based models, network models such as visual stream mapping etc. The limitations of the existing methods, gaps in the existing literature and the scope and objective of the present work are discussed.
- In chapter III, the methods of analysis used in the study, which are based on graph theoretic modeling and analysis have been discussed extensively. The basic procedure of the application of graph theoretic methodology for a general system is described and the significance of its results is discussed. The existing quantitative methods i.e. coefficient of dissimilarity, for analysis of the structures and physical interpretation of such methods is discussed. Four new quantitative measures of complexity for analysis of the impact of restructuring in manufacturing systems have been developed. The underlying assumptions of the modeling through graph theoretic methodology and the subsequent methods of quantitative analysis are also presented.
- In chapter IV, the methodology for analysis of restructuring decisions using graph theoretic modeling is applied to study the restructuring for lean manufacturing in a case of a steel industry. Different structural patterns of interaction cycles are identified using the graph theoretic model in a systematic manner. The correlation

of the values of the measures of complexity for the original and restructured manufacturing systems with the real performance measures like the reduction in cycle time have been used to validate the methodology.

- In chapter V, first case of restructuring in a packaging equipment industry has been taken for study. It includes an introduction to the products being produced at the unit, the challenges that this unit faces in meeting customer requirements and the need for restructuring and continuous improvement. The restructuring decision is to streamline the material flow within the manufacturing plant to convert the existing manufacturing system in to a leaner manufacturing system. The graph theoretic models for the original and the restructured manufacturing system are developed and the quantitative analysis using coefficient of dissimilarity by two of the criterion as well as by four new indices of complexity is carried out to compare the interaction structures of original and the restructured configuration of manufacturing systems.
- In chapter VI, second case of restructuring in the packaging equipment machines industry taken has been taken for study. It involves the streamlining of the inbound material flow from the supplier. The graph theoretic models for the original and the restructured manufacturing system are developed and the quantitative analysis using coefficient of dissimilarity by two of the criterion as well as by four new indices of complexity is carried out to compare the structural patterns of original and conceptualized restructured configurations of manufacturing systems.
- In chapter VII, the comparative analysis of restructuring cases in the packaging equipment industry is presented. Also, correlation between the values of different measures of complexity and the improvement in the performance on the dimension of on-time delivery has been investigated which shows a very strong correlation.
- The chapter VIII discusses the conclusions drawn and lists some of the tasks which may be carried out in extension of the present work.

Chapter II

LITERATURE REVIEW

In this chapter, the literature on evolution of lean manufacturing systems and different pertinent issues related to it is reviewed. The discussion is presented under sections such as developments in manufacturing systems research, evolution of lean manufacturing systems, existing studies on restructuring in manufacturing systems, graph theoretic systems methodology, complexity theory and its applications in evolving lean manufacturing systems.

2.1 Developments in manufacturing systems research

The scientific efforts to study the manufacturing systems started long back. There are several analytical/mathematical models for analysis of different issues in manufacturing systems. Buzacott (1967) was one of the pioneering authors to model and analyze production lines with finite buffers as Markov chains. The model developed by Buzacott (1967) had variables such as discrete material, unit operation times, and repair and failure times that are geometrically distributed. Thus, the journey of scientific investigation into manufacturing systems was initiated with his efforts. The finite buffer assumption is very important in factory context because inventory and the space to hold it are major costs. Later, Gershwin (1987) analyzed finite buffer production lines by developing an approximate decomposition method. Buzacott and Shantikumar (1992) addressed the issue of coordinating production in multiple-cells manufacturing system. Several similar models with different enhancements over these pioneering ones have been reported by various other researchers (Gershwin, 1994; Altiok, 1997; Kadipasaoghi et al., 1998; Dallery, 1999; Arora and Kumar, 2000; Gershwin and Schor, 2000).

Some of the other developments in this field have been the new concepts namely lean manufacturing systems (Womack et al., 1990), Bionic manufacturing system (Okino, 1989; Okino, 1992), the Fractal factory concept (Tharumarajah, 1996), Holonic manufacturing systems (Van Brussel et al., 1998) and agent based models (Ryu et al., 2003). Some work has also been reported on modeling the performance of humans in a manufacturing system with the use of artificial neural network (Baines et al., 2004). Some researchers (Blackhurst et al., 2005; Bourne et al., 2005; Gomes et al., 2006) have worked on development of different performance measures based management methods. Of all the above concepts, lean manufacturing concept has received relatively wider attention of practitioners as well as researchers all across the globe. Thus, in the next section, the evolution of this concept is discussed in greater detail.

2.2 Evolution of lean manufacturing systems

Challenges from global competitors in the past few decades have prompted many manufacturing firms to adopt new manufacturing approaches (Hall, 1987; Meredith and McTavish, 1992). Particularly salient among these is the concept of lean manufacturing (Womack et al., 1990; Womack and Jones, 1996; Dove, 2001; Pavnaskar et al., 2003). Lean manufacturing philosophy is a multi-dimensional approach that encompasses a wide variety of management practices, including just-in-time, quality systems, work teams, cellular manufacturing, supplier management, etc. in an integrated system. Lean manufacturing philosophy focuses on avoiding different fundamental wastes. It doe so by adopting several forward looking practices such as building long term relations with customers, employees and suppliers (Schonberger, 1986). Many articles on the topic of lean manufacturing have verified the positive impact of the implementation of lean principles e.g. just-in-time (JIT), total quality management (TQM), and total preventive maintenance (TPM) etc. on operational performance of organizations (Hackman and Wageman, 1995; Samson and Terziovski, 1999; McKone et al., 2001; Flynn et al., 1995; Alvarez et al., 2009). The core idea of lean manufacturing is that the above noted practices can work synergistically to create a streamlined, high quality system that produces finished products at the pace, the customer demands with little or no waste. The importance of effective management for sustainable growth and development of competitive business processes and manufacturing systems has always been at the forefront (Skinner, 1969; Buffa, 1984; Hayes and Wheelwright, 1984; Hayes et al., 1988; Hill, 1989). Many researchers (Voss et al., 1993 Vickery et al., 1993; Ward et al., 1994; Kadipasaoghi et al., 1998; Kristensen et al., 2001) have asserted that the lean capabilities can be only built by delivering well on multiple dimensions simultaneously such as quality, price, speed and flexibility (Carter and Baker, 1992; Dove, 1993; Goldman, 1995 and Kuhnle, 1996). Endsley (1996), Hitomi (1996) as well as Petrony and Bevilacqua (2002) have recommended to use synergistically the best capability of humans and advanced automated systems to achieve maximum flexibility, robustness and lean manufacturing system capability. Paranby (1997) has also discussed the need for a total approach for lean factory design where each element or subsystem fits effectively in the system as a whole using the most appropriate technologies, not necessarily the most advanced ones. Goranson (1996) and Ghalayini et al. (1997) have emphasized the concepts such as human centered production, responsive manufacturing and environment preservation, for sustainable lean manufacturing systems. Sheu et al. (1996) had made an attempt to integrate marketing with manufacturing using software tools for enhancing competitiveness by eliminating waste in this area. Duguay et al. (1997) and Gunasekaran (1998) have discussed the need for reconfigurability of the manufacturing system in the modern times so as to quickly adapt to the changing market requirements. Oakland and Oakland (1998) have investigated the links between people management, customer satisfaction and business results. The lean practices followed in a factory also play a significant role in reducing time to market (Wah, 1999; Magnan at al., 1999). Especially, the lean practices followed for new design and development go a long way in supporting the overall competitive position of a manufacturing firm owing to a strong relation between product development time and the increased market share (Blackwell, 1997; Handifield and Nichols, 1999; Shah and Ward, 2003; Pun, 2004; Lee et al., 2005). In view of the modern challenges and the success stories of lean philosophy implementation, many of the organizations have been attempting to revitalize their manufacturing bases in the last few decades through the use of lean principles (Jafari et al., 2007).

One major observation regarding the previous implementations of lean manufacturing (McDonald et al., 2002; Abdulmalek and Rajgopal, 2007) is that it needs considerable restructuring of the manufacturing systems in terms of how the resources such as materials, equipments, humans and finances are used. In general, the practical decision makers carrying out the restructuring exercise for achieving lean principles in manufacturing systems need to make system wide analysis using different tools (FMECA, Event tree analysis, cause and effect diagrams) which are generally based on heuristics and do not support adequate quantitative analysis (Sarmiento et al., 2007; Ramesh and Devadasan, 2007). A comprehensive tool for analysis of restructuring in manufacturing systems will be of great use in developing effective lean manufacturing systems. The recent focus of publications related to lean manufacturing (Wan and Chen, 2008; Singh et al., 2010; Vinodh et al., 2011; Vinodh and Chintha, 2011; Vinodh and Balaji, 2011; Vinodh and Vimal, 2011; Behrouzi and Wong, 2011) has been the development of different quantitative measures and this reveals the relevance of the alternate views to evaluate leanness of organizations. Some of these studies use data envelopment analysis (DEA) while the others present different fuzzy criteria based evaluation of multiple factors affecting leanness. In the next subsection, the literature on studies related to restructuring decisions and its relevance to the development of lean manufacturing systems and developments in related quantitative measures is discussed.

2.3 Existing studies on restructuring in manufacturing systems

The topic of corporate restructuring at the organizational level has been analyzed by number of researchers (Ansoff, 1984; Barker, 1992; 1994; Barker and Barber 1997). In general, such studies make objective assessment of cost-economics arising as a result of restructuring decisions and serve as a guide for organizations striving to restructure their organizations for better competitiveness. Barker (1992; 1994) as well as Barker and Barber (1997) have proposed some of the popular models based on time based value addition concept for analysis of restructuring decisions in manufacturing operations. Such studies provide useful guidelines for carrying out the analysis in manufacturing systems. However, the limitation of such studies is that they provide analysis based on past data only and do not support the analysis requirements at the conceptual stage of restructuring for contemplated restructuring decisions in manufacturing systems. On the other hand, simulation through animation can provide a visual and dynamic illustration to management of how the new system would work and this method has been used by number of researchers as discussed below. Carlson and Yao (1992) used simulation to pretest various flow layouts for a low-volume, mixed-model JIT assembly system. Welgama and Mills (1995) used a simulation to address design problems faced by a chemical company changing from a traditional to a JIT system, considering alternative designs for the JIT system. Galbraith and Standridge (1994) used simulation to test and validate modifications to a traditional system as it was in transition, in stages, to a JIT system. Lummus (1995) used simulation to study three production-sequencing strategies (mixed-model, minimum setup, and demand pull) as well as set-up time effects for a multi-product JIT system. Savasar and Al-Jawini (1995) studied the effects of variability in processing times and demand on push and pull production systems for various kanban levels and withdrawal policies. Most such works focus exclusively on the manufacturing processes (or an element thereof), and do not deal with the entire production system to provide the required big picture view on lean implementation at the conceptual stage. There are numerous other studies (Abdou and Dutta, 1993; Philipoom et al., 1987; Sarker and Harris, 1988; Ramesh et al., 2008) presenting the use of value stream mapping for implementation and evaluation of lean philosophy. McDonald et al. (2002) have presented an application of value stream mapping complemented by simulation methods to answer questions that could not be addressed by the static view alone. Hsu and Sha (2007) has more recent work using simulation based models to provide the analysis of restructuring issues in manufacturing systems.

All such studies reviewed above have resulted in very useful insights and successful implementation of lean manufacturing. However, there is considerable scope for exploring the development of complementary techniques of analysis owing to some limitations of the existing techniques e.g. some of the previous studies do not support the analysis at conceptual stage while the others have relatively difficult procedures. In the next section, developments in one of the newer technique known as graph theoretic approach, which can be explored for investigation of restructuring issues in manufacturing systems, have been discussed.

2.4 Evolution of graph theoretic systems methodology

For the decisions related to broader strategic issues such as restructuring in manufacturing systems, generally the system’s approaches are recommended (Sarmiento et al., 2007; Ramesh and Devadasan, 2007). The systems approach involves a systematic way of thinking to handle entities, situations, and problems of different subsystems in an interactive manner. The founders of International Society for Systems Sciences (ISSS) (http://www.isss.org) also observed that different systems approaches exist that provide a series of steps for conceptualization and analysis of different complex systems. The common elements in the widely popular system approaches are top-down holistic nature, life cycle orientation, ability to provide/define system requirements at conceptual stage and interdisciplinary, team based system design and development. Some of the available techniques for systematic analysis of broader systems issues are failure-modes and effects criticality analysis (FMECA), event-tree diagrams, cause and effect diagrams etc. (Smith, 1985; Betker, 1983; Juran and Gryna, 1993). Such methods, though only qualitative ones, give systematic direction to the thought process and are found to be highly useful by the practitioners into solving complex decision situations. On the other hand, there are certain quantitative tools such as game-theory, sequential decision tree etc., available in literature (Russel and Taylor III, 2006) which aid in such complex decision situations. However, the manufacturing managers need to depend on subjective assessment while using such tools. Mason-Jones et al (1998) records the limitations of different system approaches and observed a considerable scope for extending the work on systems approaches as none of the existing approach is all-embracing for system analysis. Thus, there is a tremendous scope to complement the existing set of methods for decision analysis related to manufacturing systems issues. Generally, for quantitative and integrative analysis of restructuring in manufacturing systems, exploration of a structure based system approach which is capable of incorporating the interactions and interdependences between various subsystems is particularly important.

The graph theoretic methodology is one of the popular systems approaches to model and analyze a complex system. This approach has the capability to make a wholesome analysis of the systems under consideration. Graph theoretic systems methodology is based on the concepts of graph theory (Refer Appendix A.1) and permanent function (Refer Appendix A.2). The graph theoretic interpretation of permanent function has been discussed by Jurkat and Ryser (1966) and Minc (1966). The permanent function is a well established concept in combinatorial mathematics applicable for a square matrix. Different features and applications of graph theory have been discussed in number of texts (Harary, 1985; Deo, 2000; Biswal, 2005). One of the pioneering applications of graph theoretic methodology for systems analysis using permanent function, which is a matrix operation similar to determinant, has been presented by Gandhi et al. (1991) for reliability analysis and evaluation of systems. The invariant nature of permanent multinomial is exploited and a reliability index of the system is proposed. The graph theory has many tools that have been used to solve a number of complex problems (Deo, 2000). The concepts related to permanent function are well established in combinatorial mathematics with the pioneering work reported by Minc (1966). Over the years, many researchers have used the permanent function based graph theoretic methodology for application in modeling of various complex systems (Mohan et al, 2003, Durai Prabhakaran at al., 2006. Venktasami and Agrawal (1996; 1997) have used graph theoretic methodology for system and structural analysis of an automobile vehicle. A group of researchers (Rao and Gandhi, 2001; 2002; Rao and Padmanabhan, 2006; Rao and Davim, 2008) have extensively applied permanent function based graph theoretic modeling in manufacturing engineering domain e.g. for selection and comparison of metal cutting fluids, for machinability evaluation of work materials and for failure cause analysis of machine tools. Rao and Padmanabhan (2006) have used digraph and matrix methods for selection of industrial robots. Faisal et al. (2007) have used graph theory and interpretive structural modeling for evaluating and analyzing the information risk mitigation in supply chains. In the above applications, the permanent multinomial has been found to provide an integrative numerical value when fed with some representative scores on Likert scale for the subsystem as well as interaction variables giving an all inclusive integrative numerical index which has used for ranking the alternatives for different kind of decision analysis. On the other hand, there are another set of papers (Venkatasamy and Agrawal, 1995; Mohan et al., 2003; Durai Prabhakaran at al., 2006; Upadhyay and Agrawal, 2007; Kumar and Agrawal, 2008; Kumar et al., 2010) reporting graph theoretic structural modeling for various complex systems such an automotive vehicle, a coal based power plant, FRP composites, electroplating plant etc. In such works, the physical interpretation of the permanent function based graph theoretic model is discussed by converting the terms of the emergent permanent multinomial into sub-graphs. Such sub-graphs identify all physical cycles of interactions with subsystems in a systematic way. The graph theoretic modeling can help in understanding the structural complexities within the manufacturing organizations through interpretations and insights offered towards their structures. Such models can be used to study the structural differences in different alternative designs of manufacturing systems.

Thus the literature related to applications of graph theoretic methodology classified into mainly two categories as below:

1. One major category (Gandhi et al., 1991; Rao and Gandhi, 2001) is where the permanent multinomial has been used to provide an integrative numerical value when fed with some representative scores on Likert scale for concerned variables. Such integrative numerical value is used as an all inclusive index which considers the properties of all subsystem as well as interactions within them and have been used for decision analysis by ranking based on permanent multinomial's numerical values.
2. On the other hand, the second category of literature (Venkatasamy and Agrawal, 1996; Mohan et al., 2003; Durai Prabhakaran at al., 2006) discusses the structural modeling of different kind of systems ranging from composite products to power plants and automobiles. The second category of literature is useful in deeper insight into the system structures where it helps to systematically identify a structural characterization set corresponding to it.

A recent work by (Baykasoglu, 2012) has reviewed all major applications of graph theoretic methodology. He has suggested to explore the use of this decision making methodology for different other areas. The structural modeling using graph theoretic methodology has been useful for differentiating the systems under comparison based on their structural aspects using mathematical formulae expressed as coefficients of dissimilarity/similarity. Such formulae rely on the results of graph theoretic models which are expressed as sub-graphs by converting the terms of the emergent permanent multinomial for the system into. The sub-graphs identify all physical cycles of interactions with subsystems in a systematic way. The graph theoretic modeling can help in understanding the structural complexities within the manufacturing organizations through interpretations and insights offered towards their structures. Such models have a scope to be used for the study of structural differences and complexity reduction in different alternative designs of manufacturing systems created after restructuring exercises. In particular, the impact of lean manufacturing efforts on complexity reduction in manufacturing systems as a result of a restructuring exercise for implementation of lean manufacturing philosophy can be estimated using such models.

2.5 Complexity theory and its applications in evolving lean manufacturing systems

Complexity of interactions within subsystems in a manufacturing system is one of the major causes for challenges faced by manufacturing systems such as longer through-put times, delays in meeting schedules, lack of responsiveness etc. The contribution of interrelations among subsystems towards complexity in any system is enormous (Delic and Dum, 2006). Thus, complexity reduction in manufacturing systems, which is one of the major objectives of lean manufacturing philosophy, can be achieved by taking such actions that simplify the interaction structure. This objective is generally achieved by first identification and then removal of various kinds of wasteful activities within the manufacturing organization which needs considerable restructuring of the work procedures with the organization. The measures of complexity reduction in a manufacturing system arising as a result of restructuring for lean initiatives can be of great help in steering such decisions in appropriate direction. Measurement of complexity in different systems has been attempted by number of researchers. Chaos Theory studies have been used to study the complexity issues (Gell-Mann, 1995; Auyang, 1998). Frizelle and Woodcock (1995) define a complexity measure using the probabilities associated with the state that each resource assumes. Buzacott (1999) suggested the use of the measure of complexity for study of manufacturing systems. A suitable method for measuring complexity may guide the efforts directed towards achieving lean manufacturing goals. Deshmukh et al, (1998) as well as Frizelle, (1998) have identified complexity as a structural property of the system where structure means arrangement of relations/interactions among individual subsystems. Buzacott (1999) as well as Sutherland and Heuval (2000) identified the material and information flows between the system components, the organizational relationships, and the communication network connecting people with other people or machines as the significant relationships in an enterprise. Arteta and Giachetti (2004) demonstrated the use of Petri Net modeling to develop a model for manufacturing system complexity as well as system agility based on the structural relations. On the similar lines, the complexity measures may be used to assess the leanness in manufacturing systems.

The graph theoretic modeling based structural identification may be used to provide a simpler method to quantitatively assess the complexity reduction in manufacturing systems which may finally aid in the decision making related to lean initiatives.

2.6 Identified research gaps

Based on all the previous sections, the following gaps have been identified in the available literature on the issues involved.

1. The implementation of lean manufacturing need considerable restructuring in the manufacturing systems for which the analysis of decisions at the conceptual stage is not supported by most of the studies in contemporary literature. Thus, there is a need for developing effective models that can support analysis of restructuring decisions related to the development of lean manufacturing system at the conceptual stage.
2. A structure based model is particularly needed for analysis of restructuring decisions of manufacturing system which is capable of incorporating the interactions and interdependences between different subsystems. Also, the models that can support the analysis of decisions at the conceptual stage are particularly desirable.
3. There is significant scope for exploring the use of graph theoretic methodology, which has been useful in modeling different other complex systems ranging from automotive vehicle to power plants as well as composite products.
4. The existing methods of quantitative analysis linked to the graph theoretic methodology also need to be extended further in order to adequately aid in the assessment of the extent of lean philosophy achievement. Particularly, the new measures related to complexity assessment need to be developed to steer the restructuring in the correct direction towards lean goals at the conceptual stage of development/restructuring of manufacturing systems.

2.7 Scope and objective of present study

The scope and objective of the present study has been presented in the following points.

1. To develop methods of analysis for guiding lean manufacturing efforts. The specific focus is to develop measures for complexity reduction due to restructuring decisions related to lean implementation
2. To investigate the practical utility of the proposed methods of analysis in case organizations where restructuring related to lean manufacturing efforts has been carried out.
3. To validate the methods of analysis by investigating the correlation with the real performance indicators of lean manufacturing (on-time delivery performance, reduction in work in process inventory)

In the next chapter, the research methodologies as well as the methods of analysis used for the study have been discussed.

Chapter III

METHODS OF ANALYSIS

As noted in the previous chapter, there is tremendous scope in using graph theoretic methodology for studying the restructuring issues in manufacturing systems in pursuit of lean philosophy goals. In this chapter, the standard procedure of this methodology is discussed. The physical interpretation of the coefficient of dissimilarity which is a quantitative method of analysis associated with this methodology has been discussed. The development of newer and more informative quantitative measures for studying the complexity reduction arising out of restructuring decisions in manufacturing systems is also discussed. The underlying assumptions for the adopted methodology are spelt out.

3.1 Methodology

The graph theoretic model based research methodology helps in understanding the complex structure of a system by systematically breaking it into different meaningful graph theoretic sub-graphs containing cycles of interactions. It uses the concept of permanent matrix, permanent multinomial and its graph theoretic interpretation for providing a unique and systematic way for analysis of complex systems. In the following subsections, the underlying assumptions, the steps in graph theoretic modeling, the features of groups and subgroups in graph theoretic models are discussed.

3.1.1 Underlying assumptions

The proposed graph theoretic models as well as new complexity measures being developed for manufacturing systems are based on assumptions as listed below.

1. Graph theoretic methodology defines a system in terms of subsystems within it as well as interactions among them. It is assumed that the subsystems and the interactions among subsystems for a manufacturing system are a representative of all important processes and procedures within it.
2. Performance of a manufacturing system depends considerably on interactions among subsystems.
3. Permanent matrix in the model is capable of capturing all important information related to the manufacturing system needed for the structural model by

associating variables representing subsystems (i.e. diagonal elements) and interconnections (i.e. off diagonal elements).

4. The number of interaction cycles, which are identified by graph theoretic model of manufacturing system reflects the complexities in the organization in terms of cyclic procedures.
5. Lean manufacturing philosophies in manufacturing systems can be achieved by such restructuring decisions in the manufacturing system, which contribute towards lowering the complexities in terms of interaction cycles among subsystems.

3.1.2 Steps in graph theoretic modeling

The main steps in the development of graph theoretic model for a system are briefly discussed below.

1. The first step is to identify the representative subsystems in the manufacturing system and the interactions among them and to develop the permanent matrix for the system. The permanent matrix is a square matrix which has the diagonal elements as the subsystem variables (Z_i*'s*) and the off-diagonal elements as the interaction variables (e.g. e_{ij} for interaction between subsystems *i* and *j*). The absence of interactions/ interconnectivities between two subsystems can be represented by entries of '0's in the permanent matrix. A typical permanent matrix is presented in the equation (3.1).

$$G = \begin{array}{c} \begin{matrix} 1 & 2 & 3 & & N \end{matrix} \\ \begin{bmatrix} Z_1 & e_{12} & e_{13} & \dots & e_{1N} \\ e_{21} & Z_2 & e_{23} & \dots & e_{2N} \\ e_{31} & e_{32} & Z_3 & \dots & e_{3N} \\ \dots & \dots & \dots & & \\ e_{N1} & e_{N2} & e_{N3} & \dots & Z_N \end{bmatrix} \begin{matrix} 1 \\ 2 \\ 3 \\ \dots \\ N \end{matrix} \end{array} \tag{3.1}$$

2. The next step is to carry out permanent function operation on the permanent matrix. The permanent function is a standard operation in combinatorial mathematics (Minc. 1966). It is defined for a square matrix and is similar to the well known operation known by the name of determinant. The definition of the permanent of a square matrix differs from that of its determinant in that the

signatures of the permutations are not taken into account. In other words, the steps in obtaining a permanent function are the same as that for a determinant with the only difference that no negative sign appear anywhere. Thus the permanent function of the permanent matrix yields a permanent multinomial with all its terms having a positive sign. The terms in the resulting permanent multinomial exhibit a typical pattern that identifies all possible cycles of interactions among the subsystems. Based on the pattern of interaction cycles, the formula for permanent function for matrix (G) can be written as below.

$$\begin{aligned}
\text{Per(G)} = & \prod_{1}^{N} Z_i + \sum_i \sum_j \sum_k \sum_l \cdots \sum_N (e_{ij} e_{ji}) Z_k Z_l .. Z_N + \\
& \left[\sum_i \sum_j \sum_k \sum_l \cdots \sum_N (e_{ij} e_{jk} e_{ki}) Z_l Z_m \ldots Z_N + \sum_i \sum_j \sum_k \sum_l \cdots \sum_N (e_{ik} e_{kj} e_{ji}) Z_l Z_m \ldots Z_N + \right] + \\
& \left[\begin{aligned} & \left\{ \sum_i \sum_j \sum_k \sum_l \cdots \sum_N (e_{ij}\ e_{ji})(e_{kl}\ e_{lk}) Z_m Z_n \ldots Z_N \right\} + \\ & \left\{ \sum_i \sum_j \sum_k \sum_l \cdots \sum_N (e_{ij}\ e_{jk} e_{kl}\ e_{li}) Z_m Z_n \ldots Z_N + \sum_i \sum_j \sum_k \sum_l \cdots \sum_N (e_{il}\ e_{lk} e_{kj}\ e_{ji}) Z_m Z_n \ldots Z_N \right\} \end{aligned} \right] + \\
& \left[\begin{aligned} & \left\{ \begin{aligned} & \sum_i \sum_j \sum_k \sum_l \cdots \sum_N (e_{ij}\ e_{ji})(e_{kl}\ e_{lm}\ e_{mk}) Z_n Z_o \ldots Z_N + \\ & \qquad \sum_i \sum_j \sum_k \sum_l \cdots \sum_N (e_{ij}\ e_{ji})(e_{km}\ e_{ml}\ e_{lk}) Z_n Z_o \ldots Z_N \end{aligned} \right\} + \\ & \left\{ \sum_i \sum_j \sum_k \sum_l \cdots \sum_N (e_{ij}\ e_{jk} e_{kl} e_{lm} e_{mi}) Z_n Z_o \ldots Z_N + \sum_i \sum_j \sum_k \sum_l \cdots \sum_N (e_{im}\ e_{ml} e_{lk} e_{kj} e_{ji}) Z_n Z_o \ldots Z_N \right\} \end{aligned} \right] \\
& + \bullet\bullet
\end{aligned} \quad (3.2)$$

3.1.3 Features of groups and subgroups in graph theoretic models

The permanent multinomial for a system with ‘n’ subsystems may have terms spread across ‘n+1’ groups. Thus, the permanent multinomial for a matrix with five subsystems can have its terms spread over a total of six groups. Similar way, the permanent multinomial for a matrix with six subsystems can have terms spread over a total of seven groups. The features of the terms in similar groups remain the same regardless of the number of subsystems in the system. The graph theoretic representation of the terms of the permanent multinomial leads to sub-graphs of the system and they demonstrate the physical meaning of the terms. The typical groups and subgroups of the sub-graphs for a system with a maximum of six subsystems are shown in Fig. 3.1. In the sub-graphs, the standalone subsystems are identified by the subsystem variables while the subsystems involved in interactions are identified through interaction variables only and thus such subsystems are shown as shaded in Fig. 3.1.

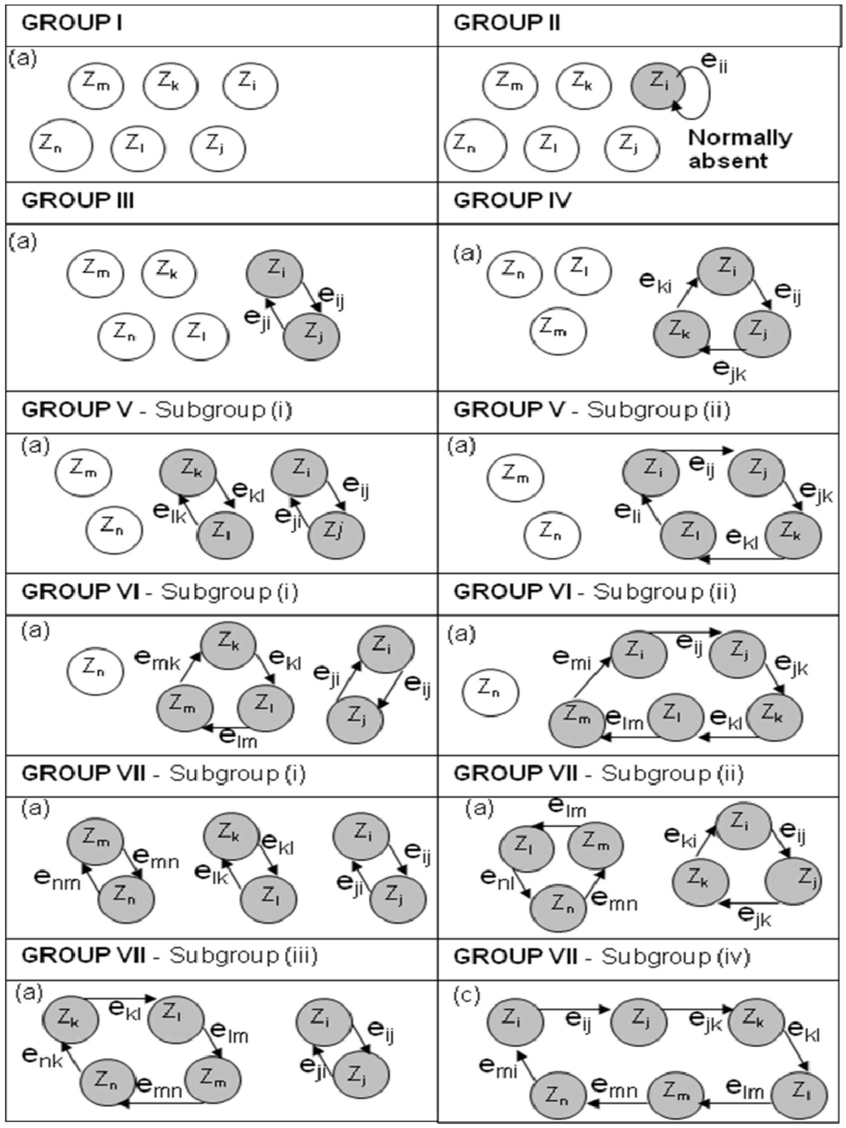


Fig. 3.1 Sub-graphs classified into groups and subgroups based on the identifying interaction cycles

LEGEND


Stand-alone subsystems not participating in interaction cycles (un-shaded circles)


Subsystems participating in interaction cycles (shaded circles)


Linkage from subsystem ‘i’ to subsystem ‘j’ shows information flow/material flow among respective subsystems

Fig. 3.1 shows all possible interaction cycles among six subsystems identified as Z_i, Z_j, Z_k, Z_l, Z_m, Z_n where i, j, k, l, m, n can take the value from 1 to 6. The salient features of the sub-graphs in the graph theoretic model are briefly discussed below.

1. The first group of sub-graphs consists of those terms, which involve no interaction variable (e_{ij}'s). The second group of sub-graphs is normally absent due to non existence of self interaction loop (e_{ii}) in the systems generally modeled. The third group will have terms with two interaction variables. Similar way, the 'n^{th}' group will have terms with 'n-1' interaction variables.
2. The fifth, sixth and seventh groups can have subgroups also based on the nature of interaction variables The features of such subgroups within groups as shown in Fig. 3.1 are discussed below.
   - Four interaction variables in fifth group terms may be distributed either in the form of two sets of two interaction variables (e_{ij} e_{ji} and e_{kl} e_{lk}) forming graph theoretic dyads or in the form of a single set of four interaction variables (e_{ij} e_{jk} e_{kl} e_{li}) forming a single graph theoretic cycle.
   - Similar way, five interaction variables in sixth group terms may be distributed either in the form of two sets, i.e. one set of two interaction variables (e_{ij} e_{ji}) for a dyad and another set of three interaction variables (e_{kl} e_{lm} e_{mk}) forming a graph theoretic cycle; or in the form of a single set of five interaction variables (e_{ij} e_{jk} e_{kl} e_{lm} e_{mi}) forming a cycle.
   - On the similar lines, the seventh group can have four subgroups, based on how six interaction variables are distributed. The first subgroup will contain three sets of two interaction variables (e_{ij} e_{ji}, e_{kl} e_{lk} and e_{mn} e_{nm}). The second subgroup will contain two sets of three interaction variables each (e_{ij} e_{jk} e_{ki} and e_{lm} e_{mn} e_{nl}). The third subgroup will contain two sets with two and four interaction variables (e_{ij} e_{ji} and e_{kl} e_{lm} e_{mn} e_{nk}). The fourth subgroup will contain terms with a single set of six interaction variables (e_{ij} e_{jk} e_{kl} e_{lm} e_{mn} e_{ni}).

In the above discussion, it is demonstrated that the graph theoretic model for a system can help in identification of different sub-graphs containing all possible interaction cycles among its subsystems in a systematic manner. In the case of a manufacturing system, it is assumed that the more the number of identified sub-graphs (and the interactions cycles within them), more will be the possibility of interaction cycles for various tasks and more will be the complexity involved. Thus, the results of graph theoretic model for manufacturing system can offer a framework for comparison of interaction structures within different manufacturing systems and can help in comparing the complexity inherent in their interaction structures.

The use of consolidated information on the number of sub-graphs generated by the graph theoretic models for different manufacturing systems can be used to quantitatively compare their interaction structures. In the next section, the existing methods for graph theoretic methodology based quantitative structural comparison of systems such as coefficient of dissimilarity by two different criteria are discussed. The limitations of the existing methods for logical comparison of manufacturing systems and the modified quantitative methods for meaningful structural comparison of manufacturing systems are discussed thereafter. Such quantitative analysis will help in comparing their performance in achieving lean and agile goals.

3.2 Existing methods for quantitative comparison of interaction structures using graph theoretic models

In order to quantitatively compare the structures of different systems ranging through mechanisms, automobile systems, fiber composites to electroplating systems using the data generated by their graph theoretic models, the two methods i.e. coefficient of dissimilarity (criterion-1) and coefficient of dissimilarity (criterion-2) are generally used by researchers (Ambekar and Agrawal, 1987; Gandhi et al., 1991; Venkatasamy and Agrawal, 1996;1997; Durai Prabhakaran et al, 2006; Kumar and Agrawal, 2008). In the context of comparing the interaction structures of alternative manufacturing systems, these methods are described as below. For the sake of quick reference, the consolidated structural information in terms of number of sub-graphs under different groups and subgroups in the graph theoretic model for a manufacturing system is written in the form of a characterization set as below.

Format for writing characterization set for a manufacturing system with five subsystems

$$= /J_1/ J_2/ J_3/ J_4/ J_{51}/ J_{52}/ J_{61}/ J_{62}/ \quad (3.3)$$

where J_k represents the total number of sub-graphs in the k^{th} group if no subgroups are present in it while J_{kl} represent the total number of sub-graphs in the l^{th} subgroup of the k^{th} group in case subgroups are present.

Also, for the purpose of defining the formulae for each method of structural comparison, two manufacturing systems (A & B) each having five subsystems as well as interactions among them, are considered and their characterization sets are defined as below.

Characterization set for manufacturing system -A= $/J_1^A/ J_2^A/ J_3^A/ J_4^A/ J_{51}^A/ J_{52}^A/ J_{61}^A/ J_{62}^A/$ (3.4)

Characterization set for manufacturing system -B= $/J_1^B/ J_2^B/ J_3^B/ J_4^B/ J_{51}^B/ J_{52}^B/ J_{61}^B/ J_{62}^B/$ (3.5)

The detailed descriptions on the two existing methods for structural comparison are presented below.

3.2.1 Coefficient of dissimilarity (Criterion-1)

The coefficient of dissimilarity by criterion-1 between the two manufacturing systems (A and B) is obtained by the following formula.

Coefficient of dissimilarity criterion-1,

$$C_{d\text{-}1} = \frac{\sum_k \sum_l \left[J_{kl}^A - J_{kl}^B \right]}{\text{maximum}\left[\sum_k \sum_l \left[J_{kl}^A \right] \text{ or } \sum_k \sum_l \left[J_{kl}^B \right] \right]} \quad (3.6)$$

The formula for coefficient of dissimilarity (criterion-1) basically has the numerator as the algebraic sum of the differences in the numbers of sub-graphs falling under different groups in the two manufacturing systems (A and B). The denominator constitutes the sum of number of sub-graphs for either of the manufacturing systems whichever has maximum value.

3.2.2 Coefficient of dissimilarity (Criterion-2)

The formula for the coefficient of dissimilarity by criterion-2 between two manufacturing systems (A and B) is obtained by the following formula.

Coefficient of dissimilarity criterion-2,

$$C_{d-2} = \sqrt{\frac{\sum_{k}\sum_{l}\left[J_{kl}^{A} - J_{kl}^{B}\right]^{2}}{\text{maximum}\left[\sum_{k}\sum_{l}\left[J_{kl}^{A}\right]^{2} or \sum_{k}\sum_{l}\left[J_{kl}^{B}\right]^{2}\right]}} \qquad (3.7)$$

The formula for coefficient of dissimilarity (criterion-2) basically has the numerator within the square root as the sum of the squares of the differences in the numbers of sub-graphs falling under different groups in the two manufacturing systems (A and B). The denominator within the square root constitutes the sum of squares of the number of sub-graphs for either of the manufacturing systems whichever has maximum value.

3.3 Physical interpretation of coefficient of dissimilarity (criterion -1 and criterion-2)

The two methods i.e. coefficients of dissimilarity (criterion-1 and criterion-2) discussed in the previous section have been used by a number of researchers earlier for structural comparison of a variety of systems ranging from automobile systems to fiber composite systems. But in the available literature, the detailed physical interpretation of such measures has not been discussed so far. To obtain greater insight and to make the analysis more useful, the physical interpretation of the above two existing measures is discussed in this section. For this purpose, the groups and subgroups in the graph theoretic model are assumed as dimensions of a Euclidian space. The number of sub-graphs under each group or subgroup provides the value of coordinates on the Euclidian space with dimensions as the groups and subgroups in the graph theoretic model. Thus the position of a system (in the present case a manufacturing system) in the Euclidian space can be fixed. Careful examination of the formula in equation (3.6) reveals that the numerator is the Cartesian distance in the Euclidian space, between two systems to be compared. The denominator in the formula in equation (3.6) represents the Cartesian distance of the farther of the two systems from the origin of Euclidian space. Thus the coefficient of dissimilarity (criterion-1) represents the ratio of the Cartesian distances between systems being compared to the Cartesian distance of one of the farther system from the origin in the Euclidian space generated by the results of graph theoretic model.

For graphical demonstration of the concept, two example systems with five subsystems are considered such that their graph theoretic models give the characterization sets as under.

Characterization set for manufacturing system -A=

$$/J_1^A / J_2^A / J_3^A / J_4^A / J_{51}^A / J_{52}^A / J_{61}^A / J_{62}^A / \quad (3.8)$$
$$/1/0/4/5/3/2/3/2/$$

Characterization set for manufacturing system -B=

$$/J_1^B / J_2^B / J_3^B / J_4^B / J_{51}^B / J_{52}^B / J_{61}^B / J_{62}^B / \quad (3.9)$$
$$=/1/0/1/4/3/2/3/2/$$

To ease the representation of the systems on a two dimensional space, the values for all the dimensions (except two i.e. Group III and Group IV) are considered to be the same for the example systems. The positions of the two systems are graphically represented on a set of two dimensions with different values (group III and group IV of graph theoretic model) in Fig. 3.2. The Cartesian distances are graphically represented on a representative set of two dimensions (group III and group IV of graph theoretic model) in Fig. 3.3. The Euclidian distances are graphically represented on the same representative set of two dimensions (group III and group IV of graph theoretic model) in Fig. 3.4.

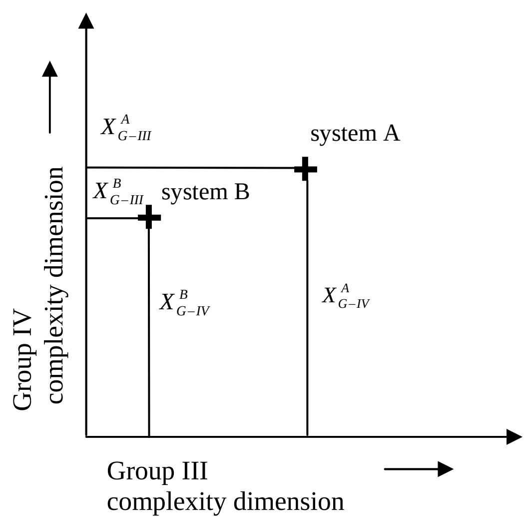


Fig. 3.2 Position of the two systems on a representative set of two dimensions (group III and group IV of graph theoretic model)

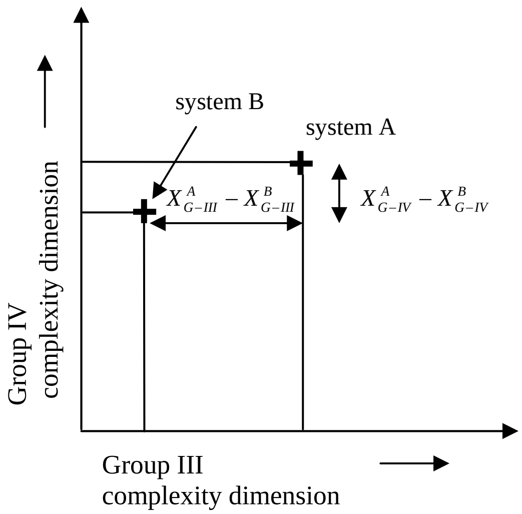


Fig. 3.3 Cartesian distances of the two systems on a representative set of two dimensions (group III and group IV of graph theoretic model)

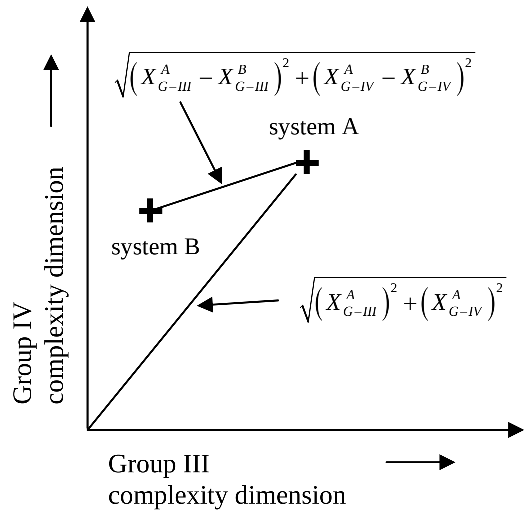


Fig. 3.4 Euclidian distance between the two systems on a representative set of two dimensions (group III and group IV of graph theoretic model)

The two criteria for coefficient of dissimilarity provide methods for structural comparison of two different systems. These methods mainly compare the systems on the ground of differences in the number of interaction cycles that are possible in their interaction structures. In the case of comparing the manufacturing system interaction structures, the specific focus on the issue of complexity is more desirable. Thus, in the next section, new methods are developed which focus more on the complexity of interaction structures.

3.4 New methods for quantitative measurement of complexity of interaction structures in manufacturing systems

As discussed in the previous section, the existing methods of analysis using the data generated by graph theoretic modeling have limitations to guide decisions related to lean manufacturing implementation in manufacturing systems and new methods of analysis are desirable. To realize the features of lean manufacturing, reduction in wasteful activities and undesirable complexity of interaction procedures within subsystems of a manufacturing system is utmost importance. Thus, in the following subsections, new methods are developed which are based on the complexity of interaction structures as discussed below.

3.4.1 Index of complexity (Cartesian distance)

In this new method, the two manufacturing systems are compared by the ratio of the magnitudes of the Cartesian distances corresponding to the position vectors of manufacturing systems in the Euclidian space of complexity. The sum of the Cartesian coordinates of the smaller position vector is taken as the numerator while that for the larger one is used as the denominator. Using the same example as discussed for coefficients of dissimilarity in the previous section, the concept is demonstrated below. Referring back to Fig. 3.2, where the position of the two systems and the Cartesian coordinates are graphically presented on a representative set of two dimensions (group III and group IV of graph theoretic model), the formula for index of complexity using Cartesian distances may be derived as below.

Index of complexity (cartesian distance)
for manufacturing system-B

$$= \frac{(X^B_{G-I}) + (X^B_{G-II}) + (X^B_{G-III}) + (X^B_{G-IV}) + (X^B_{G-V(i)}) + (X^B_{G-V(ii)}) + (X^B_{G-VI(i)}) + (X^B_{G-VI(ii)})}{\left(X^A_{G-I}\right) + \left(X^A_{G-II}\right) + \left(X^A_{G-III}\right) + \left(X^A_{G-IV}\right) + \left(X^A_{G-V(i)}\right) + \left(X^A_{G-V(ii)}\right) + \left(X^A_{G-VI(i)}\right) + \left(X^A_{G-VI(ii)}\right)}$$

$$= \frac{\sum_k \sum_l \left[J^B_{kl}\right]}{\text{maximum}\left[\sum_k \sum_l \left[J^A_{kl}\right] \; or \sum_k \sum_l \left[J^B_{kl}\right]\right]} \tag{3.10}$$

In the above formula for the index of complexity (Cartesian distance), the numerator is the algebraic sum of the numbers of sub-graphs falling under the manufacturing system-B. The denominator constitutes the sum of number of sub-graphs for either of the manufacturing systems whichever has maximum value.

3.4.2 Index of complexity (Euclidian distance)

In this new method, the two manufacturing systems are compared by the ratio of the magnitudes of the position vectors of manufacturing system in the Euclidian space of complexity. The magnitude of smaller position vector is taken as the numerator while that of the larger one is taken as the denominator. The position vectors of the two example systems discussed in previous sections are presented on a representative set of two dimensions (group III and group IV of graph theoretic model) just for demonstration purpose as in Fig. 3.5.

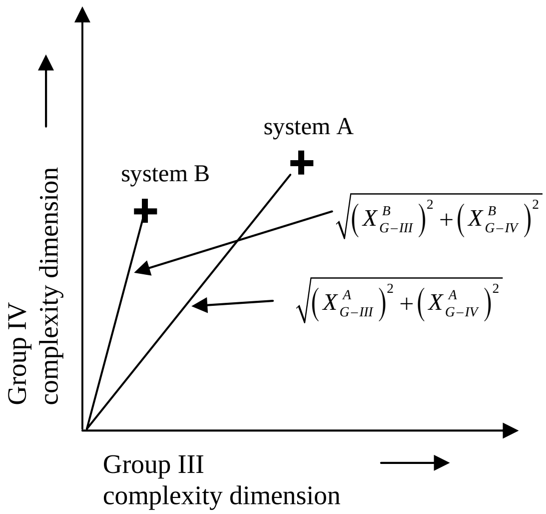


Fig. 3.5 Euclidian distances of the two systems from origin on a representative set of two dimensions (group III and group IV of graph theoretic model)

The formula for this index of complexity for system B can be derived based on the Euclidian distances in the multidimensional Euclidian space as follows.

Index of complexity (Euclidian distances)for manufacturing system-B

$$= \sqrt{\frac{(X_{G-I}^{B})^2+(X_{G-II}^{B})^2+(X_{G-III}^{B})^2+(X_{G-IV}^{B})^2+(X_{G-V(i)}^{B})^2+(X_{G-V(ii)}^{B})^2+(X_{G-VI(i)}^{B})^2+(X_{G-VI(ii)}^{B})^2}{\left(X_{G-I}^{A}\right)^2+\left(X_{G-II}^{A}\right)^2+\left(X_{G-III}^{A}\right)^2+\left(X_{G-IV}^{A}\right)^2+\left(X_{G-V(i)}^{A}\right)^2+\left(X_{G-V(ii)}^{A}\right)^2+\left(X_{G-VI(i)}^{A}\right)^2+\left(X_{G-VI(ii)}^{A}\right)^2}}$$

$$= \sqrt{\frac{\sum_{k}\sum_{l}\left[J_{kl}^{B}\right]^2}{\text{maximum}\left[\sum_{k}\sum_{l}\left[J_{kl}^{A}\right]^2 or \sum_{k}\sum_{l}\left[J_{kl}^{B}\right]^2\right]}} \tag{3.11}$$

In the above formula for the index of complexity (Euclidian distance), the numerator within the square root is the algebraic sum of the squares of the numbers of sub-graphs falling under the manufacturing system-B. The denominator constitutes the sum of the squares of the number of sub-graphs for either of the manufacturing systems whichever has maximum value.

The index of complexity (Cartesian distance) and the Index of complexity (Euclidian distance) are promising measures for evaluating complexity in manufacturing systems.

Another approach based on the methodology of a widely accepted multi-attribute decision making (MADM) tool i.e. Technique for order preference by similarity to ideal solution (TOPSIS), can also be developed. The development of new TOPSIS type indices of complexity based on TOPSIS has been discussed in the next two subsections.

3.4.3 TOPSIS type index of complexity (Cartesian distance)

The TOPSIS technique is a multi attribute decision making (MADM) method developed by Hwang and Yoon (1982). It has been successfully used by different researchers over the years (Agrawal et al., 1992; Rao and Gandhi, 2002). The TOPSIS methodology offers a systematic method to convert values from multiple attributes into a single index. The prominent feature of the TOPSIS methodology is the identification of hypothetical best and worst alternative based on highest and lowest values of attribute measures. A suitability index for each alternative is evaluated by comparing the Euclidian distances of an alternative from the hypothetical best and worst alternatives.

The TOPSIS type indices of complexity first identify two unique hypothetical manufacturing systems, one with the highest value for each dimension of complexity while the other with the lowest value for each dimension of complexity. These are named as hypothetical most-complex (MOCO) and least-complex manufacturing systems (LECO). In the first method for TOPSIS type index of complexity, the Cartesian distances of the particular manufacturing system, from the hypothetical most complex (MOCO) and hypothetical least complex (LECO) manufacturing in the Euclidian space of complexity are used to obtain this new index of complexity. The manufacturing systems can be ranked in the order of complexity based on the value of the index of complexity. For demonstrating the concept, in addition to the two example manufacturing systems described in the previous sections, two more examples (manufacturing system C and D) also need to be considered and the corresponding characterization sets are presented below.

Characterization set for manufacturing system -C=

$$/J_1^C / J_2^C / J_3^C / J_4^C / J_{51}^C / J_{52}^C / J_{61}^C / J_{62}^C / \\ =/1/0/7/2/3/2/3/2/ \qquad (3.12)$$

Characterization set for manufacturing system -D=

$$/J_1^D / J_2^D / J_3^D / J_4^D / J_{51}^D / J_{52}^D / J_{61}^D / J_{62}^D / \qquad (3.13)$$
$$=/1/0/5/1/3/2/3/2/$$

The positions of the four systems (A to D) are graphically presented on the same representative set of two dimensions (group III and group IV of graph theoretic model) in Fig. 3.6 as in the previous subsections. The identification of two hypothetical manufacturing systems, one most complex manufacturing system possible and the other least complex one in the domain of the considered manufacturing systems is also demonstrated on a representative set of two dimensions (group III and group IV of graph theoretic model) in Fig 3.6.

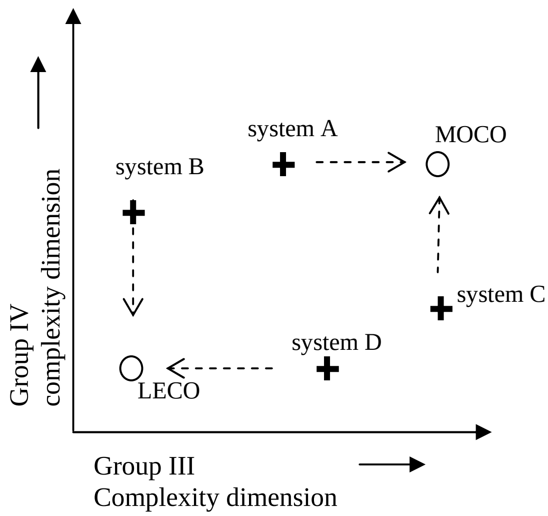


Fig. 3.6 Plotting the four systems and identification of most complex (MOCO) and least complex (LECO) systems on a representative set of two dimensions (group III and group IV of graph theoretic model)

The characterization sets for these hypothetical manufacturing systems are written as below.

Characterization set for hypothetical most complex manufacturing system -MOCO=

$$/J_1^{MOCO} / J_2^{MOCO} / J_3^{MOCO} / J_4^{MOCO} / J_{51}^{MOCO} / J_{52}^{MOCO} / J_{61}^{MOCO} / J_{62}^{MOCO} / \qquad (3.14)$$
$$=/1/0/7/5/3/2/3/2/$$

Characterization set for hypothetical least complex manufacturing system -LECO=

$$/J_1^{LECO} / J_2^{LECO} / J_3^{LECO} / J_4^{LECO} / J_{51}^{LECO} / J_{52}^{LECO} / J_{61}^{LECO} / J_{62}^{LECO} / = /1/0/1/1/3/2/3/2/ \tag{3.15}$$

The derivation for the TOPSIS type index of complexity by Cartesian criterion for manufacturing system 'B' is demonstrated below.

$$\text{Index of complexity}_{B}^{\text{TOPSIS type (cartesian distance)}}$$

$$= \frac{\left\{ \begin{array}{l} (X_{G-I}^{B} - X_{G-I}^{LECO}) + (X_{G-II}^{B} - X_{G-II}^{LECO}) + (X_{G-III}^{B} - X_{G-III}^{LECO}) + (X_{G-IV}^{B} - X_{G-IV}^{LECO}) + \\ (X_{G-V(i)}^{B} - X_{G-V(i)}^{LECO}) + (X_{G-V(ii)}^{B} - X_{G-V(ii)}^{LECO}) + (X_{G-VI(i)}^{B} - X_{G-VI(i)}^{LECO}) + (X_{G-VI(ii)}^{B} - X_{G-VI(ii)}^{LECO}) \end{array} \right\}}{\left[\begin{array}{l} \left\{ \begin{array}{l} (X_{G-I}^{B} - X_{G-I}^{LECO}) + (X_{G-II}^{B} - X_{G-II}^{LECO}) + (X_{G-III}^{B} - X_{G-III}^{LECO}) + (X_{G-IV}^{B} - X_{G-IV}^{LECO}) + \\ (X_{G-V(i)}^{B} - X_{G-V(i)}^{LECO}) + (X_{G-V(ii)}^{B} - X_{G-V(ii)}^{LECO}) + (X_{G-VI(i)}^{B} - X_{G-VI(i)}^{LECO}) + (X_{G-VI(ii)}^{B} - X_{G-VI(ii)}^{LECO}) \end{array} \right\} + \\ \left\{ \begin{array}{l} (X_{G-I}^{MOCO} - X_{G-I}^{B}) + (X_{G-II}^{MOCO} - X_{G-II}^{B}) + (X_{G-III}^{MOCO} - X_{G-III}^{B}) + (X_{G-IV}^{MOCO} - X_{G-IV}^{B}) + \\ (X_{G-V(i)}^{MOCO} - X_{G-V(i)}^{B}) + (X_{G-V(ii)}^{MOCO} - X_{G-V(ii)}^{B}) + (X_{G-VI(i)}^{MOCO} - X_{G-VI(i)}^{B}) + (X_{G-VI(ii)}^{MOCO} - X_{G-VI(ii)}^{B}) \end{array} \right\} \end{array} \right]}$$

$$= \frac{\sum_{k} \sum_{l} \left[J_{kl}^{B} - J_{kl}^{LECO} \right]}{\left[\sum_{k} \sum_{l} \left[J_{kl}^{B} - J_{kl}^{LECO} \right] + \sum_{k} \sum_{l} \left[J_{kl}^{MOCO} - J_{kl}^{B} \right] \right]} \tag{3.16}$$

In the above formula for the TOPSIS type index of complexity (Cartesian distance), the numerator represents the Cartesian distance between manufacturing system-B and the hypothetical least complex manufacturing system (LECO) in the Euclidian space with different groups/subgroups in graph theoretic model as its dimensions. The denominator is the sum of Cartesian distances of the manufacturing system-B from the hypothetical least complex as well as from the most complex manufacturing systems in the same Euclidian space.

3.4.4 TOPSIS type index of complexity (Euclidian distance)

The TOPSIS type index of complexity (Euclidian distance) is also based on identification of two hypothetical manufacturing systems, one with the highest value for each dimension of complexity while the other with the lowest value for each dimension of complexity. These are named as hypothetical most-complex (MOCO) and least-complex manufacturing systems (LECO).To obtain this index of complexity, the Euclidian distances of the manufacturing system from the hypothetical most complex (MOCO) and hypothetical least complex (LECO) manufacturing systems are used in the

Euclidian space of complexity. The position of the four example manufacturing systems as well as that of the identified MOCO and LECO manufacturing systems are graphically presented on a representative set of two dimensions (group III and group IV of graph theoretic model) in Fig. 3.7. Also, just for demonstration purpose, the Euclidian distances of manufacturing system-B from the MOCO and LECO systems are shown.

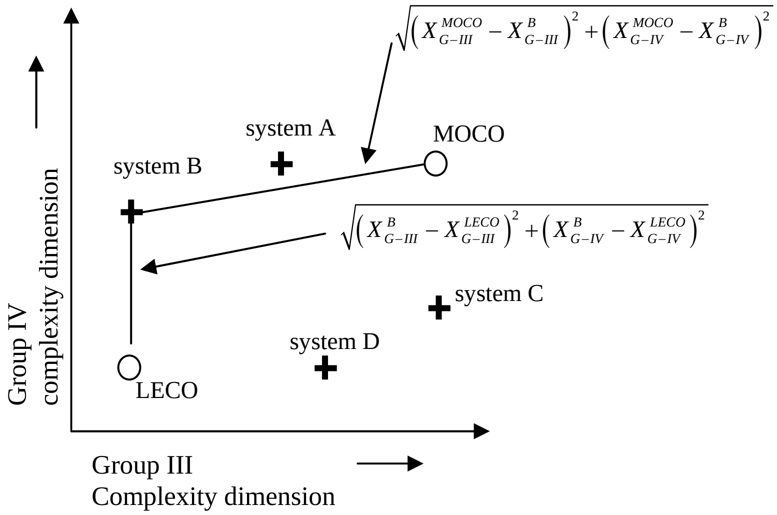


Fig. 3.7 Euclidian distances of system-B from most complex (MOCO) and least complex (LECO) systems on a representative set of two dimensions (group III and group IV of graph theoretic model)

The derivation of TOPSIS type index of complexity by Euclidian criterion for manufacturing system 'B', which uses Euclidian distances in the multi-dimensional space is presented below.

Index of complexity$_{\text{B}}^{\text{TOPSIS type (Euclidian distance)}}$

$$= \frac{\sqrt{\begin{array}{l}(X_{G-I}^{B}-X_{G-I}^{LECO})^2+(X_{G-II}^{B}-X_{G-II}^{LECO})^2+(X_{G-III}^{B}-X_{G-III}^{LECO})^2+(X_{G-IV}^{B}-X_{G-IV}^{LECO})^2+\\(X_{G-V(i)}^{B}-X_{G-V(i)}^{LECO})^2+(X_{G-V(ii)}^{B}-X_{G-V(ii)}^{LECO})^2+(X_{G-VI(i)}^{B}-X_{G-VI(i)}^{LECO})^2+(X_{G-VI(ii)}^{B}-X_{G-VI(ii)}^{LECO})^2\end{array}}}{\left[\begin{array}{l}\sqrt{\begin{array}{l}(X_{G-I}^{B}-X_{G-I}^{LECO})^2+(X_{G-II}^{B}-X_{G-II}^{LECO})^2+(X_{G-III}^{B}-X_{G-III}^{LECO})^2+(X_{G-IV}^{B}-X_{G-IV}^{LECO})^2+\\(X_{G-V(i)}^{B}-X_{G-V(i)}^{LECO})^2+(X_{G-V(ii)}^{B}-X_{G-V(ii)}^{LECO})^2+(X_{G-VI(i)}^{B}-X_{G-VI(i)}^{LECO})^2+(X_{G-VI(ii)}^{B}-X_{G-VI(ii)}^{LECO})^2\end{array}}+\\\sqrt{\begin{array}{l}(X_{G-I}^{MOCO}-X_{G-I}^{B})^2+(X_{G-II}^{MOCO}-X_{G-II}^{B})^2+(X_{G-III}^{MOCO}-X_{G-III}^{B})^2+(X_{G-IV}^{MOCO}-X_{G-IV}^{B})^2+\\(X_{G-V(i)}^{MOCO}-X_{G-V(i)}^{B})^2+(X_{G-V(ii)}^{MOCO}-X_{G-V(ii)}^{B})^2+(X_{G-VI(i)}^{MOCO}-X_{G-VI(i)}^{B})^2+(X_{G-VI(ii)}^{MOCO}-X_{G-VI(ii)}^{B})^2\end{array}}\end{array}\right]}$$

$$= \frac{\sqrt{\sum_{k}\sum_{l}\left[J_{kl}^{B}-J_{kl}^{LECO}\right]^2}}{\left[\sqrt{\sum_{k}\sum_{l}\left[J_{kl}^{B}-J_{kl}^{LECO}\right]^2}\right]+\left[\sqrt{\sum_{k}\sum_{l}\left[J_{kl}^{MOCO}-J_{kl}^{B}\right]^2}\right]}$$

(3.17)

In the above formula for the TOPSIS type index of complexity (Euclidian distance), the numerator represents the Euclidian distance between manufacturing system-B and the hypothetical least complex manufacturing system (LECO) in the Euclidian space with different groups/subgroups in graph theoretic model as its dimensions. The denominator is the sum of Euclidian distances of the manufacturing system-B from the hypothetical least complex as well as from the most complex manufacturing systems in the same Euclidian space. The detailed steps of calculation of values for proposed six measures of complexity for manufacturing systems are presented in Appendix A.3. Calculation procedures for such measures are discussed using the characterization sets presented in equations (3.8 and 3.9) as well as equations (3.12 and 3.13).

3.5 Summary

In this chapter, different methods of analysis to quantitatively compare the manufacturing systems based on their information exchange structures identified through their graph theoretic models have been discussed. The following points may be summarized for this chapter.

- Coefficient of dissimilarity (both criterion-1 and criterion-2), which are established tools for graph theoretic model based structural analysis have been presented as tools for evaluation of complexity reduction due to restructuring in manufacturing systems.
- The physical interpretation of the above established tools i.e. coefficients of dissimilarity in n-dimensional Euclidian space of complexity has been used to define newer methods for this type of comparison such as index of complexity (Cartesian distance and Euclidian distance) as well as TOPSIS type index of complexity (Cartesian distance and Euclidian distance).
- The focus of newer methods is to provide a robust comparison of systems on the dimension of complexity. These methods can provide an insight into the possible outcome of structural changes in the manufacturing systems.
- For a restructuring exercise to reduce the complexity in a manufacturing system, the values of coefficients of dissimilarity of the new restructured configuration with respect to the original configuration may provide a measure of reduction in

complexity. On the other hand, the other four measures of complexity give direct measure of complexity.

In the oncoming chapters, the methods of analysis discussed have been applied to the different industrial cases.

Chapter IV

CASE OF LEAN MANUFACTURING IN A STEEL INDUSTRY

In this chapter, the methods of analysis presented in the previous chapter are applied to study the restructuring for lean manufacturing in a case of a steel industry. The inputs needed for this study have been taken from Abdulmalek and Rajgopal (2007). The graph theoretic models for the original and the future state map of the steel plant are developed. The methods of analysis have been validated by verifying the correlation of the values of new measures of complexity for the original and restructured manufacturing systems with the reduction in lead time.

4.1 Case Description

The case study on steel mill is used to illustrate the usefulness of proposed methods of analysis for lean manufacturing. The case organization under study produces several grades of steel. The focus of this study is on annealed products family. Some of the basic processes in the steel making industry are presented in Fig. 4.1.

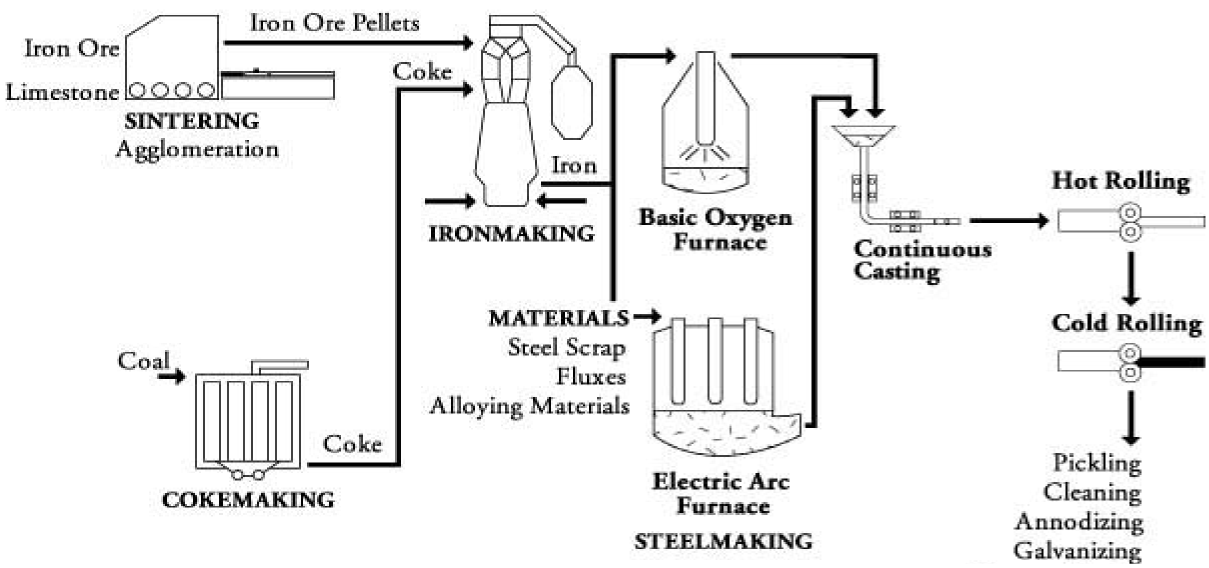


Fig. 4.1 Basic steel making process (www.sail.co.in)

The work flow and other processes in manufacturing an annealed product in an integrated steel plant are discussed in the following points:

- In this organization, the business planning department receives demands from two types of customers: repeat and spot business (open market).

    - The repeat demand is received on a weekly basis, where major customers call or send through Electronic Data Interchange (EDI), their requirements for the weeks ahead. Since these are committed customers the quantity and the order delivery time are more or less fixed.
    - On the other hand, spot customers generate daily schedules.
- The processes for the product family chosen for study start with a blast furnace where raw material including skips of iron ore, coke, and limestone are charged at the top of the furnace on a daily basis.
- The melted raw material is then poured into sub-ladles from the tap hole at the bottom of the furnace. The liquid iron is moved in the sub-ladle to the basic oxygen process (BOP) where scrap is added and oxygen is blown in to burn off excess carbon and obtain the initial form of liquid steel.
- Depending on the grade of the final steel to be produced this initial liquid steel can go either to a ladle metallurgical facility (LMF) or a Degasser to further refine and remove impurities from the liquid steel.
- The refined liquid steel then goes to a continuous caster where steel slabs are cast in accordance with specific customer widths.
- The hot slabs are then shipped on railroad and rack cars from the continuous caster process to the finishing mill facility for further refining processes, which include the hot strip mill (HSM), pickling, cold reduction (CR), open coil annealing (OCA), hydrogen batch annealing (HBA) or continuous annealing (CA), temper mill (TM), and finally, shipping.

Abdulmalek and Rajgopal (2007) used value stream mapping (VSM) to map the current operating state for the steel plant and proposed a future state map with lean tools applied to it. A value stream is a collection of all actions (value added as well as non-value-added) that are required to bring a product (or a group of products that use the same resources) through the main flows, starting with raw material and ending with the customer (Lasa et al., 2008). A simulation based study was also used to quantify the benefits gained from using lean tools and techniques. The explanation of the symbols used in the technique of value stream mapping is presented in Appendix A.4. The value stream map of the current state and the future lean state of the steel plant are described in the following subsections:

4.1.1 Current state map

Fig. 4.2 shows the value stream map (VSM) of the current state. The processes are connected by arrows in the map which represent how each workstation receives its schedule from business planning. It also depicts the data on material flow such as inventory levels, process cycle times (CTs), number of workers, and changeover (CO) times from the blast furnace process to the shipping department. The small boxes in the map represent the processes and the number inside the box is the number of workers at each process. A data box below each process contains the process cycle time (CT), machine reliability (MR), the number of shifts, and the changeover (CO) time. The data represents the processing and set-up times based on the average of historical data.

- There are currently two separate scheduling groups: one is for the hot end liquid steel, i.e. the processes from blast furnace to the caster, and the second is for the finishing mill, which handles the product from the HSM through shipping.
- When an order arrives, business planning enters it into the planning system, estimates the date by which it is expected to be completed, and rough-schedule orders on the production units on a weekly basis.
- Next, a routing is affixed on the order and a ‘‘plan week’’ is assigned to it. This schedule on the operating side becomes the basis to monitor day-by-day and week-by-week increments against how closely they are in accordance with the schedule.
- The schedules can then be updated further on an as-needed basis to daily or even bi-daily schedules.
- The timeline at the bottom of the current state map in Fig. 4.2 has two components:
    1. The first component is the production waiting time (in days), which is obtained by summing the lead-time numbers from each inventory triangle before each process. The time for one inventory triangle is calculated by dividing the inventory quantity by the daily customer requirements. The total observed value for the waiting time is around 46 days. Other than about three

days that are required for the coils to cool down after processing at the hot strip milling, the rest of this time is non-value added time.

2. The second element of the timeline is the processing (or value-added) time, which is about two days. This time is calculated by adding the processing time for each process in the value stream. Thus the total lead time is around 48 days. By considering three days required for the coils to cool down after processing at the HSM as the value adding time, a total of about five days (429,030 s) value-added time is obtained which works out to slightly over 10% of the total production lead time.

4.1.2 Future state map

As can be seen from that in the current state of the steel plant in Fig.4.2, the schedules for different processes are transmitted to individually. However, in this way, the processes may keep working on wrong priorities as they may tend to ignore immediate requirements from the next processing centers. The process of defining and describing the future state map starts while developing the current state map where target areas for improvement start to show up. The current state map for the steel plant shows the presence of large inventories, the high difference between the total production lead-time (around 51 days) and the value added time (5 days), and non synchronous processes (i.e. each process producing to its own schedule). In creating the ideal future state map, attempt is made to identify lean manufacturing tools to drive down large inventories as well as lead time. The future state map for the steel plant is shown in Fig. 4.3. The main features of the future state map are pointed as below.

- The supermarkets are placed between different processes after the HSM to cause a pull signal for the previous process.
- The organization now receives two schedules only; one at the continuous caster for the push system at the hot end and the other one at the TM for the pull system at the finishing end.
- With the new improvements at steel plant, the value added time (5 days) is up from approximately one-tenth of the production lead-time in the old system, to approximately one-third of the total production lead-time of slightly under 15 days (12.84 days in waiting plus about 2 days in processing).

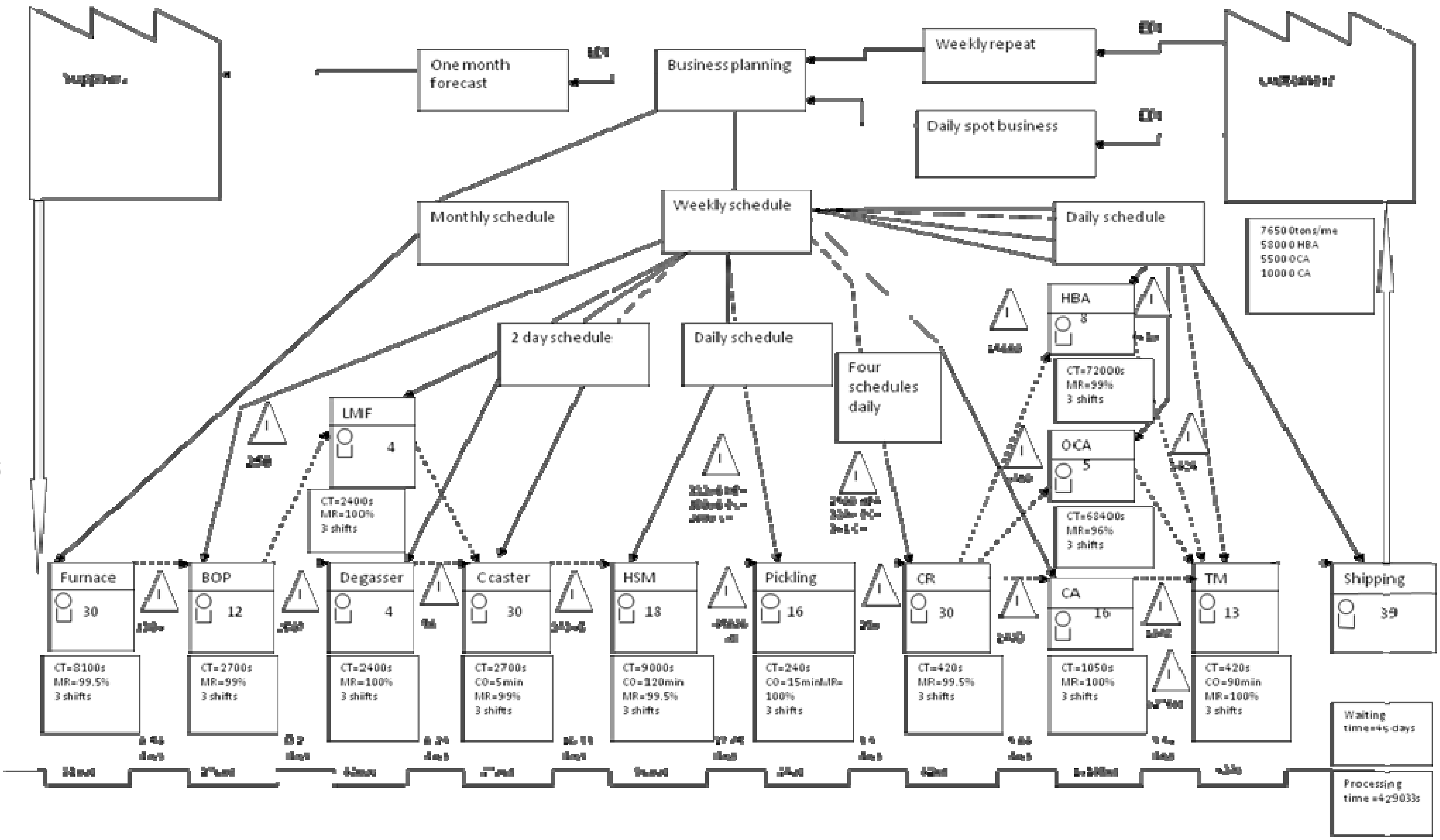


Fig. 4.2 Current state map of the steel plant under study using value stream mapping technique (Ref: Abdulmalek and Rajgopal, 2007)

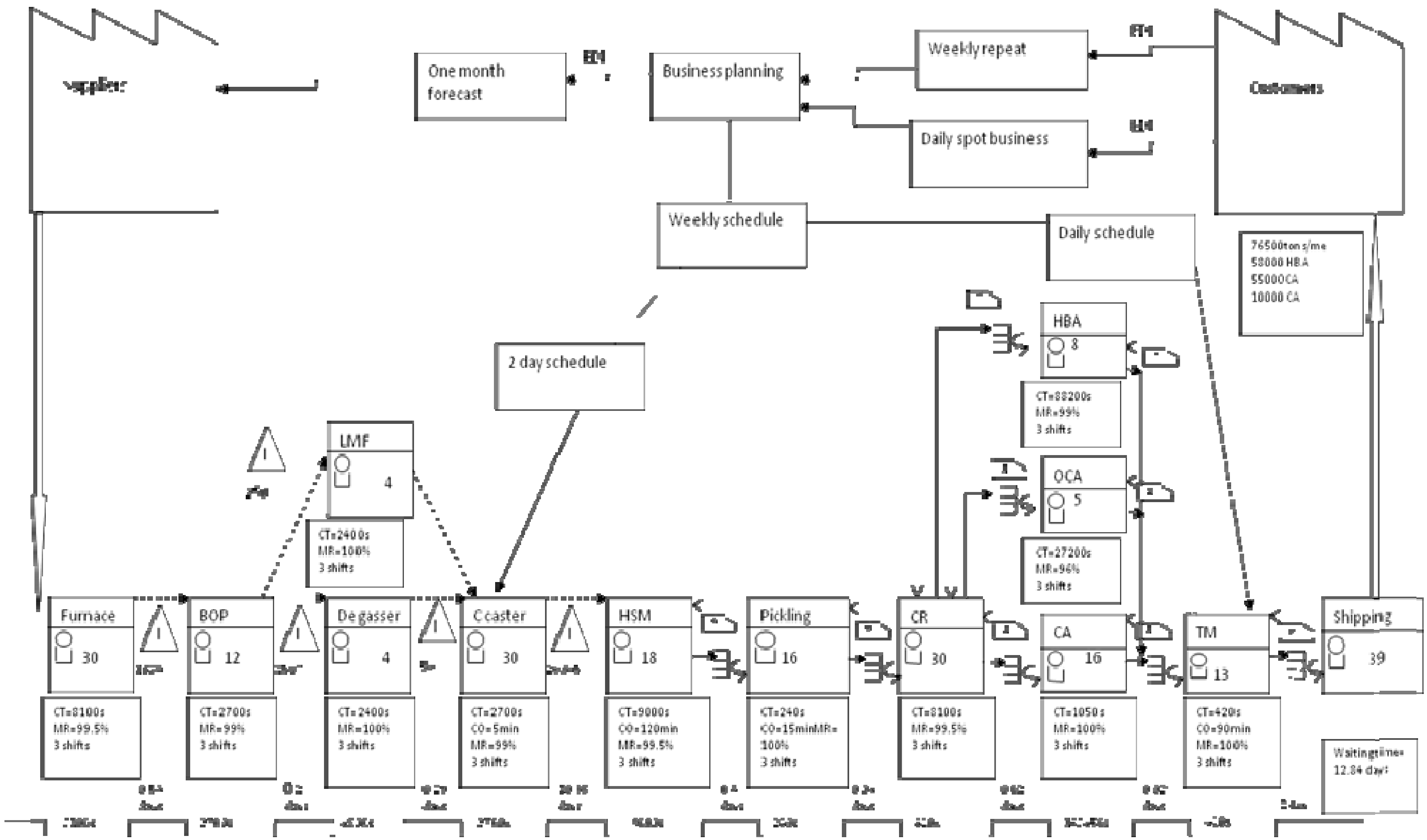


Fig. 4.3 Future state map of the steel plant under study using value stream mapping technique (Ref: Abdulmalek and Rajgopal, 2007)

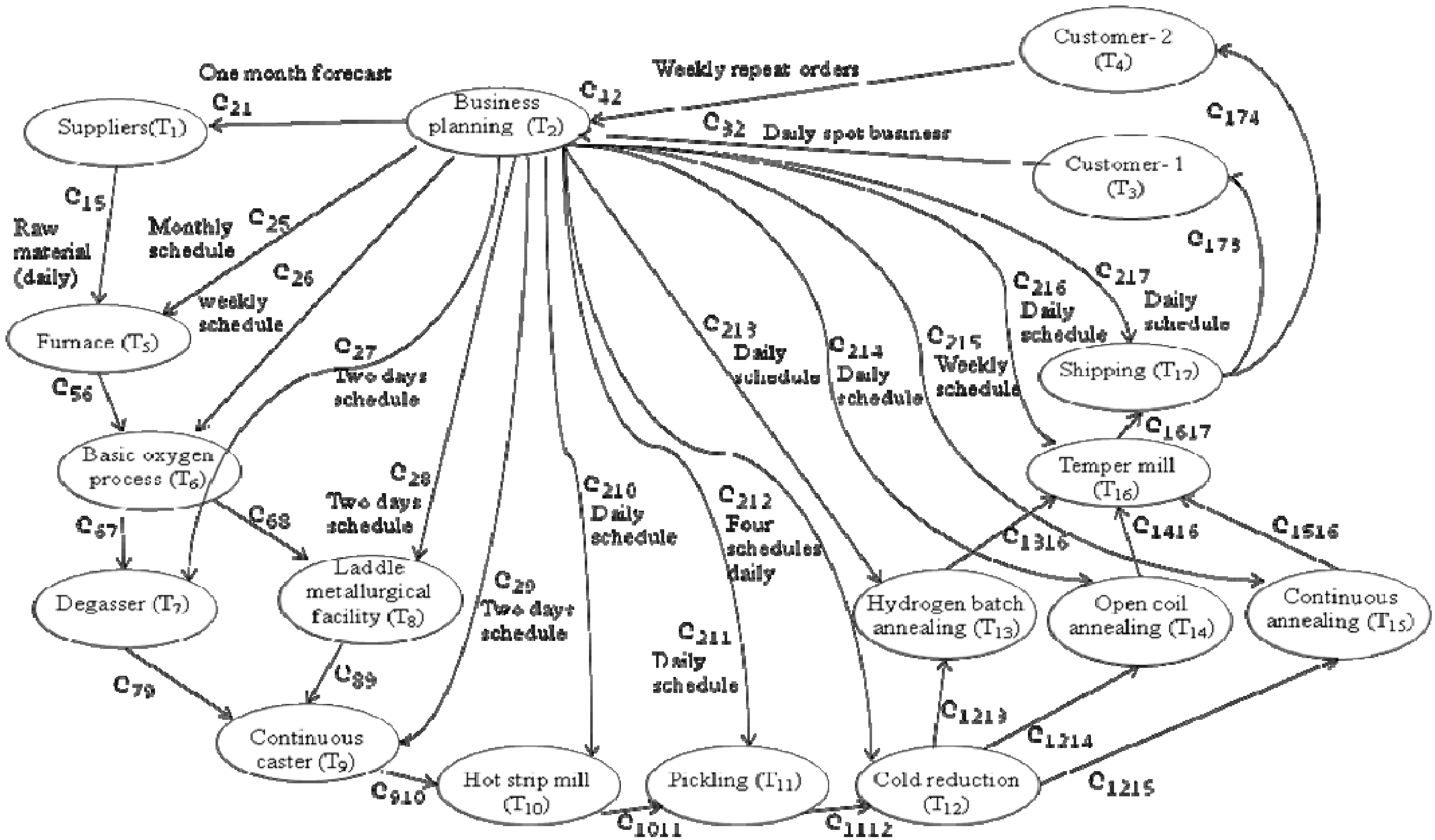


Fig. 4.4 The graph of steel plant in the current state

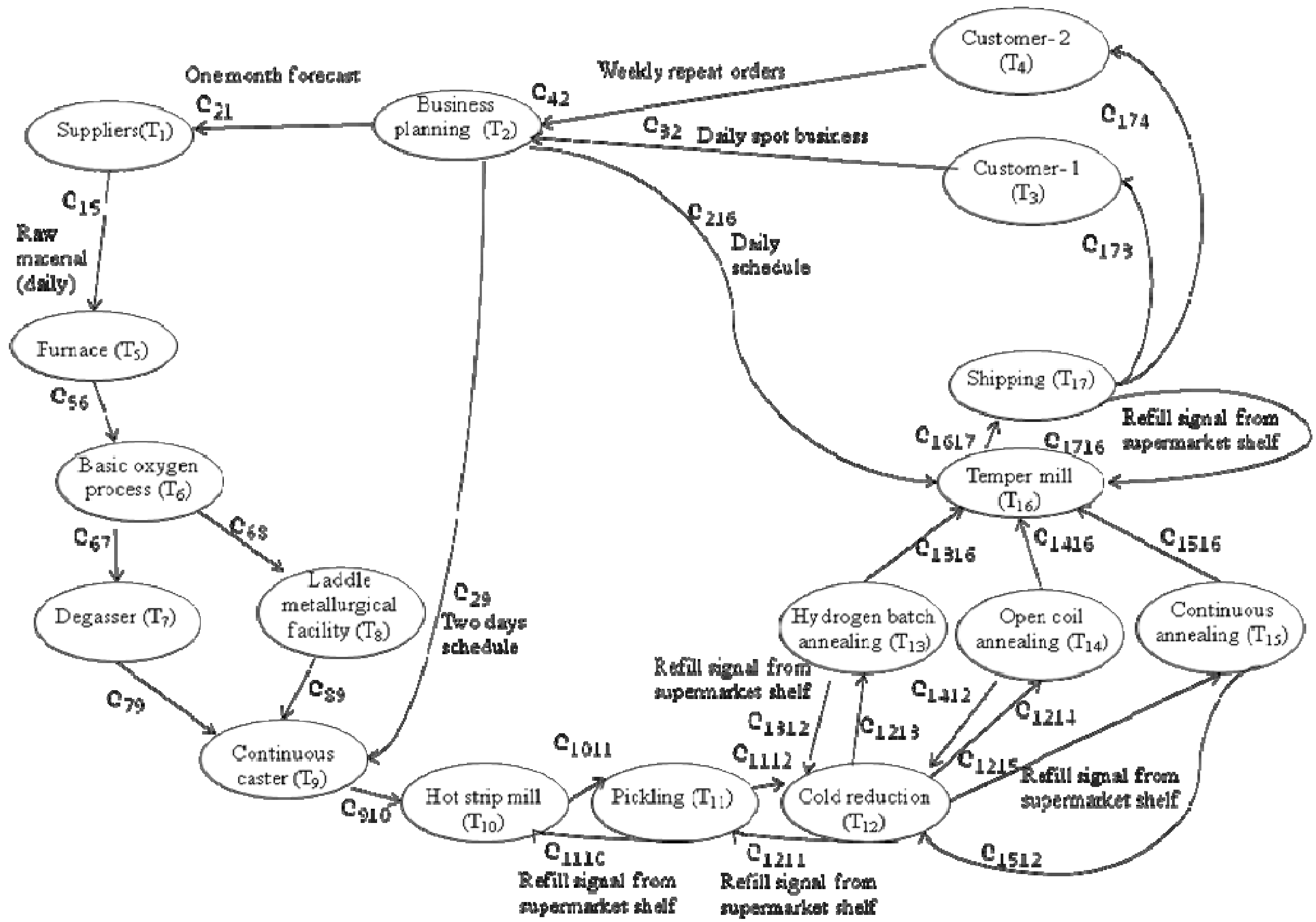


Fig. 4.5 The graph of steel plant in the desired future state (restructured configuration)

Table 4.1 Description of subsystems in the steel plant

Subsystem	Description
T_1 Supplier Subsystem	Suppliers provide different raw materials for steel making such as lime stone, iron ore, coke as per the requirements generated by the business planning unit.
T_2 Business planning subsystem	It receives demands from two types of customers: repeat and spot business (open market) and communicates the schedules/plans to meet such requirements.
T_3 Customer-1 Subsystem	These are committed customers the quantity and the order delivery time are more or less fixed.
T_4 Customer-2 Subsystem	It refers to the spot customers that generate daily schedules.
T_5 Furnace Subsystem	It is the blast furnace where raw material including skips of iron ore, coke, and limestone are charged at the top of the furnace on a daily basis.
T_6 Basic oxygen process (BOP) Subsystem	It is the process where the scrap is added and oxygen is blown in to burn off excess carbon and obtain the initial form of liquid steel.
T_7 Degasser Subsystem	Degasser is used to refine and remove impurities from the liquid steel depending on the grade of steel to be produced.
T_8 Ladle metallurgical facility (LMF) subsystem	Liquid steel can go either to a ladle metallurgical facility (LMF)
T_9 Continuous caster Subsystem	The refined liquid steel then goes to a continuous caster where steel slabs are cast in accordance with specific customer widths.
T_{10} Hot strip mill (HSM) Subsystem	The specific thickness of the strip is regulated at this process as per customer requirement.
T_{11} Pickling Subsystem	This process removes the scales formed on the metal surfaces due to hot working. All the steel is required to undergo this process
T_{12} Cold reduction (CR) Subsystem	This process is carried out to improve the material properties and to give required diameter to the rolling stock. Another feature of this process is that it imparts directional properties to the steel. All steel manufactured undergoes this process.
T_{13} Hydrogen batch annealing (HBA) Subsystem	It is a type of heat treatment used to impart softness to the steel and process is carried out in batches. Some of the types of steel need this process to be carried out.
T_{14} Open coil annealing (OCA) subsystem	It is another type of heat treatment used to impart softness to the steel. Some types of steel products are required to undergo this type of annealing.
T_{15} Continuous annealing Subsystem	It is also another type of heat treatment used to impart softness to the steel. Some other types of steel products are required to undergo this type of annealing.
T_{16} Temper mill Subsystem	Tempering is another heat treatment process that improves the toughness strength of the steel.
T_{17} Shipping Subsystem	The steel stock produced is shipped to the customers in this department.

4.2 Graph theoretic modeling of the steel plant

The graph theoretic methodology can be used to model the current and the future states of the steel plant discussed in the previous section. It can be seen in the current state of the steel plant in Fig.4.2 that the centralized schedules for different processes are transmitted individually whereas in the proposed future state as in Fig. 4.3, the schedules are transmitted only to two of the processes. In the future state, for the processes in the hot end, the push signal is used for schedule while for the cold end the pull signal from the supermarket is used for schedule. The pull signal helps in avoiding the need for centralized planed schedule to be communicated to individual process/subsystems. This in turn helps the plant to do away with some of the cycles of interactions that are needed in the current state, for meeting frequent changes in scheduling as per immediate requirements from customer processes. E.g., in the current state as in Fig. 4.2 and Fig. 4.4, the cycles (e_{212} e_{1213} $e_{1316}e_{1617}e_{174}e_{42}$), ($e_{212}$ e_{1214} $e_{1416}e_{1617}e_{174}e_{42}$) and ($e_{212}$ e_{1215} $e_{1516}e_{1617}e_{174}e_{42}$) get into operation whenever, there is a schedule transmitted from business planning subsystem (T_2) to the cold reduction process (T_{12}). On the other hand, in the future state as shown in Fig. 4.3 and Fig. 4.5, it may be gauged that the use of supermarkets in between the processes after hot strip mill (T_{11}) help to remove this link (e_{212}) which will totally remove the above three interaction cycles. Thus, some simplification in the operation of the steel plant is achieved. In the future state, several other interactions are also removed. The future state also has removal of many other such linkages and along with them several of the interaction cycles. The graph theoretic modeling can help in the systematic identification and thus comparison of all such cycles of scheduling related interactions among the processes/subsystems of the steel plant in the current and the proposed future state. The resulting characterization information in terms of the count of cycles of interactions under different groups/subgroups can be used to estimate the resulting simplification in the steel plant in the future state map. Thus, graph theoretic modeling can help in analyzing the effect of restructuring the steel plant for realization of lean principles and the main steps for the same are presented below.

- The first step in this direction is to transform the VSM maps as shown in Fig. 4.2 and Fig. 4.3 for the current and the desired future states into graph form. For this purpose, the processes and departments in the steel plant are represented as subsystems (represented by variables T_1 to T_{17}) and are discussed in Table 4.1. The graph form for the current state map in Fig.4.2 is shown in Fig. 4.4 while that for the future state map in Fig.4.3 is shown in Fig. 4.5. All the processes shown in the VSM maps for the steel plant are as subsystems depicted nodes while the interactions among subsystems are modeled by linkages.

- The next step for graph theoretic modeling of the two states of the steel plant is to develop the permanent matrices for the current as well as the future state maps of the steel plant. The permanent matrices for the current state and the desired future state (restructured configuration) of the steel plant are presented in equations (4.1 and 4.2) where the diagonal elements show the subsystem variables (T_1 to T_{17}) while the off-diagonal elements show the interactions (e_{ij}) among various subsystems.
- After this, the permanent function operation on permanent matrices *(A and $A^{'}$)* in equations (4.1 and 4.2) for current and future states of steel plant are carried out and the resulting permanent multinomial are appended in equations (A.5.1 and A.5.2) in Appendix A.5.
- The terms in the permanent multinomial are represented as sub-graphs where isolated subsystems correspond to subsystems variables in the terms of the multinomial while the shaded subsystems interacting in the form of interaction cycles correspond to various interaction variables. Based on the pattern of interaction cycles, the terms of the multinomial can be clubbed into different groups and subgroups. One of the representative sub-graphs from each group or subgroup in the graph theoretic models for the current and the desired future states of the steel plant are drawn in Fig. 4.6 and Fig. 4.7 respectively.
- The sub-graphs in the graph theoretic model correspond to the real sub-sets of the steel plant and represent the combinations of subsystems interacting in the form of various cycles as shown in Fig. 4.6 and Fig. 4.7.

$$A=\begin{bmatrix}
T_1 & 0 & 0 & 0 & e_{15} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
e_{21} & T_2 & 0 & 0 & e_{25} & e_{26} & e_{27} & e_{28} & e_{29} & e_{210} & e_{211} & e_{212} & e_{213} & e_{214} & e_{215} & e_{216} & e_{217} \\
0 & e_{32} & T_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & e_{42} & 0 & T_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & T_5 & e_{56} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & T_6 & e_{67} & e_{68} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & T_7 & 0 & e_{79} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & T_8 & e_{89} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_9 & e_{910} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{10} & e_{1011} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{11} & e_{1112} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{12} & e_{1213} & e_{1214} & e_{1215} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{13} & 0 & 0 & e_{1316} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{14} & 0 & e_{1416} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{15} & e_{1516} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{16} & e_{1617} \\
0 & 0 & e_{173} & e_{174} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{17}
\end{bmatrix}$$

(4.1)

$$A^{'}=\begin{bmatrix}
T_1 & 0 & 0 & 0 & e_{15} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
e_{21} & T_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & e_{216} & e_{217} \\
0 & e_{32} & T_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & e_{42} & 0 & T_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & T_5 & e_{56} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & T_6 & e_{67} & e_{68} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & T_7 & 0 & e_{79} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & T_8 & e_{89} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_9 & e_{910} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{10} & e_{1011} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & e_{1110} & T_{11} & e_{1112} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & e_{1211} & T_{12} & e_{1213} & e_{1214} & e_{1215} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & e_{1312} & T_{13} & 0 & 0 & e_{1316} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & e_{1412} & 0 & T_{14} & 0 & e_{1416} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & e_{1512} & 0 & 0 & T_{15} & e_{1516} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{16} & e_{1617} \\
0 & 0 & e_{173} & e_{174} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & e_{1716} & T_{17}
\end{bmatrix}$$

(4.2)

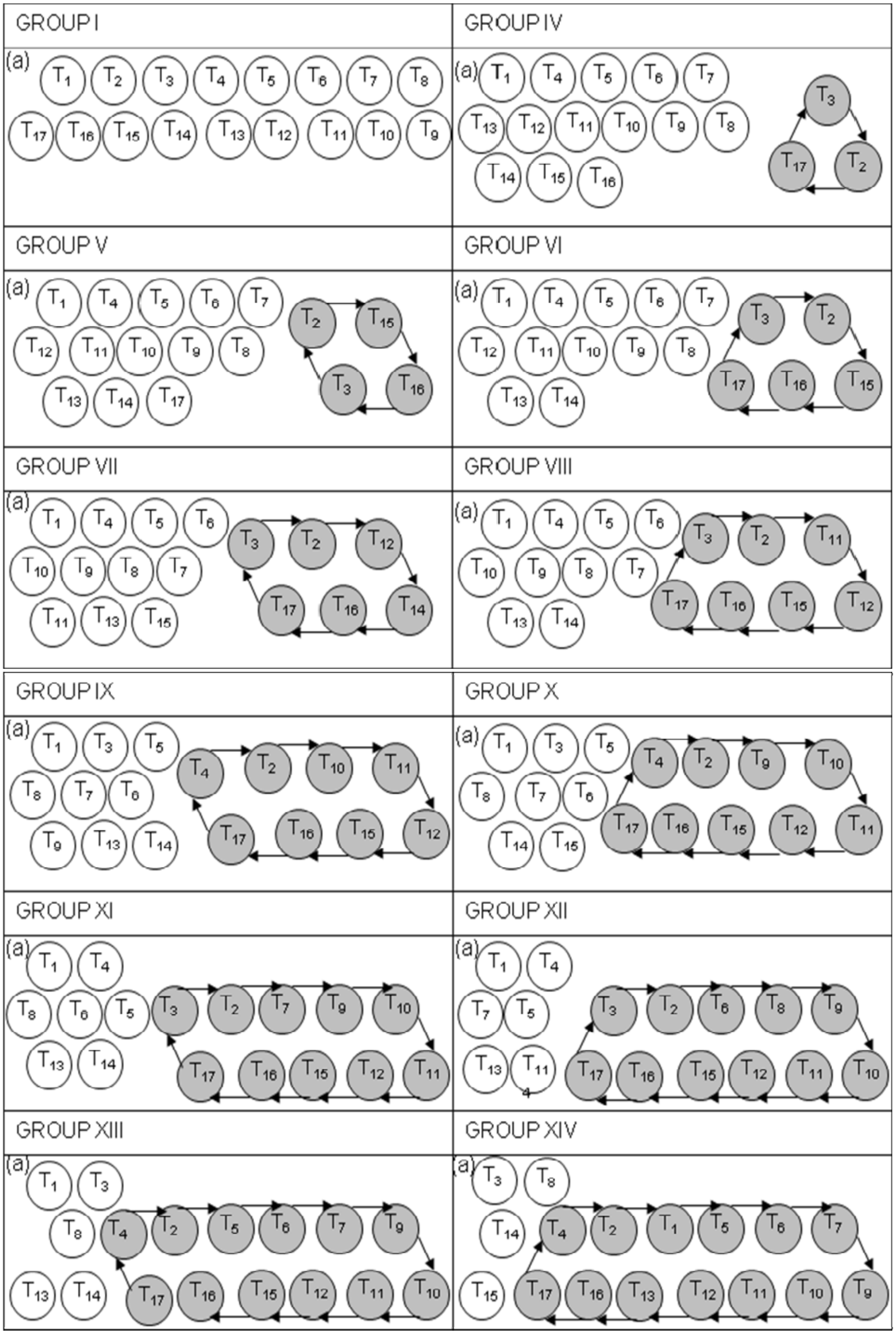


Fig. 4.6 Representative sub-graphs in the current state of steel plant

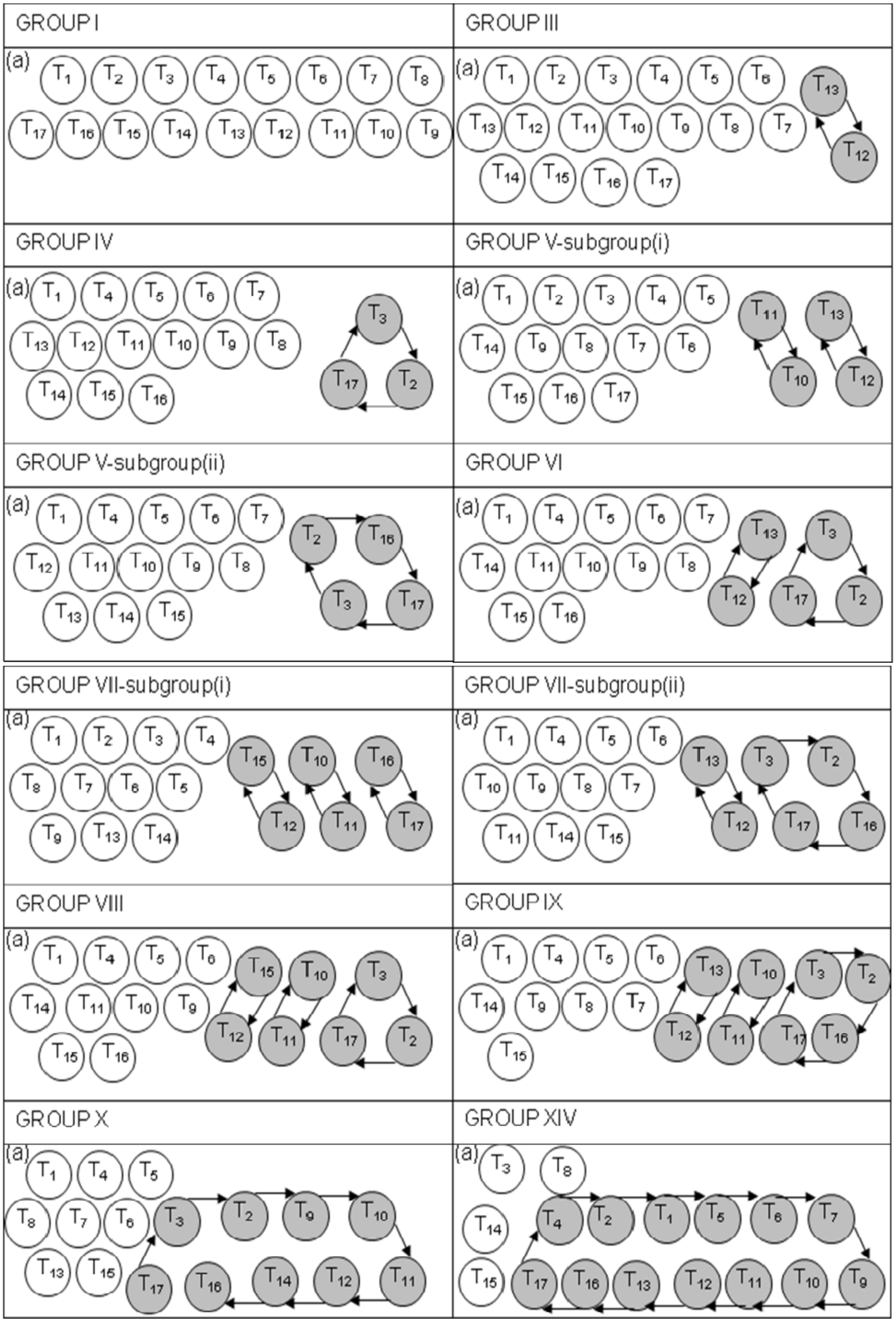
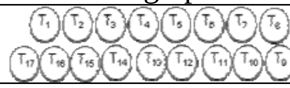
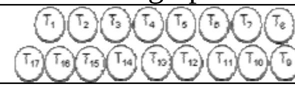
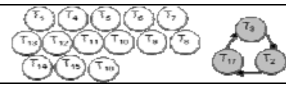
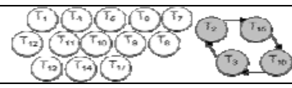
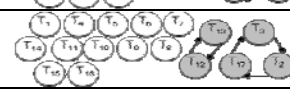
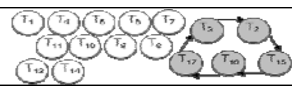
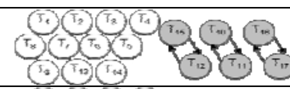
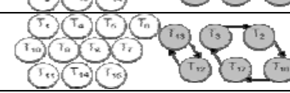
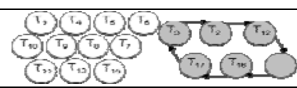
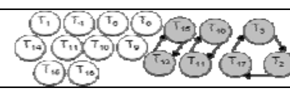
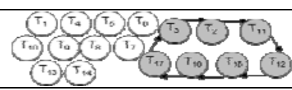
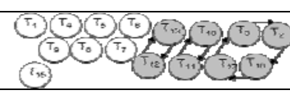
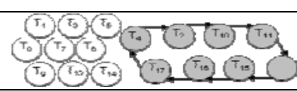
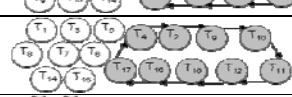
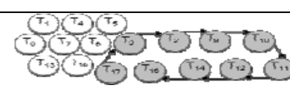
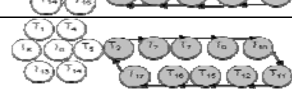
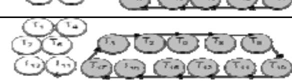
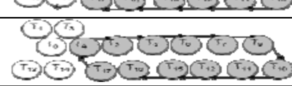
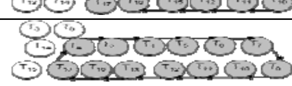
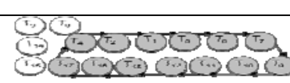


Fig. 4.7 Representative sub-graphs in the future state of steel plant (restructured config.)

Table 4.2 Count of sub-graphs under various groups and subgroups for the graph theoretic models of steel plant in the current and future states

Group/subgroup	Current state		Future state	
	Representative sub-graph	Number of sub-graphs	Representative sub-graph	Number of sub-graphs
Group I		1		1
Group II	Absent	0	Absent	0
Group III	Absent	0		6
Group IV		2		2
Group V-subgroup (i)	Absent	0		8
Group V-subgroup (ii)		2		2
Group VI-subgroup (i)	Absent	0		10
Group VI-subgroup (ii)		6	Absent	0
Group VII-subgroup (i)	Absent	0		2
Group VII-subgroup (ii)	Absent	0		10
Group VII-subgroup (iii)		6	Absent	0
Group VIII-subgroup (i)	Absent	0		7
Group VIII-subgroup (ii)		6	Absent	0
Group IX-subgroup (i)	Absent	0		6
Group IX-subgroup (ii)		6	Absent	0
Group X		6		6
Group XI		12	Absent	0
Group XII		12	Absent	0
Group XIII		12	Absent	0
Group XIV		12		12
Total		83		72

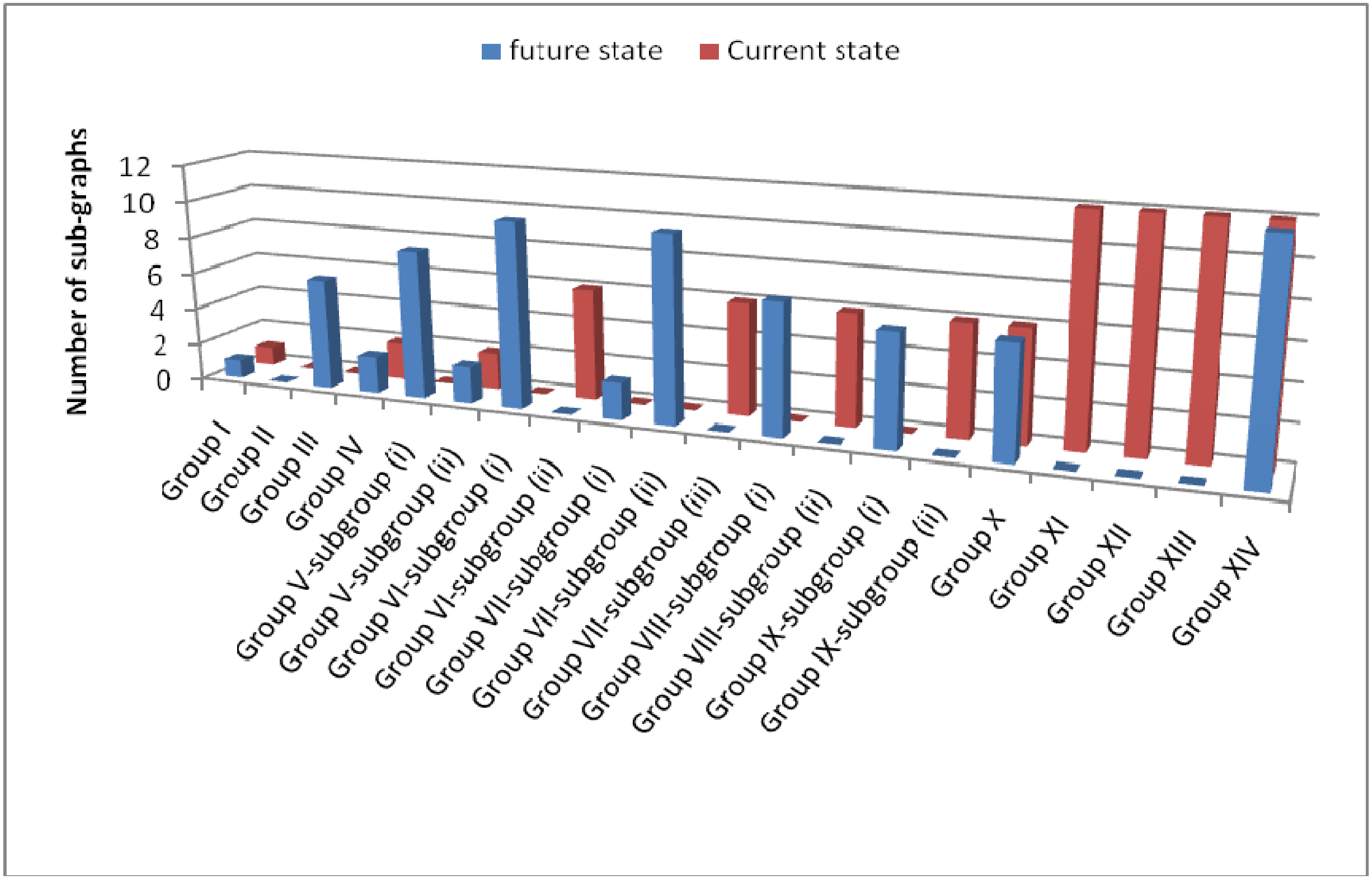


Fig. 4.8 Graphical representation of the count of sub-graphs in the current and future states of steel plant

4.3 Analysis of results

The terms in the permanent multinomial for matrices *A* and A' correspond to the real sub-sets of the steel plant and represent the combinations of subsystems interacting in the form of various cycles as shown in Fig. 4.6 and Fig. 4.7. As discussed earlier, the patterns of interaction cycles have been used to club the terms of the permanent multinomial into various groups and subgroups. The number of such terms under each distinct group and subgroup in the graph theoretic models of the current and future states of the steel plant are summarized in Table 4.2. The summary of the data recorded in Table 4.2 is presented in Fig.4.8 where the reduction in sub-graphs for the future state of steel plant in comparison to the current state can be visualized. It may be inferred from Fig. 4.8 that the sub-graphs involving bigger interaction cycles are eliminated in the future state while some new sub-graphs in the initial groups crop up in the future state. So, to have a clear insight into the complexity reduction for the future state map of the steel plant, the data from Table 4.2 can be used in equations (3.6 & 3.7, 3.10 & 3.11 and 3.16 & 3.17) to evaluate different measures of complexity, as presented in the previous chapter. The calculated values of various such measures are recorded in the Table 4.3 below.

Table 4.3 Values of different complexity measures for current and future states and the reduction in complexity

Complexity measure	Current state of steel plant	Future state of steel plant	Percent complexity reduction
TOPSIS type index of complexity (Euclidian distance)	0.5424	0.4492	9.32
TOPSIS type index of complexity (Cartesian distance)	0.5357	0.4375	9.82
Index of complexity (Euclidian distance)	1	0.8692	13.08
Index of complexity (Cartesian distance)	1	0.8675	13.25
Coefficient of dissimilarity criterion-2	0	1.1231	NA
Coefficient of dissimilarity criterion-1	0	0.1325	13.25

The following salient points may be observed from Table 4.3.

- The first four measures in Table 4.3 directly indicate the complexity of interactions within the steel plant. So, for estimating the level of complexity reduction due to lean initiative, the complexity measure values for the future state of the steel plant are subtracted from the complexity measure values for the original state. On the other hand, the value of coefficient of dissimilarity with respect to the original state, measure the reduction in complexity with respect to the original state. So, the reduction in complexity is directly measured by its value.
- The reduction in complexity due to restructuring of the steel plant for lean manufacturing has been indicated by the values of most of complexity measures except coefficient of dissimilarity by criterion-2. The level of complexity reduction indicated by most measures is marginal.
- The coefficient of dissimilarity (criterion-2) fails to measure the reduction in complexity for future state of steel plant. The reason for this failure has been explored and is explained by using a simplified example for better physical interpretation of the coefficient of dissimilarity (criterion-2). For this purpose, definition of the coefficient of dissimilarity (criterion-2) is again recalled which basically gives a ratio of the Euclidian distance between two systems under comparison to the Euclidian distance of the farther system from the origin in a multi-dimensional Euclidian space characterized by the groups and subgroups of the graph theoretic model. Fig. 4.9 shows the example of two systems on a two dimensional space where for the value of coefficient of dissimilarity (criterion-2) (i.e. ratio x/y) will be greater than unity.

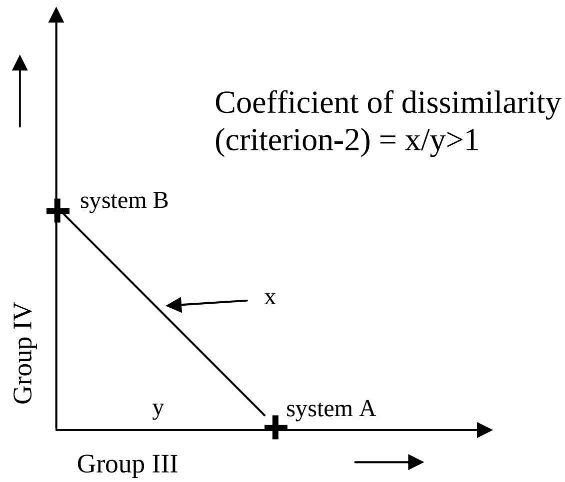


Fig. 4.9 Representative position of two systems on a set of two-dimensions (group III and group IV of graph theoretic model) for coefficient of dissimilarity greater than unity

The value of greater than unity for coefficient of dissimilarity (criterion-2) is also contrary to the claims in literature where its value is subtracted from unity to define another measure known as coefficient of similarity (Venkatasamy and Agrawal, 1995). This also strengthens the justification for usefulness of new methods of analysis.

The changes in the real performance indicators such as production lead time, work in process inventory and proportion of value addition to total production lead time for the current and future states of the steel plant as reported by Abdulmalek and Rajgopal (2007) along with the two computed measures of complexity are presented in Table 4.4 below.

Table 4.4 Values of lean performance measures for the current and future states of steel plant

Lean performance indicator	Current state	Future state
TOPSIS type index of complexity (Euclidian distance)	0.5424	0.4492
TOPSIS type index of complexity (Cartesian distance)	0.5357	0.4375
Total production lead time	48 days	15 days
Work in process inventory between pickling and temper mill	96 coils	10 coils
Proportion of value added to total production lead time	0.1	0.33

It may be observed that the values of the real performance indicators for the current and future states of the steel plant in Table 4.4 point to the real reduction in complexity in the operating procedures in the steel plant. The production lead time has reduced considerably (around 68%) while the work in process inventory has also reduced by a huge proportion (around 89 %). Though, the corresponding computed measures of complexity have not shown a proportionally large reduction in complexity, but still can be considered to be correlating with the overall trend. Since the study involved only two states, the numerical value of standard correlation coefficient (Russel and Taylor III, 2006) is indicating complete correlation between most of the computed complexity measures in the study and the corresponding real performance indicators when just the trend is matching. However, investigation of correlation between any two quantities has inherent limitations when only two states are under investigation and at least investigations on three states are recommended for such studies. Thus, the present study of correlation validates the measures of complexity in a limited manner. More such studies investigating greater number of states of manufacturing systems are recommended to completely realize the potential of the measures developed in the study as well as to validate such measures overcoming the present limitations.

4.4 Summary

The key points that may be summarized from this chapter are presented below.

- In this chapter, the graph theoretic modeling and the complexity measures have been used for evaluation of lean philosophy implementation in a steel plant. The changes in the organization structure in terms of rearrangement of interactions have been modeled.
- The values of complexity measures calculated for the current and future states of the steel plant showed a good correlation with the real performance measures such as total production lead time as well as work in process inventory.
- A new finding has been the limitation of the coefficient of dissimilarity (criterion-2) whose value turns out to be greater than unity in the present case in contrast to discussions in literature. This makes it unsuitable as measure of reduction in complexity due to restructuring in manufacturing systems while the usefulness of

other measures stands strengthened and validated by observing the correlations with real performance indicators.

To discuss the usefulness of the proposed methodology for guiding the restructuring in diverse industries and to meaningfully validate the methodology, few more industrial cases have been discussed in the upcoming chapters.

Chapter V

RESTRUCTURING PLAN FOR A PACKAGING EQUIPMENT INDUSTRY

In this chapter, cases in a packaging equipment manufacturing industry have been reported where different lean manufacturing efforts have been implemented. The set of restructuring cases taken in this industry are listed as:

- Case I- Restructuring of internal material flow from store using kitting system (discussed in this chapter)
- Case II- Restructuring of external material flow with suppliers using Quality-at-Source (discussed in chapter VI)
- Case III- Combined analysis of case I and case II of restructuring (discussed in chapter VII)

The case I of the restructuring efforts in the packaging equipment industry has been discussed in detail in the present chapter. First, the major product lines and the work flow in the industrial unit under study are discussed. Next, the work flow in the original configuration of the case manufacturing system is converted in the form of a schematic diagram and subsequently the graph theoretic model is developed. The structure of interaction cycles in the original configuration of the industrial set-up, are identified. The restructuring effort aims at simplifying the structure of the manufacturing system using the quality at source concept in the internal material flow. It has been represented by a restructured configuration where it is depicted by removal of appropriate interaction links in the original manufacturing system. Then, the graph theoretic model is developed for the restructured manufacturing system for identification of the simplifications in the interaction structure. The improvements evident through the results of graph theoretic model and subsequently from complexity measure value are discussed.

5.1 Description of organization

The industrial unit considered for study is one of the leading producers of sophisticated packaging technology equipments for industrial customers. The equipments produced are popular in fast moving consumer goods (FMCG) industries for their product packaging activities such as candy wrapping, solid food and biscuit packaging as well as packing vials, ampoules and syringes for the pharmaceutical industry. The company offers modularly structured products to fulfill customer's requirements effectively. The range of equipments offered is broadly classified into the categories such as Vertical Form Fill Seal Machines (VFFS), Horizontal Form Fill Seal Machines (HFFS) and Pharmaceutical Machines. The brief descriptions of each category as well as the lists of specific machines produced under each category are provided below.

5.1.1 Vertical Form Fill Seal Machines

These are the machines wherein the product is fed from the top through a forming tube by a dozing system and the sealing of the film is carried out in vertical plane and some of such equipments are shown in Fig. 5.1.

Fig. 5.1 Views of the Vertical-Form-Fill-Seal (VFFS) type packaging equipment

5.1.2 Horizontal Form Fill Seal machines

These are the machines where-in the sealing of the product film is carried out in horizontal plane with the product entering the seal also in horizontal plane and one such equipment is shown in Fig. 5.2. This machine is useful for wrapping soft bakery items, chocolate bars, biscuits, and non-food items. These machines are provided with options of tightness control as well as air evacuation among other options.

Fig. 5.2 View of the Horizontal-Form-Fill-Seal (HFFS) type packaging equipment

5.1.3 Pharmaceutical Machines

The pharmaceutical-packaging-machines manufactured in the plant have two functions; one for sterilizing the vials for filling and the other drying the bottles and filling the product in the vial. The packaging solutions for items like ampoules and injection bottles, injection and infusion bottles, screw neck bottles, cartridges, ready-to-use syringes and needle-free injections are offered. Typical equipment on offer is shown in Fig. 5.3.

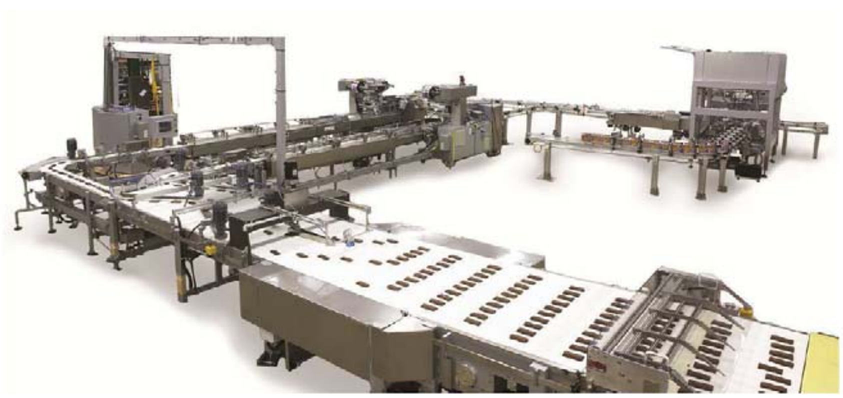


Fig. 5.3 Complete line for collection, washing, sterilization, filling and packing of pharmaceutical ampoules

5.1.4 Modules offered as options

The company provides a range of final product choices through different modular parts (also named as format parts) such as dozing systems, platforms, film printers, rejection systems etc. Different technologies are provided to meet special requirements for protecting the food items and two of the solutions are Nutrafill and Aroma Protection valves. Neutrafill is for packaging oxygen-sensitive products by filling the space with nitrogen. The line is sealed from feed point of the filled product resulting in residual oxygen values of less than one percent. Aroma protection valve is used for economic packaging of degassing products such as coffee. The company offers different filling systems as shown in Fig. 5.4. like Cup doser, Auger doser, Linear Weigher, Multihead Weigher etc. Cup Doser is used for volumetric filling of free flowing products, the Auger Doser is used for precise and accurate dosing. The Linear Weigher is preferred for gentle handling and accurate dosing of food products. The Multihead Weigher is for fast, precise and maximum weight accuracy.

Fig. 5.4 Different dozing systems on offer

5.2 Work flow in the original configuration

In this section, the work flow in the organization in the original form is explained below:

- Customer triggers the production at the case manufacturing system by specifying the requirements for the desired machine.
- The sales department takes lead in planning process and communicates the target timelines to the design department, purchase department and PPC department.
- The design department devises the designs and the bill of materials for the required components and communicates them to the purchase and PPC departments for purchase of raw material and also their subsequent manufacture and assembly.
- The purchase department communicates the net requirements in the form of purchase orders to mainly three vendors for this equipment, after evaluating the current status of inventory available at store for different raw materials/parts/components.
- The vendors send in the raw materials/parts to the plant where it is subjected to purchase quality inspection. The poor quality or non conforming material (if any)

is returned back to the vendor and the vendor is rated by the purchase department based on delivery performance for penalty or reward. The material found appropriate is transferred to the store.

- The store sends the raw material/components/parts to the appropriate locations/work stations in the manufacturing in the form of racks as per plan received from PPC.
- Any shortage in material at the manufacturing department is reported through a notice board to the store and the store in turn takes action to fill up the deficient material.
- The self certification capability is developed in consumable vendor so that the quality is built at source and the incoming material can be directly supplied to the consumable supermarket store without subjecting the incoming material to quality inspection. The level of consumables can be easily gauged through a color coding scheme by the store which further triggers the purchase process when the level of consumables reaches a predetermined low level.
- The assembly of the machine is carried out at in the manufacturing section and after that it is subjected to quality inspection where it is tested on meeting various parameters such as specified speed requirement, safety requirement, loose parts/operator safety, sealing defects and variation of packaged weight. If there is any defective function, the machine is sent back to the manufacturing and after corrective action and positive quality inspection report, it is transferred to the logistics department for packaging and dispatch to the customer.

5.3 Graph theoretic modeling of original configuration

The graph theoretic modeling can help in understanding the workflow discussed in the previous section in a greater way. For this purpose, the workflow in the industrial organization under study in the original configuration is condition is represented in a schematic form as in Fig. 5.5. The departments/entities in the organization are represented as nodes in the schematic diagram while the interactions among the departments are represented by edges among nodes.

Table 5.1 Description of subsystems in the Packaging equipment industry

Subsystem	Description
S_1 Customer Subsystem	Since the company produces customized solutions for different packaging requirements, the interactions with customer are an important component.
S_2 Sales and marketing subsystem	This subsystem receives orders and plans the schedule in interaction with the customer as well as the design and purchase and PPC subsystems.
S_3 Design Subsystem	The design department devises the designs and the bill of materials for the required components and communicates them to the purchase and PPC departments for purchase of raw material and also their subsequent manufacture and assembly
S_4 Purchase Subsystem	This department is responsible for raw materials (mainly components for final assembly) as per requirement of customer orders and for their timely delivery at the plant premises.
S_5,S_6, S_7 Vendor Subsystems	Vendor is the external entity who supplies the component parts as per order. For the particular machine being studied, there are three vendors for different types of components.
S_8 Purchase quality subsystem	This subsystem verifies that the incoming components are of right quality and as per requirements specified.
S_9 PPC Subsystem	This subsystem schedules the assembly activities in the plant so as to meet the delivery deadlines.
S_{10} Store Subsystem	The store subsystem receives the incoming material from the vendors and supplies to the manufacturing subsystems as per requirements of the master schedule specified by PPC.
S_{11} Consumable vendor Subsystem	The general consumable items which are required for all types of machines are regulated by the supermarket concept and are sourced through self certified vendors, whose products reach the manufacturing subsystem without any requirement for purchase quality inspection.
S_{12} Manufacturing Subsystem	This is the department where actual assemblies of machines take place.
S_{13} Quality control Subsystem	This department is responsible for maintaining the required specifications for the outgoing machines which have been completed at the manufacturing subsystem.
S_{14} Logistics subsystem	The logistics subsystem is responsible for safe and timely delivery of the machines to the customer premises.

The next step in developing the graph theoretic model for the industrial organization is to write a permanent matrix for the schematic diagram in Fig. 5.5 as in equation (5.1) where each department is represented as a subsystem. The subsystem variables (S_i's) corresponding to each subsystem are placed on the diagonal of the permanent matrix while the interaction variables (e_{ij}'s) represent different interactions among subsystems and placed at appropriate off-diagonal positions.

$$P = \begin{bmatrix} S_1 & e_{12} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & S_2 & e_{23} & e_{24} & 0 & 0 & 0 & 0 & e_{29} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & S_3 & e_{34} & 0 & 0 & 0 & 0 & e_{39} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & S_4 & e_{45} & e_{46} & e_{47} & 0 & 0 & 0 & e_{411} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & S_5 & 0 & 0 & e_{58} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & S_6 & 0 & e_{68} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & S_7 & e_{78} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & e_{85} & e_{86} & e_{87} & S_8 & 0 & e_{810} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_9 & e_{910} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & e_{104} & 0 & 0 & 0 & 0 & 0 & S_{10} & 0 & e_{1012} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & e_{1110} & S_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & e_{1210} & 0 & S_{12} & e_{1213} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & e_{1312} & S_{13} & e_{1314} \\ e_{141} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{14} \end{bmatrix} \tag{5.1}$$

The next step is to carry out the permanent function operation on matrix *P* and the resulting permanent multinomial is given in Appendix A.5. The permanent multinomial for matrix *P* forms the basis for graph theoretic model for the manufacturing system and gives all possible sub-graphs having interaction cycles among subsystems as shown from Fig. 5.6 to Fig. 5.8.

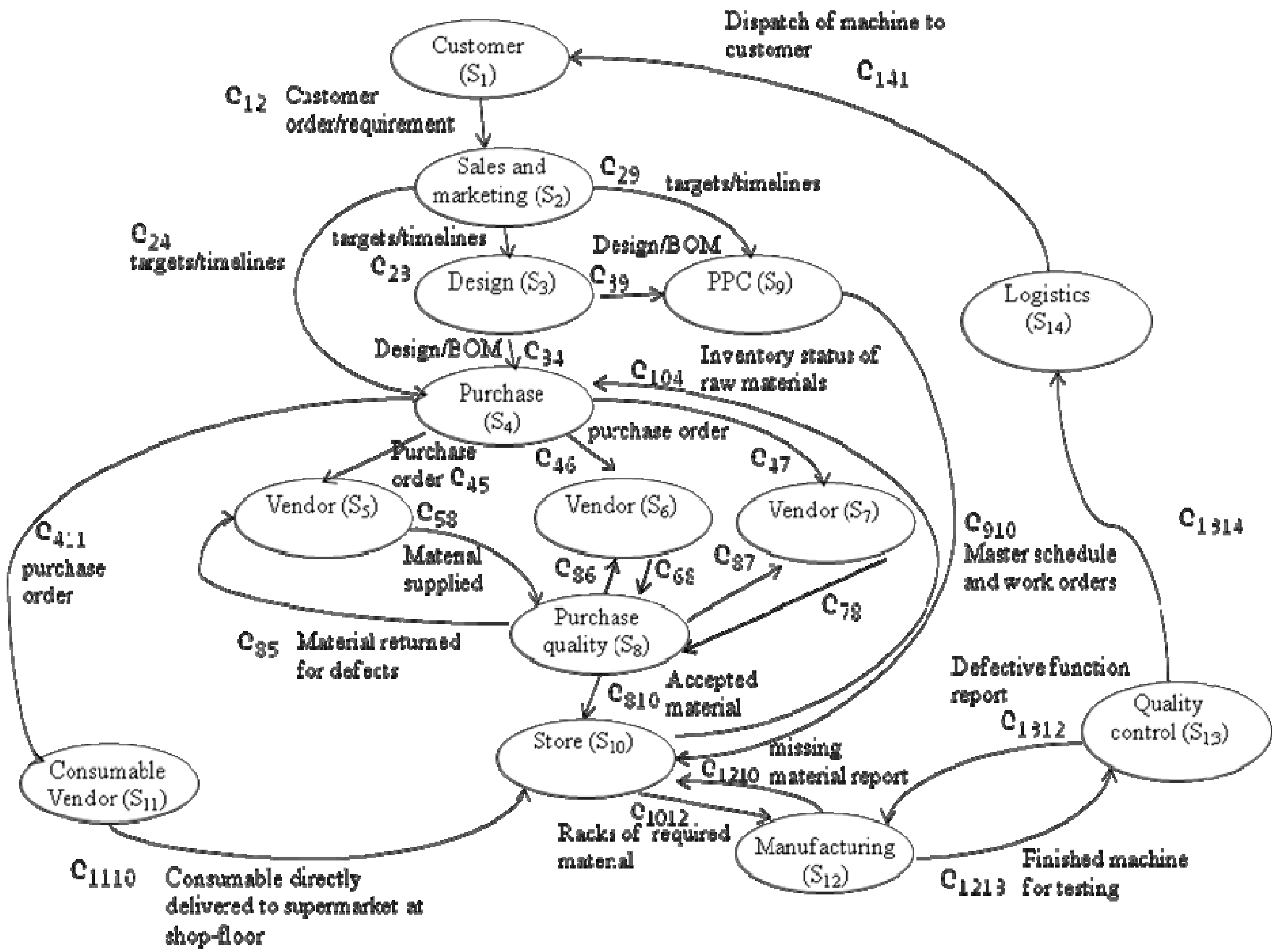


Fig. 5.5 Schematic representation of work flow among subsystems in the original packaging equipment industry (original configuration)

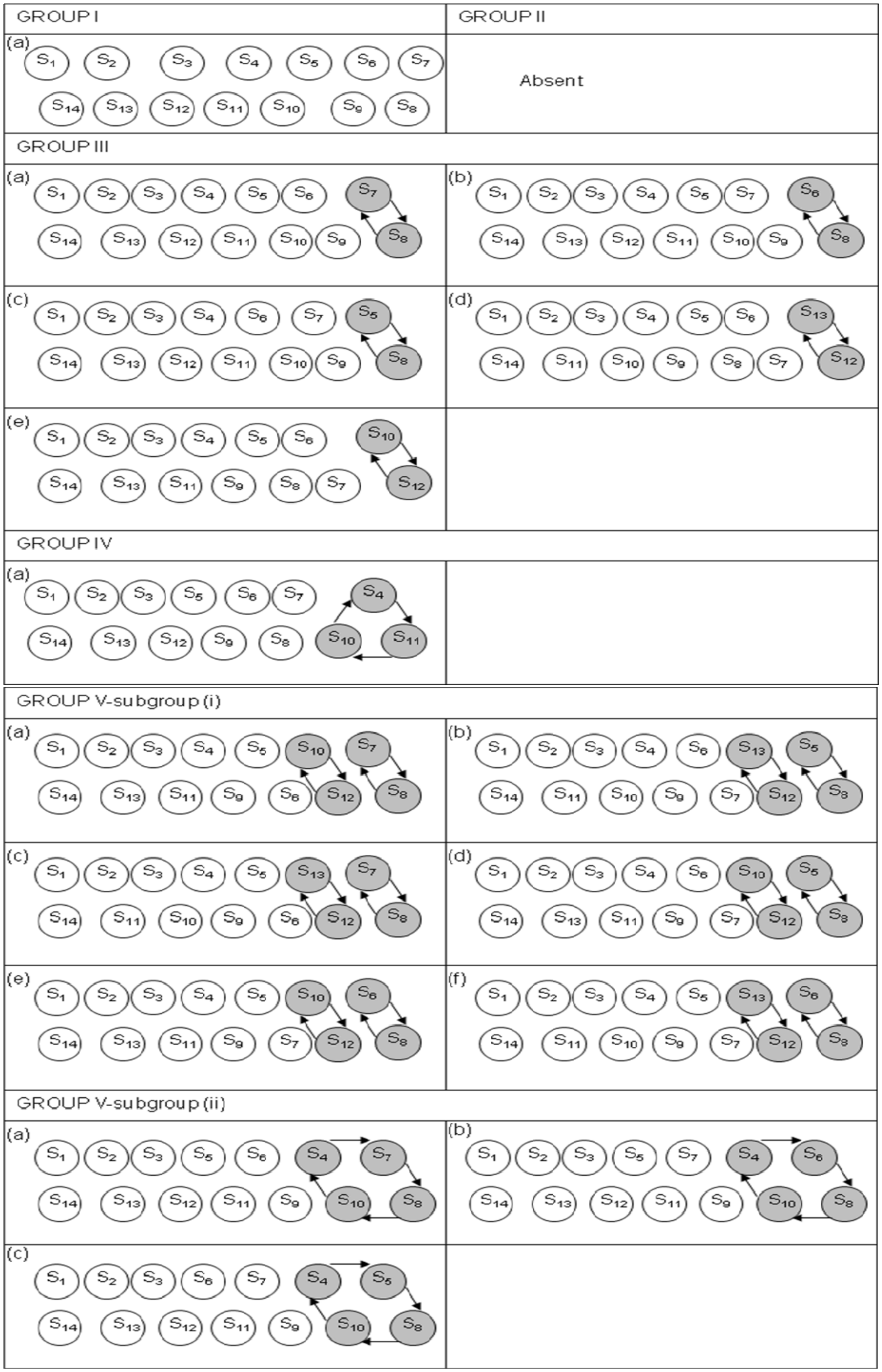


Fig. 5.6 Sub-graphs identified by graph theoretic model of original packaging equipment industry (Group I to Group V)

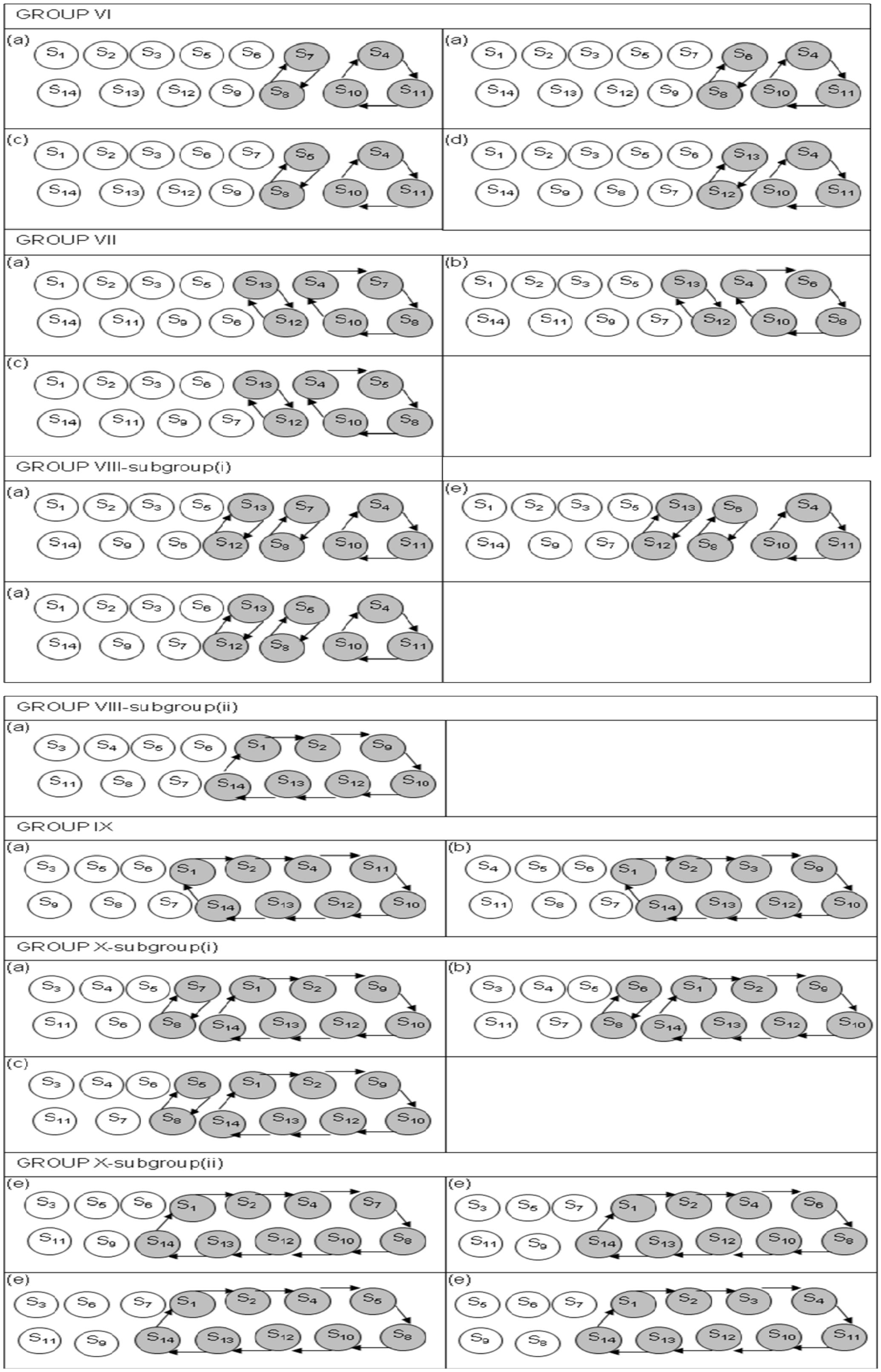


Fig. 5.7 Sub-graphs identified by graph theoretic model of original packaging equipment industry (Group VI to Group X)

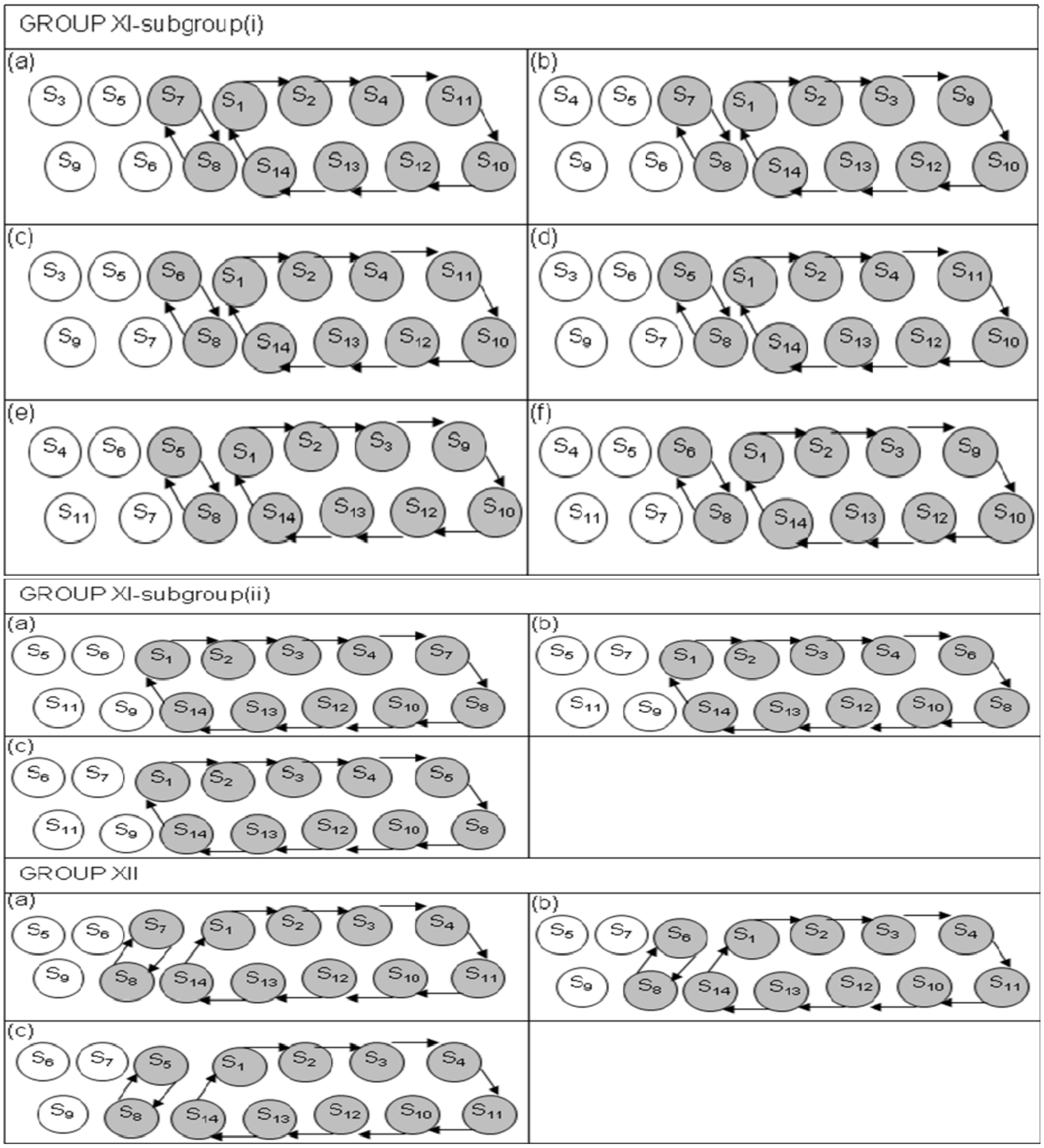
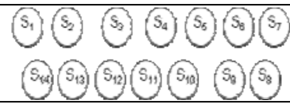
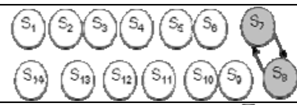
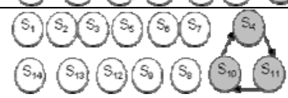
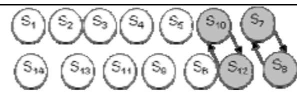
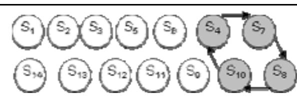
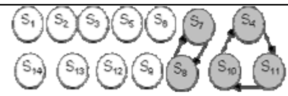
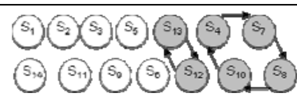
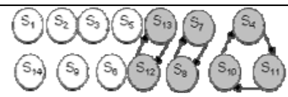
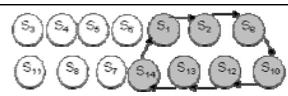
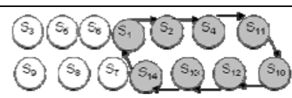
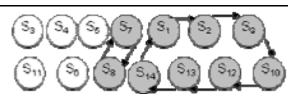
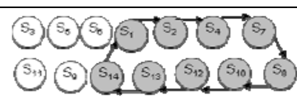
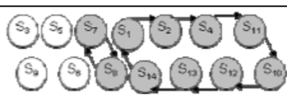
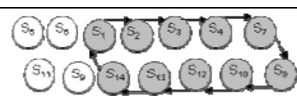
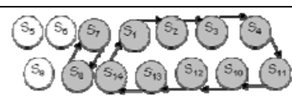


Fig. 5.8 Sub-graphs identified by graph theoretic model of original packaging equipment industry (Group XI and Group XII)

It may be noted that the sub-graphs in Fig. 5.6 to Fig. 5.8 exhibit a structured pattern of interaction cycles under different groups and subgroups. The information from graph theoretic model of the manufacturing system may also be used to identify the causes/chances of triggering the major interaction cycles again and again. As an example, the interaction cycle between quality control department (S_{12}) and the manufacturing department (S_{11}) may be the cause of triggering many bigger interaction cycles (e.g in Group VII). The removal of the cause of quality problem can remove several such possibilities. The salient observations on each group of sub-graphs and the specific numbers of sub-graphs under each group or subgroup are summarized in Table 5.2 below.

Table 5.2 Sub-graphs under various groups and subgroups and their numbers

Group/ subgroup	Representative sub-graph	Number of sub-graphs
Group I		1
Group II	Absent	0
Group III		5
Group IV		1
Group V-subgroup (i)		6
Group V-subgroup (ii)		3
Group VI		4
Group VII		3
Group VIII-subgroup (i)		3
Group VIII-subgroup (ii)		1
Group IX		2
Group X-subgroup (i)		3
Group X-subgroup (ii)		4
Group XI-subgroup (i)		6
Group XI-subgroup (ii)		3
Group XII		3

The information summarized in Table 5.2 is useful for analysis of manufacturing system under study as discussed below.

- The different forms of interaction cycles among subsystems of manufacturing system are systematically identified.
- The greater count of sub-graphs means greater number of interaction cycles among subsystems resulting in greater amount of overall effort for the requirement to be fulfilled.
- Thus, the count of sub-graphs in the graph theoretic model of the manufacturing system reveals the level of complexity of interaction cycles in the manufacturing system operation.

5.4 Identification of restructuring opportunity

To identify the opportunities for restructuring, the work flow in the original configuration is investigated in detail. The aim is to evolve the organization towards a leaner structure by way of defining simplified procedures. By carefully observing the sub-graphs in Fig. 5.6 to Fig. 5.8 from the graph theoretic modeling of the original configuration of the organization, it was evident that the work flow in the organization may be made smoother if the lean principle of quality-at-source is implemented. This principle may help in avoiding many repetitive interaction cycles among subsystems. The smooth flow of production may be particularly enhanced if the internal movement of material may be made foolproof. In the first restructuring effort, it was suggested to establish a kitting system for the supply of material from store to the manufacturing for a particular line of its products. The kitting system consisted of preformed multi-layered boxes as shown in Fig. 5.9 for transfer of material. Such a system helped the store to avoid the chance of missing-to-supply some of the required material. It basically acted as a check list where the missed raw material will be readily visible through the empty slot and thus the problem may be avoided at the source itself after exposure. When the newly designed multilayered preformed boxes were used, the manufacturing department no longer needed to report material inadequacy as there were none. Thus the restructured configuration was developed by modifying the schematic diagram in Fig. 5.5. In the new restructured configuration shown in Fig. 5.10, the link from manufacturing (S_{12}) to store

(S_{10}) was removed and the restructured configuration for case I of restructuring was named as configuration-1.

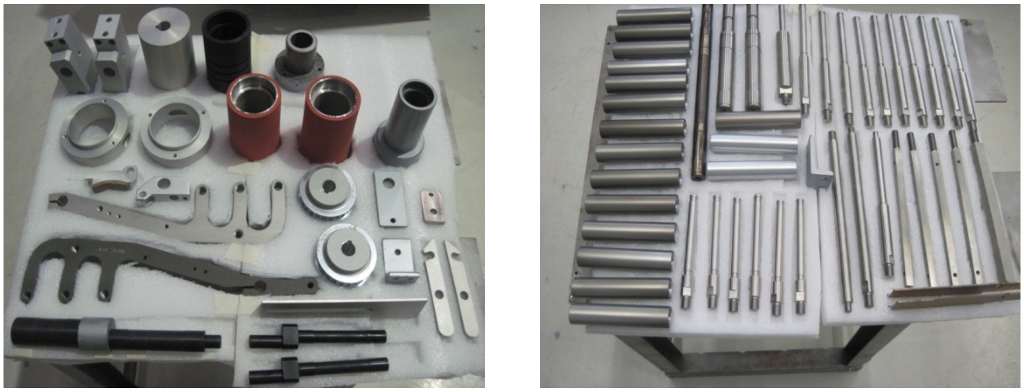


Fig. 5.9 Kitting system in the form of pre-formed multi-layered boxes for supply of material from store to manufacturing department

5.5 Graph theoretic modeling of case-I restructuring

For the graph theoretic modeling of the restructured configuration of the organization, the standard steps for developing the graph theoretic model are implemented.

- A permanent matrix is written for the case I restructured configuration of the organization in equation (5.2).
- The permanent function operation on matrix $P^{'}$ yields the corresponding permanent multinomial which is appended in Appendix A.5.
- The permanent multinomial gives sub-graphs having interaction cycles among subsystems as shown in Fig. 5.11 to Fig. 5.13.

$$P^{'} = \begin{bmatrix} S_1 & e_{12} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & S_2 & e_{23} & e_{24} & 0 & 0 & 0 & 0 & e_{29} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & S_3 & e_{34} & 0 & 0 & 0 & 0 & e_{39} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & S_4 & e_{45} & e_{46} & e_{47} & 0 & 0 & 0 & e_{411} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & S_5 & 0 & 0 & e_{58} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & S_6 & 0 & e_{68} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & S_7 & e_{78} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & e_{85} & e_{86} & e_{87} & S_8 & 0 & e_{810} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_9 & e_{910} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & e_{104} & 0 & 0 & 0 & 0 & 0 & S_{10} & 0 & e_{1012} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & e_{1110} & S_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{12} & e_{1213} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & e_{1312} & S_{13} & e_{1314} \\ e_{141} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{14} \end{bmatrix} \quad (5.2)$$

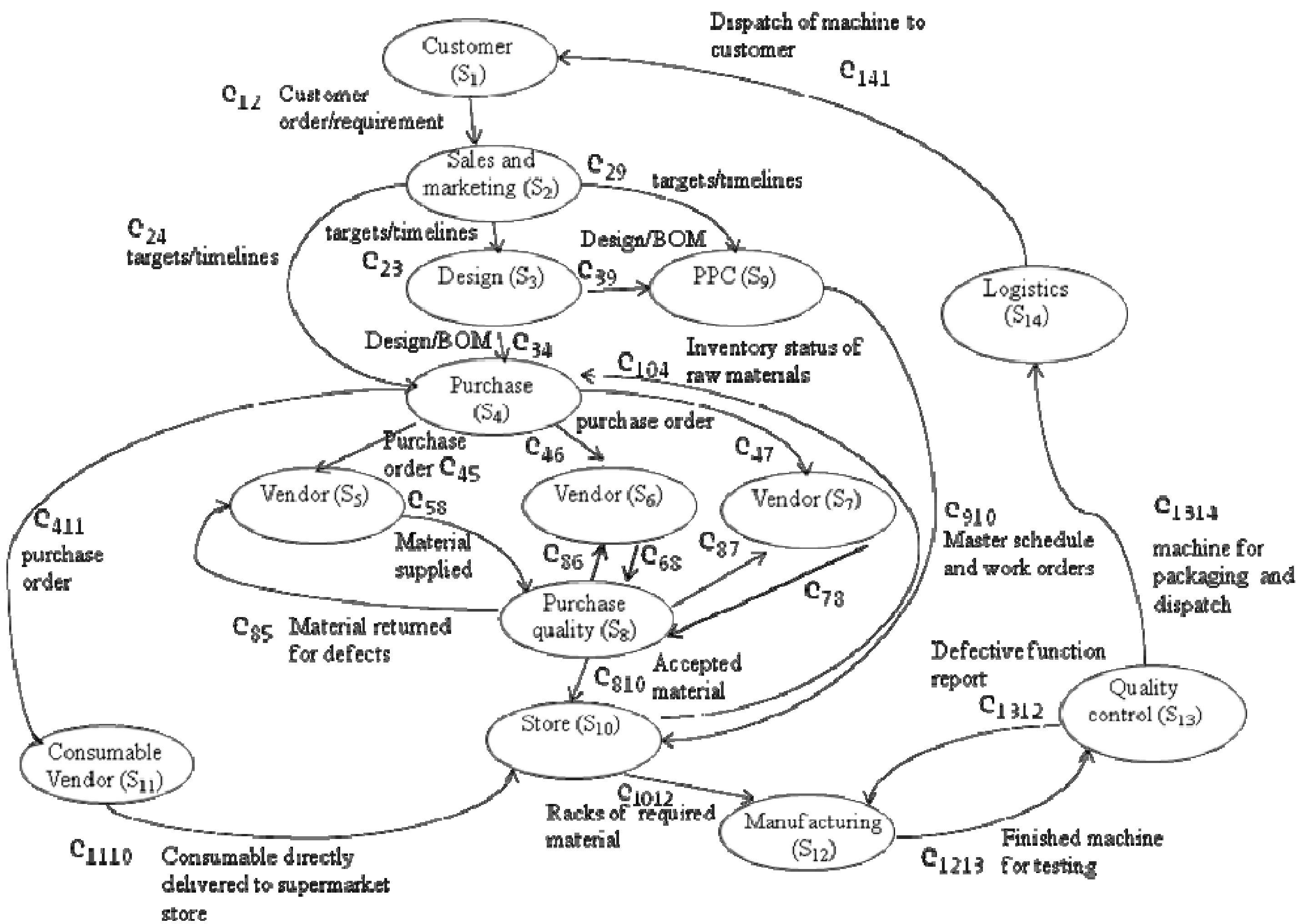


Fig. 5.10 Schematic representation of work flow among subsystems after case I restructuring in packaging equipment industry (restructured configuration-1)

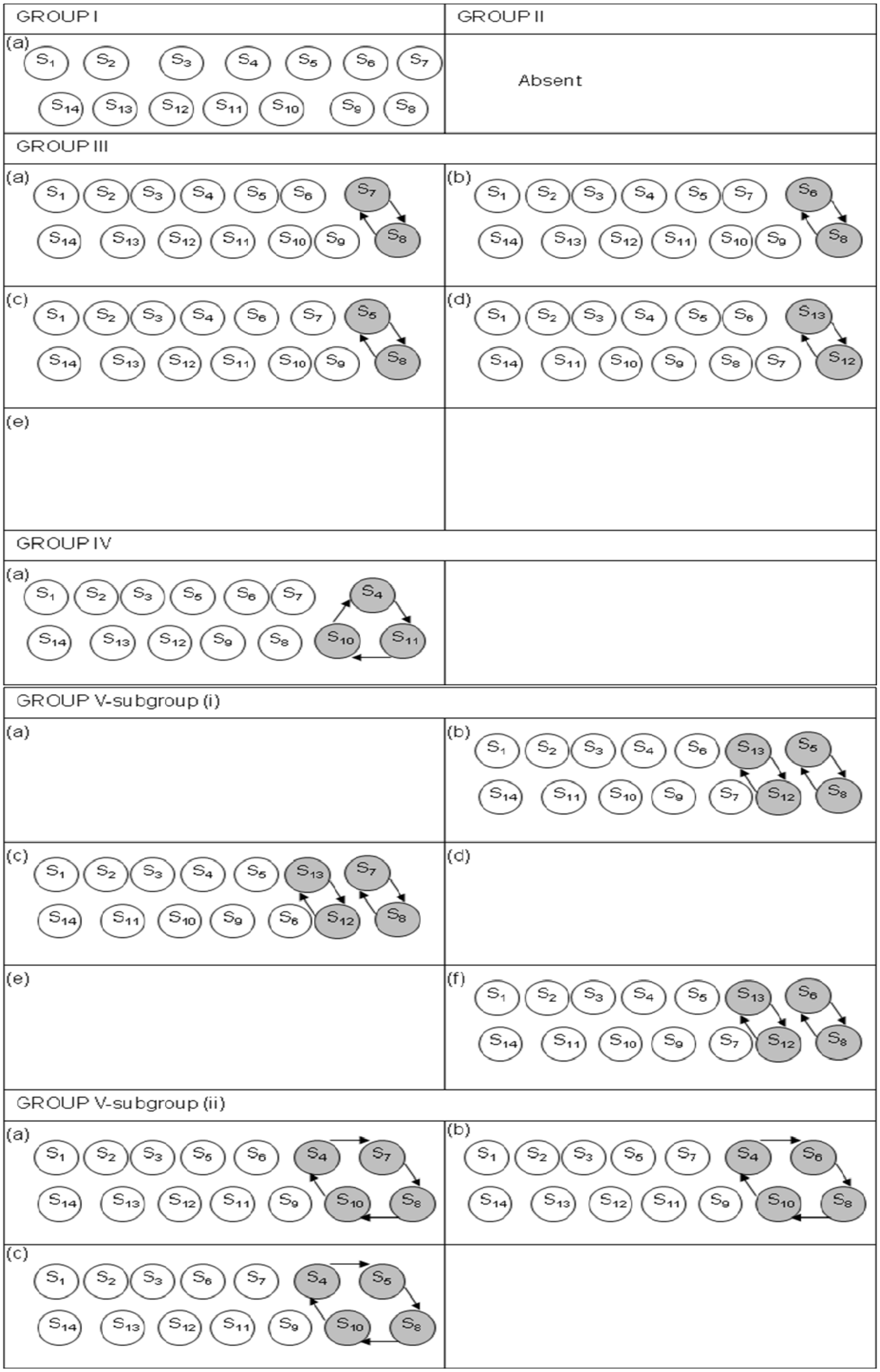


Fig. 5.11 Sub-graphs identified by graph theoretic model of restructured configuration-1for packaging equipment industry (Group I to Group V)

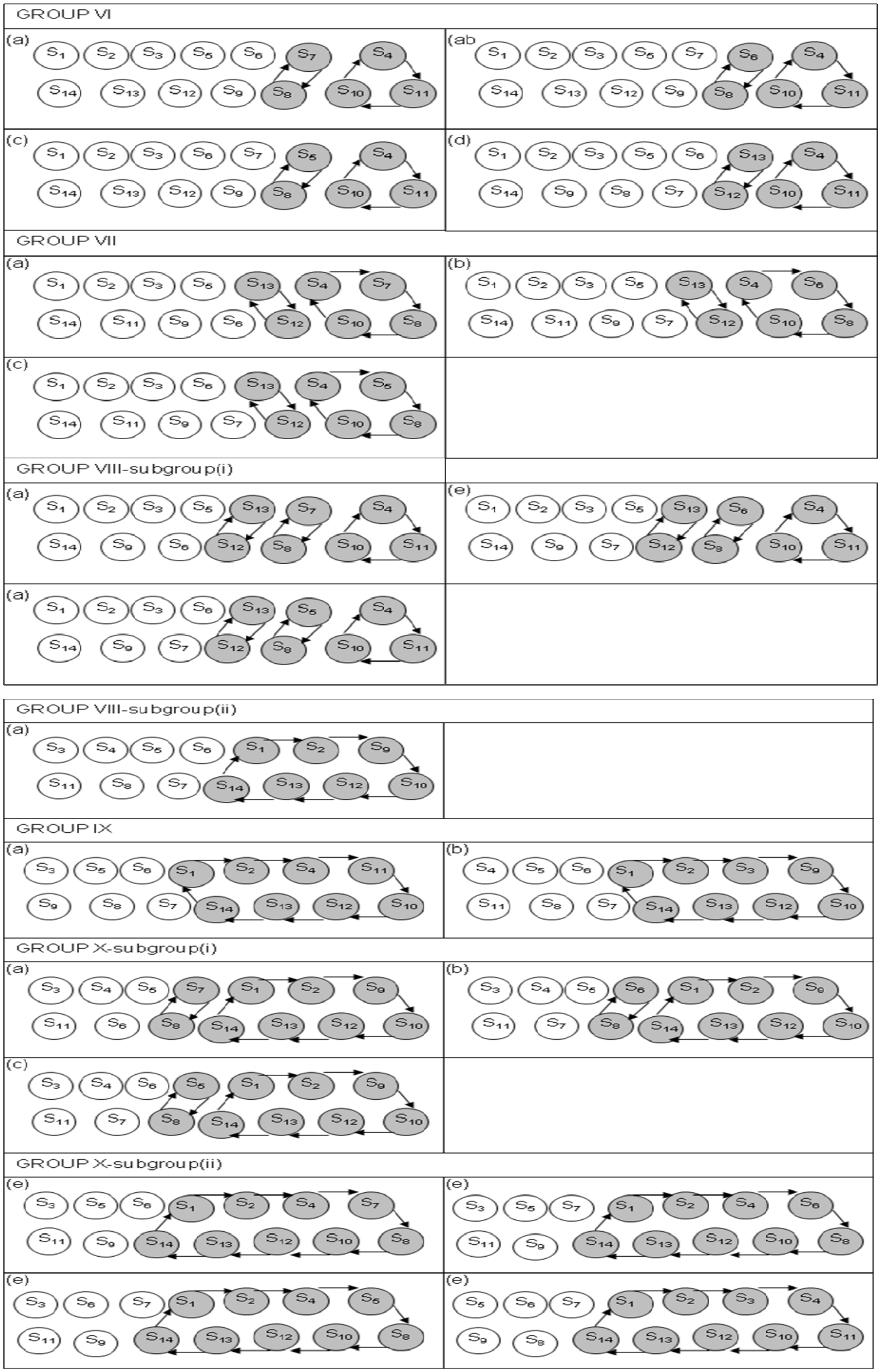


Fig. 5.12 Sub-graphs identified by graph theoretic model of restructured configuration-1for packaging equipment industry (Group VI to Group X)

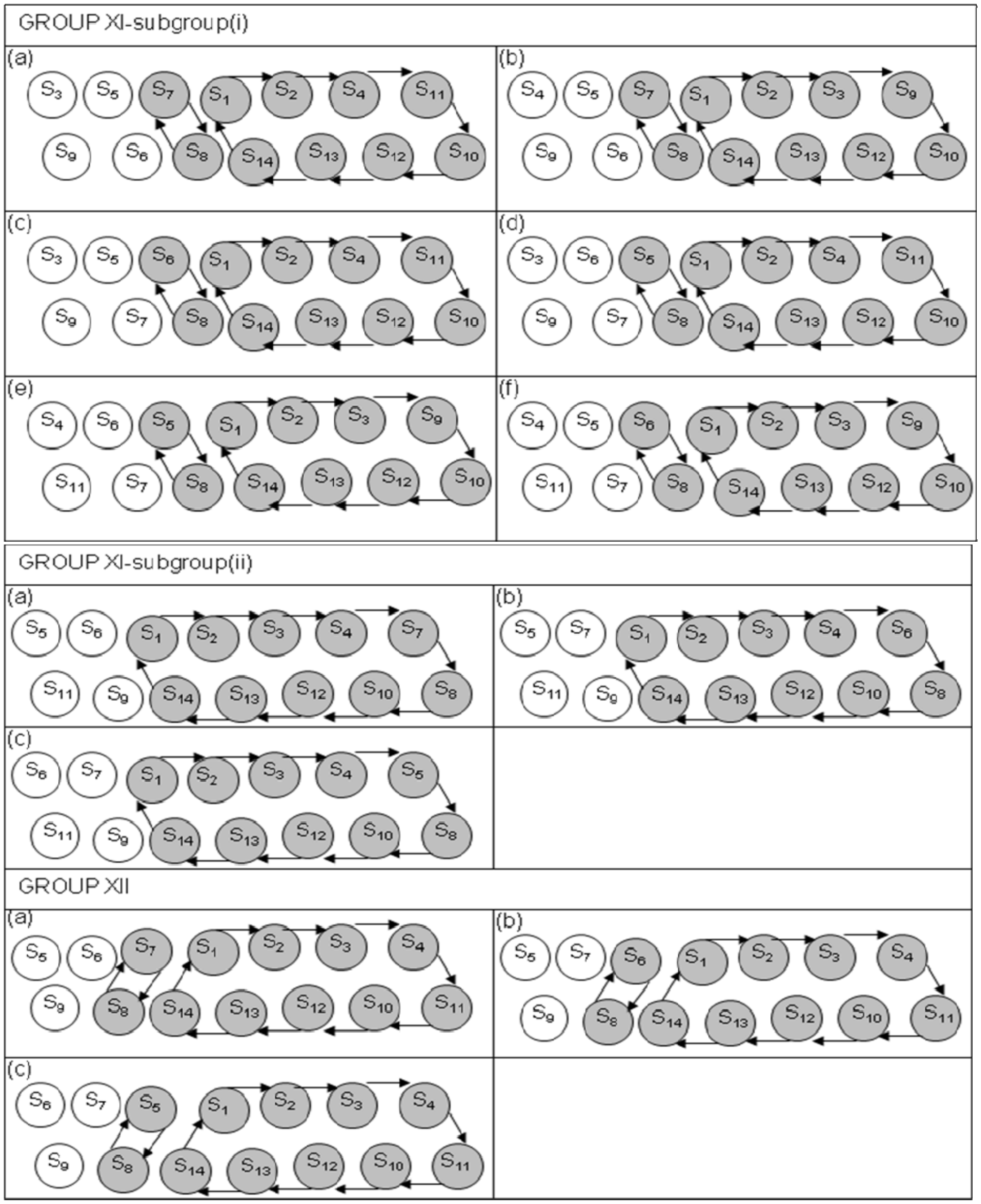
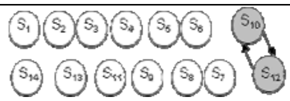
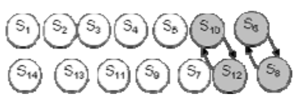
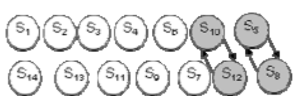


Fig. 5.13 Sub-graphs identified by graph theoretic model of restructured configuration-1for packaging equipment industry (Group XI and Group XII)

5.6 Analysis of results

It may be noted that the sub-graphs shown in Fig. 5.11 to Fig. 5.13 for the restructured manufacturing system differ from those for the original manufacturing system only at four places. Mainly, the four sub-graphs are missing in the restructured configuration. The salient features of the four eliminated sub-graphs due to restructuring decision are summarized in Table 5.3.

Table 5.3 Salient features of the eliminated sub-graphs by the restructuring decision

 Group III part(e)	The elimination of this sub-graph from the permanent multinomial signifies that the cycle of interactions (e_{1210} e_{1012}) between store subsystem (S_{10}) and the manufacturing subsystem (S_{10}), which represents the reporting and corrections for wrong quantity of material provided can be eliminated by the present restructuring decision.
 Group V-subgroup (i) part(a)	The elimination of this sub-graph from the permanent multinomial signifies that the elimination of cycle of interactions (e_{1210} e_{1012}) between store subsystem (S_{10}) and the manufacturing subsystem (S_{10}) also eliminates the chance of triggering another cycle ($e_{78}e_{87}$) of material return as well as resupply between vendor (S_7) and purchase quality subsystem (S_8).
 Group V-subgroup (i) part(d)	The elimination of this sub-graph from the permanent multinomial signifies that the elimination of cycle of interactions (e_{1210} e_{1012}) between store subsystem (S_{10}) and the manufacturing subsystem (S_{10}) also eliminates the chance of triggering another cycle ($e_{68}e_{86}$) of material return as well as resupply between vendor (S_6) and purchase quality subsystem (S_8).
 Group V-subgroup (i) part(e)	The elimination of this sub-graph from the permanent multinomial signifies that the elimination of cycle of interactions (e_{1210} e_{1012}) between store subsystem (S_{10}) and the manufacturing subsystem (S_{10}) also eliminates the chance of triggering another cycle ($e_{58}e_{85}$) of material return as well as resupply between vendor (S_5) and purchase quality subsystem (S_8).

To have a quantitative estimation of the impact of case I restructuring on the complexity reduction, the data from Table 5.2 as well as Table 5.3 can be used in equations (3.6 & 3.7, 3.10 & 3.11 and 3.16 & 3.17) to evaluate different measures of complexity presented in the chapter III. The calculated values of various such measures are recorded in the Table 5.4.

Table 5.4 Values for six different measures of complexity for original and restructured configuration-1 of the organization

Complexity measure	Original configuration	Restructured configuration-1
TOPSIS type index of complexity (Euclidian distance)	1	0
TOPSIS type index of complexity (Cartesian distance)	1	0
Index of complexity (Euclidian distance)	1	0.9003
Index of complexity (Cartesian distance)	1	0.9167
Coefficient of dissimilarity (criteriaon-2)	0	0.2294
Coefficient of dissimilarity (criteriaon-1)	0	0.0833

The following salient points may be observed from Table 5.4.

- The first four complexity measures in Table 5.4 directly give a measure of complexity. On the other hand, the value of coefficient of dissimilarity with respect to the original state, measure the reduction in complexity with respect to the original configuration. So, the reduction in complexity is directly measured by its value.
- The reduction in complexity due to restructuring of the packaging equipment industry for lean manufacturing has been indicated by the values of all complexity measures. The level of complexity reduction indicated by most measures is marginal except for TOPSIS type indices of complexity whose value fluctuated from maximum to minimum. The TOPSIS type indices of complexity can thus be considered too sensitive to simple restructuring situations like case I restructuring in packaging equipment industry which can be modeled just by removal of one link in the graph for original configuration.

5.7 Summary

The following points may be summarized from the chapter:

- In this chapter, first the graph theoretic model has been developed for a packaging equipment industry for its original configuration. The graph theoretic model of case industry helped in generating systematic information about all possible interaction cycles in it. The interaction cycles revealed all possible cyclic activities and guided in identifying the restructuring opportunity for effective complexity reduction towards achieving the goal of lean manufacturing.

- The identified opportunity for restructuring the case industry involved an effort to improve the workflow within the manufacturing plant. This was achieved mainly by the use of kitting system in the form of pre-formed multilayered boxes for material transfer within the plant.
- The improvement in the work flow was represented by a restructured configuration of the manufacturing system. Graph theoretic model for the restructured manufacturing system was also developed. The comparison of the results of graph theoretic model for the restructured configuration of manufacturing system with the original configurations indicated marginal simplification in the interaction structure within the subsystems of the case industry. It was evident by the elimination of four sub-graphs as a result of restructuring exercise and the values of complexity measures which show a simplification in the range of 10 to 20 percent (baring TOPSIS type indices of complexity which show drastic simplification). TOPSIS type indices are thus considered too sensitive for analyzing simple restructuring situations which can be modeled using graph theoretic methodology by just removal of linkages in the original configuration.

In the next chapter, a new restructuring decision in the same packaging equipment industry is discussed which aims to improve the external workflow. The second restructuring effort mainly focuses on improvement of workflow with the suppliers with the use of quality-at-source concept. The concept is implemented by appointing a third party as the quality vendor which ensures that only appropriate quality items in appropriate assembly kits are dispatched to the main plant. This enables the implementation of just-in-time lean principle for interactions related to the vendors.

Chapter VI

RESTRUCTURING EXTERNAL MATERIAL FLOW IN PACKAGING EQUIPMENT INDUSTRY

In this chapter, second restructuring of the work flow in the packaging equipment industry is discussed. The second restructuring seeks to simplify the external material replenishment cycles with vendors by using lean principles like just-in-time (JIT) as well as the quality-at-source. The graph theoretic model is developed for such restructured configuration of the organization. The simplification in the interaction structure due to restructuring is then evaluated using complexity measures. The improvements evident through the results of graph theoretic model are discussed.

6.1 Description

It is planned to implement the lean concept of just-in-time (JIT) for improving the receipt of components from vendors. This system is expected to be beneficial in reducing the inventory levels and the related problems. In the current state, to address the threat of inadequate supply of required components, considerable inventory of the different components is maintained. The major difficulty in implementing JIT is that the vendors are located at far off places (hundreds of kilometers away). Mainly the difficulty arises from a chance of any poor quality material or inappropriate quantity of material being shipped to the plant which may cause disruption in the production process. This in turn may also result in poorer delivery performance of the industrial organization for delivering the final products. To address such challenges, a third party was appointed as purchase quality vendor which inspected the material before dispatch to the plant i.e. right quality was ensured at the source itself. The quality vendor ensured that the incoming material conformed to the requirement both in terms of quality as well as quantity. The use of kitting system as shown in Fig. 5.9 was now extended to the external material replenishment from the vendor where the purchase quality vendor was used to transport material for each equipment manufactured in the organization machine, similar to those in as discussed in previous chapter which were used to move material from store to manufacturing within the plant after first restructuring decision was implemented. So, there is no chance for an item to be missed or lack in conformance and it is thus possible to be received directly by the manufacturing department (S_{12}). This restructuring decision thus eliminates the need for store subsystem (S_{10}) as well as the purchase quality departments from within the manufacturing system.

6.2 Graph theoretic modeling

For graph theoretic modeling, the restructured state is first represented by the second restructured configuration (configuration-2) in terms of a schematic diagram as shown in Fig. 6.1. It may be noted that the material suppliers or vendors as well as the purchase quality vendor are shown in a bold enclosure. This is to highlight the fact that the interactions between the vendors and the purchase quality vendor are not going to affect the performance of the organization as only the material with right quantity and quantity only is finally shipped by the purchase quality vendor.

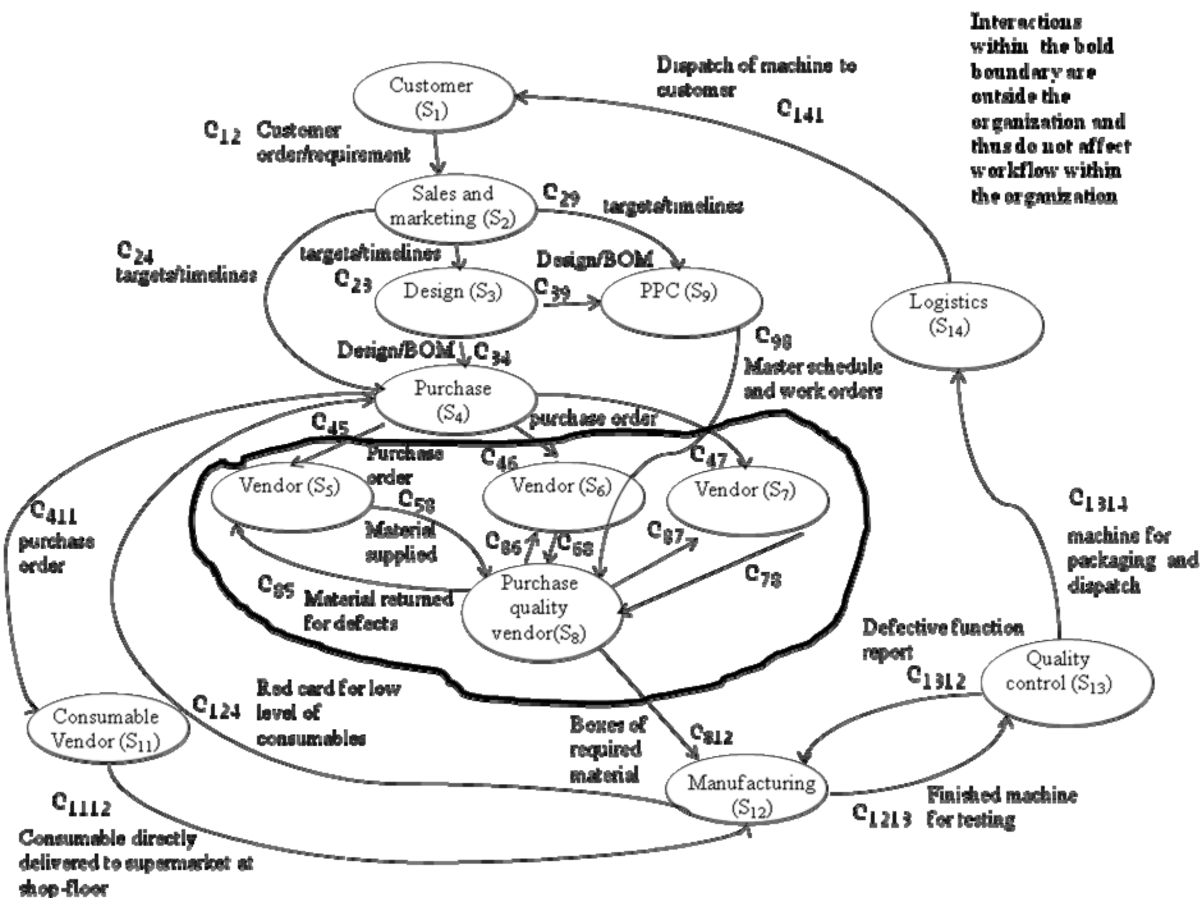


Fig. 6.1 Schematic representation of work flow among subsystems after case II restructuring in packaging equipment industry (restructured configuration-2)

The other distinguishing features of work flow in the second restructured configuration as depicted in the schematic diagram in Fig. 6.1 are discussed below.

- The master schedule is communicated to the purchase quality vendor by the PPC which makes this vendor to send the required material to manufacturing department following just in time.
- In this restructured configuration, the inspection of purchased material is carried out by an outside party located near the source of material and the quality is built at the source. Thus, there is normally no chance that can lead to any repetitive cycles for material delivery process due to lack of conformance of materials.
- The already developed self certification capability in consumable vendor is maintained so that the quality is built at source and the incoming material can be directly supplied to the consumable supermarket store (which is located at the manufacturing area) without subjecting the incoming material to quality inspection. The level of consumables can be easily gauged by the manufacturing department which can trigger purchase process when the level of consumables reaches a predetermined low level.

The standard steps for developing the graph theoretic model are implemented to obtain the graph theoretic model for the second restructured configuration represented by schematic diagram in Fig. 6.1. The permanent matrix for the restructured configuration of the manufacturing system is developed and then the permanent function operation is carried out on the permanent matrix to obtain the corresponding permanent multinomial. The permanent matrix for the second restructured configuration of the manufacturing system is written as below.

$$
P^{''}=\begin{bmatrix}
S_1 & e_{12} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & S_2 & e_{23} & e_{24} & 0 & 0 & 0 & 0 & e_{29} & 0 & 0 & 0 & 0 \\
0 & 0 & S_3 & e_{34} & 0 & 0 & 0 & 0 & e_{39} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & S_4 & e_{45} & e_{46} & e_{47} & 0 & 0 & e_{411} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & S_5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & S_6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & S_7 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & S_8 & 0 & 0 & e_{812} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & e_{98} & S_9 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{11} & e_{1112} & 0 & 0 \\
0 & 0 & 0 & e_{124} & 0 & 0 & 0 & 0 & 0 & 0 & S_{12} & e_{1213} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & e_{1312} & S_{13} & e_{1314} \\
e_{141} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{14}
\end{bmatrix}
\tag{6.1}
$$

To model the schematic diagram in Fig. 6.1, the interactions outside the bold enclosed space and interactions that are crossing the bold enclosed space border are considered in the permanent matrix above i.e. the interactions among subsystems falling within the enclosed space are not considered while the subsystem variables are considered for such subsystems in the permanent matrix. The permanent function operation on matrix $P^{''}$ yields the corresponding permanent multinomial which is appended in equation (A.5.5) in Appendix A.5. The permanent multinomial for matrix $P^{''}$ gives the graph theoretic model for the second restructured manufacturing system in the form of all possible sub-graphs having interaction cycles among subsystems as shown in Fig. 6.2. The un-shaded subsystems in the sub-graphs point to their independent functions while those involved in interactions with others are shown as shaded.

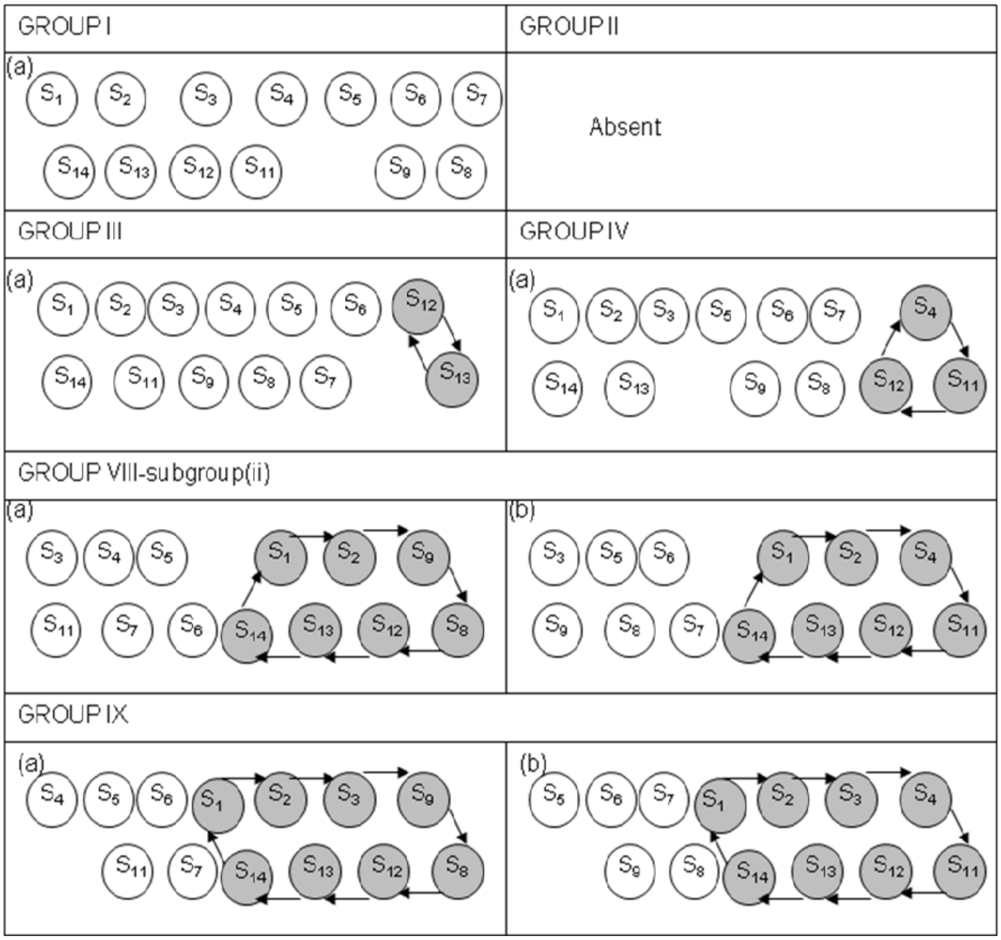


Fig. 6.2 Sub-graphs identified by graph theoretic model of restructured configuration-2 for packaging equipment industry

6.3 Analysis of results

The case II restructuring decision drastically reduces the number of sub-graphs from 48 in the original manufacturing system to 7 in the present restructured configuration. The physical significance of interaction cycles in each of the sub-graph in the present restructured configuration of the packaging equipment industry has been discussed in Table 6.1.

The physical interpretation of sub-graphs in the restructured configuration-2 in Table 6.1 indicates that the sub-graphs covering the interactions cycles for basic operations only are remaining after case II of restructuring in the packaging equipment industry. Thus, it may be inferred that this restructuring has a major impact on complexity reduction in the industrial organization and can serve as very important step in achieving the lean goals. The data on number of sub-graphs under different groups/subgroups in the original configuration as well as restructured configuration-2 of the packaging equipment industry is summarized in Table 6.2.

Table 6.1 Physical interpretation on sub-graphs in the restructured configuration-2 of packaging equipment industry

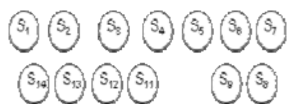
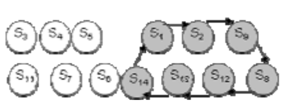
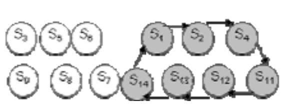
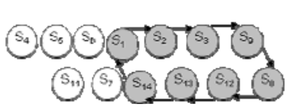
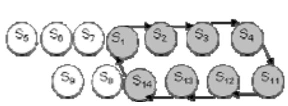
	This sub-graph indicates the independent internal operations within thirteen subsystems of the manufacturing organization. The purchase quality subsystem (S_8) is now an outside agency while the store subsystem (S_{10}) in the original subsystem is not required in the restructured system.
	This sub-graph indicates the presence of interaction cycle between manufacturing subsystem (S_{12}) and quality control subsystem (S_{13}) in addition to the independent functions of all other subsystems. This is basic interaction cycle representing quality inspection for the manufactured product and its possible return for rework.
	This sub-graph indicates the presence of interaction cycle among three subsystems i.e. among manufacturing subsystem (S_{12}), purchase subsystem (S_4) and consumable vendor subsystem (S_{11}). In addition, the independent functions of all other subsystems are also indicated. This is another basic interaction cycle representing refilling of the different consumable supermarkets by the consumable vendor via purchase orders from the purchase subsystem.
	This sub-graph indicates the presence of a basic cycle of interactions among seven subsystems i.e. customer (S_1), sales and marketing (S_2), PPC (S_9), purchase quality vendor (S_8), manufacturing (S_{12}), quality control (S_{13}) and logistics (S_{14}) for fulfillment of the customer order.
	This sub-graph also indicates the presence another basic cycle of interactions among seven subsystems i.e. customer (S_1), sales and marketing (S_2), purchase (S_4), consumable vendor (S_{11}), manufacturing (S_{12}), quality control (S_{13}) and logistics (S_{14}) for fulfillment of the customer order.
	This sub-graph indicates the presence another basic cycle of interactions among eight subsystems i.e. customer (S_1), sales and marketing (S_2), design (S_3), PPC (S_9), purchase quality vendor (S_8), manufacturing (S_{12}), quality control (S_{13}) and logistics (S_{14}) for fulfillment of the customer order.
	This sub-graph indicates the presence another basic cycle of interactions among eight subsystems i.e. customer (S_1), sales and marketing (S_2), design (S_3), purchase (S_4), consumable vendor (S_{11}), manufacturing (S_{12}), quality control (S_{13}) and logistics (S_{14}) for fulfillment of the customer order.

Table 6.2 Sub-graphs under different groups and subgroups and their numbers for original and restructured configuration-2

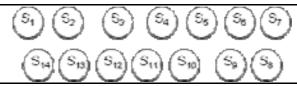
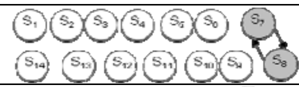
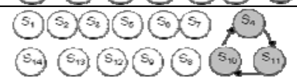
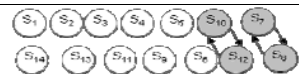
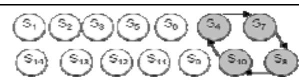
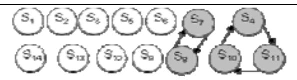
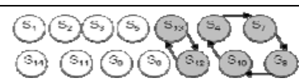
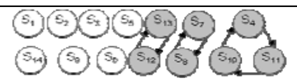
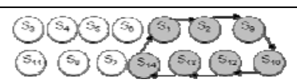
Group/ Subgroup	Representative sub-graph from original configuration	Number of sub-graphs in respective groups/subgroups for three configurations of manufacturing system	
		Original	config-2
Group I		1	1
Group II	Absent	0	0
Group III		5	1
Group IV		1	1
Group V-subgroup (i)		6	0
Group V-subgroup (ii)		3	0
Group VI		4	0
Group VII		3	0
Group VIII-subgroup (i)		3	0
Group VIII-subgroup (ii)		1	2
Group IX		2	2
Group X-subgroup (i)		3	0
Group X-subgroup (ii)		4	0
Group XI-subgroup (i)		6	0
Group XI-subgroup (ii)		3	0
Group XII		3	0
Total		48	7

Table 6.2 indicates the reduction in the number of sub-graphs in the restructured configuration-2 in comparison to the original configuration for almost all groups/subgroups except Group VIII-subgroup (ii) under which the number of sub-graphs increased. To have a clear and quantitative estimation of the impact of case II of restructuring in the packaging equipment industry on the complexity reduction, equations (3.6 & 3.7, 3.10 & 3.11 and 3.16 & 3.17) can be used to evaluate different measures of complexity presented in the chapter III. The calculated values of various quantitative measures for complexity are recorded in the Table 6.3.

Table 6.3 Values for six different measures of complexity for original and restructured configuration-2 of the organization

Name of the measure	Original configuration	Restructured configuration-2
TOPSIS type index of complexity (Euclidian distance)	1	0.0705
TOPSIS type index of complexity (Cartesian distance)	1	0.0233
Index of complexity (Euclidian distance)	1	0.2406
Index of complexity (Cartesian distance)	1	0.1458
Coefficient of dissimilarity (Criterion-2)	0	0.9597
Coefficient of dissimilarity (Criterion-1)	0	0.8542

The following salient points may be observed from Table 6.3.

- All the computed values for different complexity measures indicate its reduction.
- Considerable reduction in complexity (more than 75 %) has been indicated by the values of all complexity measures due to case II restructuring of the packaging equipment industry.
- Unlike case I of restructuring, the value of TOPSIS type indices of complexity in this case has not fluctuated to the minimum possible value. Still the TOPSIS type indices of complexity are more sensitive to this restructuring situation also.

6.4 Summary

The following points may be summarized from this chapter.

- In this chapter, the restructuring effort has a focus to implement the concept of just-in-time for receipt of materials from vendors. The JIT implementation forced considerable restructuring in the original manufacturing system so that quality is built at source.
- The improvement in the work flow is represented by a restructured configuration of the manufacturing system. Graph theoretic model for the restructured configuration was developed. The comparison of the results of graph theoretic model for the restructured configuration with the original configuration indicated considerable simplification in the interaction structure in the organization. The number of sub-graphs reduced from 48 in the original configuration to 7 in the restructured configuration.
- Considerable reduction in complexity (more than 75%) has also been indicated the different complexity measures due to this restructuring decision.

In the next chapter, a comparative analysis of the restructuring cases in the packaging equipment industry has been presented for gaining deeper insight into the impact of restructuring cases discussed so far in this chapter and chapter V.

Chapter VII

OVERALL ASSESSMENT OF RESTRUCTURING

IN PACKAGING EQUIPMENT INDUSTRY

In this chapter, a comparative analysis of the reduction in complexity due to restructuring cases in the packaging equipment industry has been presented. Initially, the summary of the results of graph theoretic modeling of the restructuring decisions is presented in a tabular form. The quantitative measures have been computed in the overall domain. The correlation between the quantitative results on complexity measures for manufacturing system and the improvements in real performance measures like percentage of on-time deliveries has also been presented to practically validate the methodology presented.

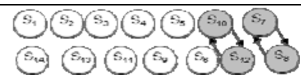
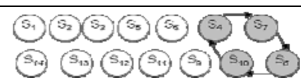
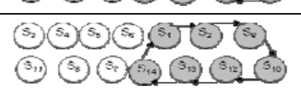
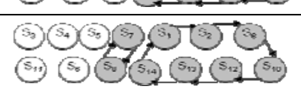
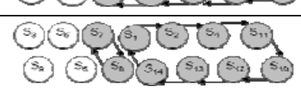
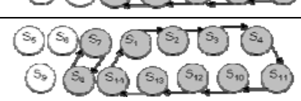
7.1 Overall data for cases in packaging equipment industry

The summary of the information related to the results of graph theoretic modeling for the original and two restructured configurations with respect to the case I and case II of restructuring in the packaging equipment industry is presented in Table 7.1. The salient features of this data are discussed below.

- The table records the count of sub-graphs under different groups and subgroups as discussed in detail in the previous chapters.
- There is reduction in the count of sub-graphs under all the groups/subgroups except in Group VIII subgroup (ii).
- For detailed interpretation of the consolidated information in the above table, such information is presented graphically in Fig 7.1.
- The areas of change in complexity due to restructuring decisions with respect to the original configuration are easily visible in Fig. 7.1.

In the next section, the data in Table 7.1 has been used to compute the values for measures of complexity to quantitatively estimate of the impact of restructuring decisions.

Table 7.1 Number of sub-graphs under different groups and subgroups for original and restructured configurations of packaging equipment industry

Group/Subgroup	Representative sub-graph from original configuration	Number of sub-graphs in respective groups/subgroups for three configurations of packaging equipment industry		
		Original configuration	After internal material flow restructuring	After quality at source at supplier
Group I		1	1	1
Group II	Absent	0	0	0
Group III		5	4	1
Group IV		1	1	1
Group V-subgroup (i)		6	3	0
Group V-subgroup (ii)		3	3	0
Group VI		4	4	0
Group VII		3	3	0
Group VIII-subgroup (i)		3	3	0
Group VIII-subgroup (ii)		1	1	2
Group IX		2	2	2
Group X-subgroup (i)		3	3	0
Group X-subgroup (ii)		4	4	0
Group XI-subgroup (i)		6	6	0
Group XI-subgroup (ii)		3	3	0
Group XII		3	3	0
Total		48	44	7

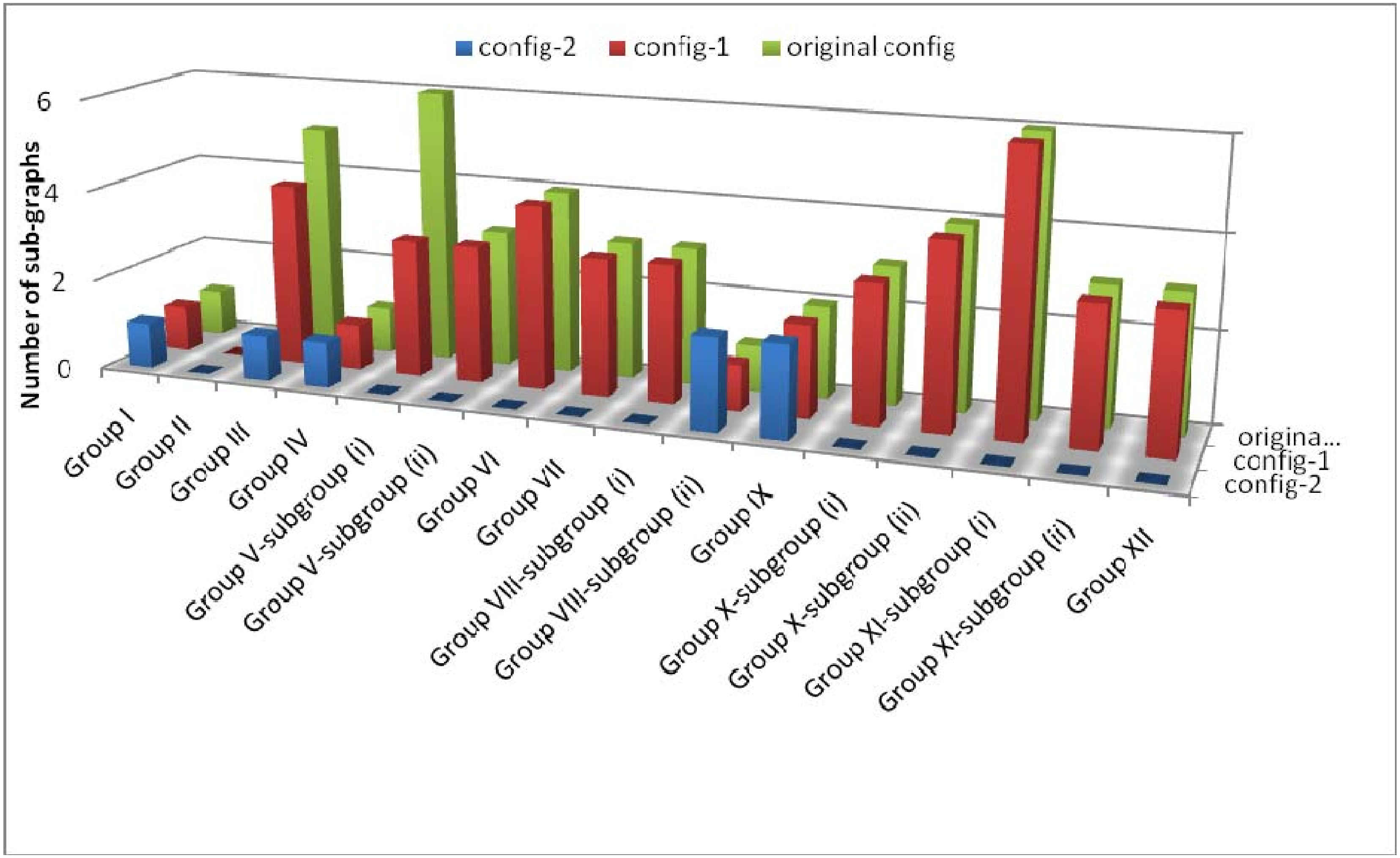


Fig. 7.1 Graphical representation of sub-graphs in the original and restructured configurations of packaging equipment industry

7.2 Overall quantitative impact of restructuring

Similar to previous chapters, the quantitative estimation of the impact of both cases of restructuring in the packaging equipment industry on the complexity reduction can be made with consolidated data summary in Table 7.1 using equations (3.6 & 3.7, 3.10 & 3.11 and 3.16 & 3.17). The calculated values of various quantitative measures for complexity are recorded in the Table 7.2 and the values of indices of complexity are represented graphically in Fig. 7.2 for better interpretation.

Table 7.2 Values for six different measures to quantify complexity of restructured configurations of the packaging equipment industry

Name of the measure	Original configuration	After internal material flow restructuring (Config-1)	After external material flow restructuring (Config-2)
TOPSIS type index of complexity (Euclidian distance)	0.9295	0.7811	0.0705
TOPSIS type index of complexity (Cartesian distance)	0.9767	0.8837	0.0232
Index of complexity (Euclidian distance)	1	0.9003	0.2406
Index of complexity (Cartesian distance)	1	0.9167	0.1458
Coefficient of dissimilarity (Criterion-2)	0	0.2294	0.9597
Coefficient of dissimilarity (Criterion-1)	0	0.0833	0.8542

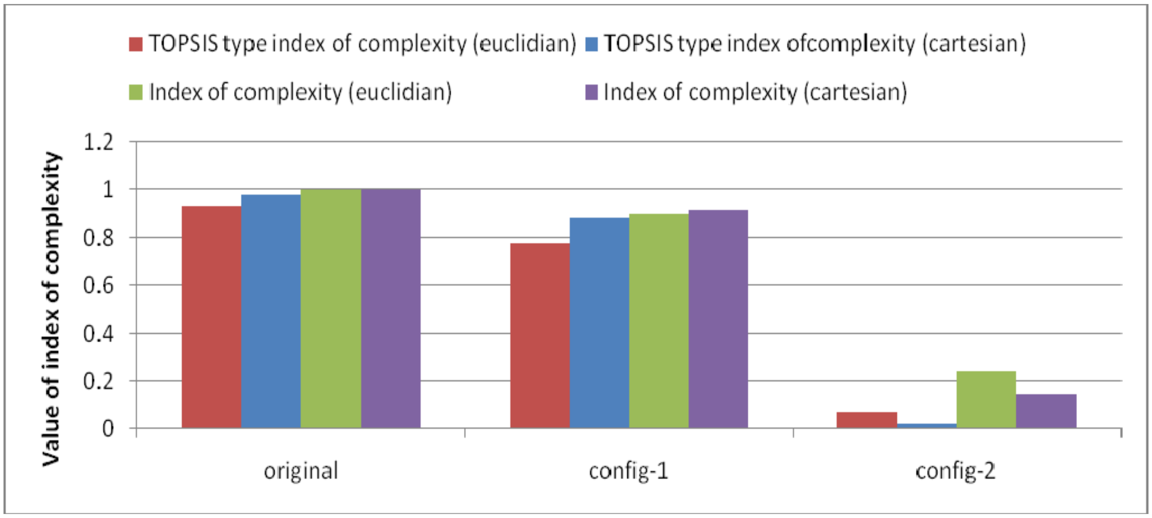


Fig. 7.2 Graphical representation of the values of different indices of complexity of the original and restructured configurations of manufacturing system

The values of last four complexity measures for the restructured configurations have remained the same as they were in the previous chapters in Table 5.4 as well as in Table 6.4. However, it may be noted that the values of the TOPSIS type indices of complexity for the restructured configurations have changed considerably in the overall analysis in comparison to the individual case analysis as in previous chapters. In the current overall analysis which offers a broader domain, their values are varying in a narrower range. In Fig. 7.2, the four values of different measures of complexity for the restructured configurations as well as the original configuration of the organization indicate the similar trend of reduction in complexity achieved through the respective restructuring decisions.

7.3 Correlation with on-time delivery performance

Some of the real performance indicators of a manufacturing plant are on-time delivery performance, productivity, production rate etc. For any meaningful utilization of the newly developed methods of analyzing different decisions in manufacturing systems, the correlation with changes in such real performance measures needs to be investigated. For this purpose, the improvement in one of such important area of performance i.e. percentage of on-time deliveries was observed and is presented in Table 7.3.

Table 7.3 Values of percent improvement in on-time delivery performance after two different restructuring decisions

	After internal material flow restructuring (Config-1)	After external material flow restructuring (Config-2)
Percent improvement in on-time delivery performance	6.25%	18.75%

The standard method of statistics i.e. evaluation of the coefficient of correlation (Russell and Taylor III, 2006) between the values of two variables (X and Y) has been used to investigate the correlation between the improvement in on-time delivery performance and the values of the complexity measures. The formula for calculation of coefficient of correlation is reproduced as below (Ref: Russell and Taylor III, 2006).

Coefficient of correlation, $$r = \frac{n\sum XY - \sum X \sum Y}{\sqrt{\left[n\sum X^2 - \left(\sum X\right)^2\right]\left[n\sum Y^2 - \left(\sum Y\right)^2\right]}} \quad (7.1)$$

The value of coefficient of correlation closer to 1 or -1 indicates very high level of correlation between the considered variables whereas value of 0 indicates no correlation at all. A detailed sample calculation for the evaluation of coefficient of correlation between the values of improvement in on-time delivery performance and the value of TOPSIS type index of complexity for the manufacturing system configurations under study is demonstrated below by Table 7.4 where the improvement in on-time delivery is considered as variable X and while the one of the new quantitative measure is taken as Y.

Table 7.4 Sample calculations for evaluating correlation coefficient between improvement in on-time delivery and TOPSIS type index of complexity (Euclidian distance)

	X	Y	XY	X^2	Y^2
	Improvement in on-time delivery	Value of TOPSIS type index of complexity (Euclidian distance)			
Original configuration	0	0.9295	0	0	0.8640
Restructured configuration-1	0.0625	0.7811	0.0488	0.0039	0.6100
Restructured configuration-2	0.1875	0.0705	0.0132	0.0352	0.0050
	$\sum X =$ 0.2500	$\sum Y =$ 1.7811	$\sum XY =$ 0.0620	$\sum X^2 =$ 0.0391	$\sum Y^2 =$ 1.4791
Coefficient of correlation, r =*-0.9854* ; Coefficient of variance, r^2=*0.971*					

In the above case, a very high level of correlation (*r=0.9854*) is observed between the new quantitative measure and the improvement in on-time delivery performance. Similar way, the correlation between all newly developed measures of complexity reduction and the real performance improvement as evident from the improvement in the on-time delivery due to the restructuring decisions are investigated and the values of the correlation coefficients are compiled in Table 7.5.

Table 7.5 Values of correlation coefficient between different new measures of complexity and percent improvement in on-time delivery performance

Name of the measure	Correlation coefficient with real performance
coefficient of dissimilarity (criterion-1)	0.9702
coefficient of dissimilarity(criterion-2)	0.9947
index of complexity-Cartesian	-0.9702
index of complexity- Euclidian	-0.9775
TOPSIS type index of complexity –Cartesian	-0.9702
TOPSIS type index of complexity -Euclidian	-0.9854

7.4 Analysis of results

The salient observations from the results are discussed in the following points.

- Six different measures have been used to evaluate the reduction in complexity of the manufacturing system due to the restructuring decisions. All the measures show very close correlation (value of coefficient of correlation near 1 or -1) of the value of complexity measures with the improvement in on-time delivery performance.
- The zero value of coefficient of dissimilarity for the original configuration is as per expectation as the original configuration of the manufacturing system is being compared with itself. The indices of complexity indicate that the original configuration is the most complex configuration among the configurations being compared.
- In the cases of restructuring in packaging equipment industry all the measures of complexity correctly indicates the reduction of complexity of the organization.

7.5 Summary

The following points may be summarized from this chapter.

- In this chapter, first the results of the graph theoretic modeling of the original and the restructured configurations of the industrial case study have been summarized. Such results have been used to quantitatively assess the simplification achieved as a result of restructuring decisions.

- The quantitative measures for assessing the complexity reduction have been validated by establishing their correlation with the improvements in the real performance.

In the next chapter, the overall conclusions drawn from the entire study are summarized.

Chapter VIII

CONCLUSIONS AND FUTURE SCOPE

This chapter discusses the overall conclusions drawn from this study. It also lists some of the tasks which may be carried out in extension of the present work as a future scope.

8.1 Conclusions

The following points may be concluded from the present study.

- The study investigated the case of restructuring in a steel plant and two cases of restructuring in a packaging equipment industry for implementing lean philosophy. The restructuring decision in the steel plant was related to implementation of pull production system. On the other hand, one of the restructuring decisions in the packaging equipment industry involved the improvement in the internal work flow by introducing the concept of error proofing in the supply of material using a kitting system. The other restructuring decision involved major improvement in the material flow associated with external suppliers by implementing the concept of built-in quality at the source through an external quality inspection vendor. The restructuring decisions in the steel plant have resulted in improvements in the proportion of value adding time to total lead time from 10 to 33 percent while the two restructuring decisions in the packaging equipment industry have resulted in improvements in the on time delivery performance by 6.25 percent and 18.75 percent respectively.
- The study uses graph theoretic modeling for analysis of restructuring decisions in industrial organizations in order to effectively achieve the lean philosophy objectives. The graph theoretic models developed for different industrial organizations and their configurations in this study offered a unique way of their analysis. Such models identified different sub-graphs containing all possible interaction cycles in the manufacturing system which represent different cyclic activities. The sub-graphs were classified into different groups and subgroups depending on the pattern of interaction cycles. The number of sub-graphs under

groups and subgroups were used for unique characterization of the interaction structure within organizations.

- The fundamental contribution of the thesis is the development of new methods of analysis for more effective quantitative comparison and analysis of restructuring decisions in manufacturing systems as indices of complexity. The new methods are proposed based on the physical interpretation of the existing quantitative methods of coefficients of dissimilarity based on the results of graph theoretic models in a multi-dimensional Euclidian space and have a focus on complexity reduction in lean manufacturing systems. Out of the four new methods, two are based on Cartesian distances and the rest two on Euclidian distances in multi-dimensional Euclidian space. Two of the methods also have their name based on a popular multi attribute decision making (MADM) technique of TOPSIS.
- The real performance indicators such as improvement in on-time delivery performance from industrial case studies indicate a strong correlation with the values of proposed indices of complexity based on graph theoretic modeling. Such correlations have been investigated mathematically using the coefficient of correlation and the modulus of the values of coefficient of correlation is found to be all above 0.95 which indicates a very strong correlation. The results of the case study on restructuring in steel plant confirmed the limitation of the coefficient of dissimilarity to effectively analyze the impact of restructuring decisions. At the same time, the overall study validates the newly developed measures i.e. the indices of complexity as an effective means of studying the impact of lean manufacturing implementation.

8.2 Future scope

The present study has great potential of extension to solve different other types of problems/situations in manufacturing industries. It opens up different new avenues for future research as discussed below.

- Graph theoretic methodology based structural analysis may be applied as an aid in reviving the low performing industrial units by digging the problem area and identifying the specific problems for taking appropriate restructuring actions. The restructuring efforts can be analyzed to take the manufacturing system to the next level of competence.

- The methodology presented in this study may be used to develop software tools as decision support tools. Such tools may prove beneficial for the practicing engineers before the complex, time consuming and capital intensive decisions are made.
- The validation studies may be further strengthened by modeling more number of restructuring situations in a single industry.
- On the other hand, the proposed methods of analysis for complexity in manufacturing systems using graph theoretic modeling may be explored for evaluation of simplification in product designs. Not only manufacturing domain, similar issues in different other areas may also be modeled and analyzed.
- The proposed methodology may be used to study the possible improvements and restructuring requirements in case of a medical hospital for quick action on emergency patient care needs as well as on administrative reforms in public services.

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APPENDICES

APPENDIX A.1
GRAPH THEORY

Graph theory is a field of mathematics which studies different natural and human-made structures. A graph in graph theory differs from graph of functions and it refers to a collection of vertices or 'nodes' and edges. The most important aspect in graph theory is the information on which vertices are connected to which others and by how many edges and not the exact layout. In practice it is often difficult to decide if two drawings represent the same graph. Some of the example applications of graph theory are the link structure of a website and problems in travel, biology, computer chip design etc.

The work by Leonhard Euler on the Seven Bridges of Konigsberg in 1736 is regarded as the pioneering work in the history of graph theory (Minc, 1966). Cayley used differential calculus to study a particular class of graphs, the trees. This study had many implications in theoretical chemistry (Minc, 1966). The fusion of the ideas coming from mathematics with those coming from chemistry is at the origin of a part of the standard terminology of graph theory. The first textbook on graph theory was written by Denes Konig, and published in 1936. A later textbook by Frank Harary, published in 1969, was enormously popular and enabled mathematicians, chemists, electrical engineers and social scientists to talk to each other. The autonomous development of topology also fertilized ideas in graph theory. The common development of graph theory and topology came from the use of the techniques of modern algebra. The introduction of probabilistic methods in graph theory gave rise to yet another branch, known as random graph theory, which has been a fruitful source of graph-theoretic results.

In particular, the development of algorithms to handle graphs is of major interest to researchers in computer science due to its applicability to vast set of problems. In computer science, the transformation of graphs is generally represented by graph rewrite systems. On the other hand, graph databases are used for transaction-safe, persistent storing and querying of graph-structured data. Such concepts use rule-based in-memory manipulation of graphs. Graph-theoretic methods have also proven useful in linguistics. Methods in phonology and morphology are common in the analysis of language as a graph. Graph theory is also used to study molecules in chemistry and physics. In condensed matter physics, the three dimensional structure of complicated simulated atomic structures can be studied quantitatively by gathering statistics on graph-theoretic properties related to the topology of the atoms. This approach is especially used in computer processing of molecular structures. In statistical physics, graphs can represent local connections between interacting parts of a system, as well as the dynamics of a physical process on such systems. Graph theory is also widely used in sociology to measure actors' prestige or to explore diffusion mechanisms. Graph theory is useful in biology for tracking the spread of disease, parasites or how changes to the movement can affect other species. In mathematics, graphs are useful in geometry and certain parts of topology, e.g. Knot Theory. Algebraic graph theory has close links with group theory. A graph structure can be extended by assigning a weight to each edge of the graph. Graphs with weights, or weighted graphs, are used to represent structures in which pair-wise connections have some numerical values. A digraph with weighted edges in the context of graph theory is called a network. Networks have many uses in the practical side of graph theory, network analysis (for example, to model and analyze traffic networks).

A.1 Graph-theoretic data structures

There are different ways to store graphs in a computer system. The data structure used depends on both the graph structure and the algorithm used for manipulating the graph. Two types of structures are in use i.e. the list structure and the matrix structure. The list structures are often preferred for sparse graphs as they have smaller memory requirements. Matrix structures on the other hand provide faster access for some applications but can consume huge amounts of memory. Some of the common matrix structures are explained below.

A.1.1 Incidence matrix

The graph can be represented by a matrix number of vertices as rows and number of edges as columns. In this matrix, the entries of ‘0’s and ‘1’s contain the edge's endpoint data with incident depicted by 1 and not incident depicted by ‘0’s.

A.1.2 Adjacency matrix

This is an ‘n’ by ‘n’ matrix, where n is the number of vertices in the graph. If there is an edge from a vertex x to a vertex y, then the element $a_{x,y}$ is 1, otherwise it is 0. In computing, this matrix makes it easy to find sub-graphs, and to reverse a directed graph.

A.1.3 Laplacian matrix or "Kirchhoff matrix" or "Admittance matrix"

This is defined by subtracting adjacency matrix from the diagonal degree matrix. It explicitly contains both adjacency information and degree information. However, there are other, similar matrices that are also called "Laplacian matrices" of a graph.

A.1.3 Permanent matrix

The permanent matrix is defined by some set of researchers for carrying out some set of operations such as permanent function (explained in detail in Appendix A.2) to generate a specific type of sub-graphs. This matrix has its diagonal elements as variables corresponding to the vertices while its off-diagonal elements as variables corresponding to the edges between specific vertices.

APPENDIX A.2

PERMANENT FUNCTION AND ITS PROPERTIES

In linear algebra, the permanent of a square matrix is a function similar to the determinant. The permanent, as well as the determinant, is a polynomial in the entries of the matrix. Both permanent and determinant are special cases of a more general function of a matrix called the immanant. The permanent of an *n*-by-*n* matrix $A = (a_{i,j})$ where *i* represents the row and *j* represents the column is defined as

$$per(A) = \sum_{\sigma \in S_n}^{n} \prod_{i=1}^{n} a_{i,\sigma(i)} \tag{A.2.1}$$

The sum here extends over all elements σ of the symmetric group S_n, i.e. over all permutations of the numbers 1, 2, ..., n. For example,

$$per\begin{pmatrix} a & b \\ c & d \end{pmatrix} = ad + bc \tag{A.2.2}$$

The definition of the permanent of *A* differs from that of the determinant of *A* in that the signatures of the permutations are not taken into account. If the permanent is viewed as a map that takes *n* vectors as arguments, then it is a multilinear map and it is symmetric (meaning that any order of the vectors results in the same permanent). A formula similar to Laplace's for the development of a determinant along a row or column is also valid for the permanent; all signs have to be ignored for the permanent. Unlike the determinant, the permanent has no easy geometrical interpretation; it is mainly used in combinatorics and in treating boson Green's functions in quantum field theory. However, it has two graph-theoretic interpretations: as the sum of weights of cycle covers of a directed graph and as the sum of weights of perfect matching’s in a bipartite graph.

A.2.1 Generalization of the Permanent Function Model for manufacturing systems

For a general manufacturing system with N subsystems, the manufacturing system permanent matrix, P_1 may be written as in equation (A.2.3) below.

$$
P_{GEN} = \begin{matrix} \\ 1 \\ 2 \\ 3 \\ \cdots \\ N \end{matrix}
\begin{matrix} 1 & 2 & 3 & \cdots & N \\ \end{matrix}
\begin{bmatrix} S_1 & e_{12} & e_{13} & \cdots & e_{1N} \\ e_{21} & S_2 & e_{23} & \cdots & e_{2N} \\ e_{31} & e_{32} & S_3 & \cdots & e_{3N} \\ \cdots & \cdots & \cdots & & \\ e_{N1} & e_{N2} & e_{N3} & \cdots & S_N \end{bmatrix} \qquad (A.2.3)
$$

Equation (A.2.1) gives the formula for obtaining the permanent multinomial for a general matrix. In a graph theoretic context, generally a permanent matrix is defined as in equation (A.2.3) for a system with N number of subsystems and all possible pair-wise interactions among them. The permanent multinomial is defined in that context as in equation (A.2.4) below. For a general N subsystem manufacturing system with all the subsystems linked together, the total number of terms of the permanent function shall be equal to N!.

$$
\begin{aligned}
per(P_{GEN}) = & \prod_1^N S_i + \sum_i\sum_j\sum_k\sum_l\cdots\sum_N e_{ij}e_{ji}S_kS_l..S_N + \\
& \left[\sum_i\sum_j\sum_k\sum_l\cdots\sum_N (e_{ij}e_{jk}e_{ki})\, S_lS_m\ldots S_N + \sum_i\sum_j\sum_k\sum_l\cdots\sum_N (e_{ik}e_{kj}e_{ji})\, S_lS_m\ldots S_N + \right] + \\
& \left[\begin{aligned} & \left\{\sum_i\sum_j\sum_k\sum_l\cdots\sum_N (e_{ij}\, e_{ji})\, (e_{kl}\, e_{lk})\, S_mS_n\ldots S_N\right\} + \\ & \left\{\sum_i\sum_j\sum_k\sum_l\cdots\sum_N (e_{ij}\, e_{jk}e_{kl}\, e_{li})\, S_mS_n\ldots S_N + \sum_i\sum_j\sum_k\sum_l\cdots\sum_N (e_{il}\, e_{lk}e_{kj}\, e_{ji})\, S_mS_n\ldots S_N\right\} \end{aligned}\right] + \\
& \left[\begin{aligned} & \left\{\begin{aligned} & \sum_i\sum_j\sum_k\sum_l\cdots\sum_N (e_{ij}\, e_{ji})(e_{kl}\, e_{lm}\, e_{mk})\, S_nS_o\ldots S_N + \\ & \sum_i\sum_j\sum_k\sum_l\cdots\sum_N (e_{ij}\, e_{ji})(e_{km}\, e_{ml}\, e_{lk})\, S_nS_o\ldots S_N \end{aligned}\right\} + \\ & \left\{\sum_i\sum_j\sum_k\sum_l\cdots\sum_N (e_{ij}\, e_{jk}e_{kl}e_{lm}e_{mi})S_nS_o\ldots S_N + \sum_i\sum_j\sum_k\sum_l\cdots\sum_N (e_{im}\, e_{ml}e_{lk}e_{kj}e_{ji})S_nS_o\ldots S_N\right\} \end{aligned}\right] \\
& + \bullet\bullet\bullet
\end{aligned} \qquad (A.2.4)
$$

These terms may be expanded into 'N+1' groups. The interrelations which are not actually present in the system will take the value of zero and thus eliminating the non existent terms.

APPENDIX A.3

CALCULATION PROCEDURE FOR COMPLEXITY INDICES

This appendix supplements chapter III with the detailed steps in the calculations of different numerical indices proposed. Chapter III reports different measures for ascertaining the reduction in complexity of manufacturing systems arising from restructuring decisions such as coefficients of dissimilarity (criterion-1 and 2), the index of complexity (Cartesian and Euclidian distance) as well as TOPSIS type index of complexity (Cartesian and Euclidian distance). Calculation procedures for such measures are discussed below using the characterization sets presented in equations (3.8 and 3.9) as well as equations (3.12 and 3.13) in chapter III.

A.3.1 Coefficient of dissimilarity (criterion -1)

The value of coefficient of dissimilarity by criterion-1 can be calculated as below. The data has been used from characterization sets presented in equations (3.8 and 3.9) in chapter III.

Coefficient of dissimilarity criterion-1,

$$C_{d\text{-}1} = \frac{\sum_k \sum_l \left[J_{kl}^A - J_{kl}^B \right]}{\text{maximum}\left[\sum_k \sum_l \left[J_{kl}^A \right] and \sum_k \sum_l \left[J_{kl}^B \right] \right]}$$

$$= \frac{(1-1)+(0-0)+(4-1)+(5-4)+(3-3)+(2-2)+(3-3)+(2-2)}{\text{maximum}\left[1+0+4+5+3+2+3+2 \text{ and } 1+0+1+4+3+2+3+2\right]}$$

$$= \frac{3+1}{1+0+4+5+3+2+3+2} = 0.2$$

A.3.2 Coefficient of dissimilarity (criterion -2)

The value of coefficient of dissimilarity by criterion-2 can be calculated as below. The data has been used from characterization sets presented in equations (3.8 and 3.9) in chapter III.

Coefficient of dissimilarity criterion-2,

$$C_{d\text{-}2} = \sqrt{\frac{\sum_k \sum_l \left[J_{kl}^A - J_{kl}^B \right]^2}{\text{maximum}\left[\sum_k \sum_l \left[J_{kl}^A \right]^2 and \sum_k \sum_l \left[J_{kl}^B \right]^2 \right]}}$$

$$= \sqrt{\frac{(1-1)^2+(0-0)^2+(4-1)^2+(5-4)^2+(3-3)^2+(2-2)^2+(3-3)^2+(2-2)^2}{\text{maximum}\left[(1^2+0^2+4^2+5^2+3^2+2^2+3^2+2^2) \text{ and } (1^2+0^2+1^2+4^2+3^2+2^2+3^2+2^2)\right]}}$$

$$= \sqrt{\frac{3^2+1^2}{1^2+0^2+4^2+5^2+3^2+2^2+3^2+2^2}} = 0.38$$

A.3.3 Index of complexity (Cartesian distance)

The value of index of complexity (Cartesian distance) can be calculated as below. Here also, the data has been used from characterization sets presented in equations (3.8 and 3.9) in chapter III.

Index of complexity (cartesian distance)
for manufacturing system-B

$$= \frac{\sum_k \sum_l \left[J_{kl}^B\right]}{\text{maximum}\left[\sum_k \sum_l \left[J_{kl}^A\right] and \sum_k \sum_l \left[J_{kl}^B\right]\right]}$$

$$= \frac{(1+0+1+4+3+2+3+2)}{(1+0+4+5+3+2+3+2)}$$

$$= \frac{16}{20} = 0.8000$$

A.3.4 Index of complexity (Euclidian distance)

The value of index of complexity (Euclidian distance) can be calculated as below. As earlier, the data has been used from characterization sets presented in equations (3.8 and 3.9) in chapter III.

Simple index of complexity (Euclidian criterion)for manufacturing system-B=

$$= \sqrt{\frac{\sum_k \sum_l \left[J_{kl}^B\right]^2}{\text{maximum}\left[\sum_k \sum_l \left[J_{kl}^A\right]^2 and \sum_k \sum_l \left[J_{kl}^B\right]^2\right]}}$$

$$= \sqrt{\frac{(1^2+0^2+1^2+4^2+3^2+2^2+3^2+2^2)}{(1^2+0^2+4^2+5^2+3^2+2^2+3^2+2^2)}}$$

$$= \sqrt{\frac{44}{68}} = \sqrt{0.647} = 0.8044$$

A.3.5 TOPSIS type index of complexity (Cartesian distance)

The calculation for the TOPSIS type index of complexity by Cartesian distance for manufacturing system 'B' is demonstrated below. The data has been used from equations (3.8 and 3.9) as well as from equations (3.12, 3.13, 3.14 and 3.15) in chapter III.

$$\text{Index of complexity}_{\text{B}}^{\text{TOPSIS type (cartesian distance)}}$$

$$= \frac{\sum_k \sum_l \left[J_{kl}^{B} - J_{kl}^{LECO} \right]}{\left[\sum_k \sum_l \left[J_{kl}^{B} - J_{kl}^{LECO} \right] + \sum_k \sum_l \left[J_{kl}^{MOCO} - J_{kl}^{B} \right] \right]}$$

$$= \frac{\{(1-1)+(0-0)+(1-1)+(4-1)+(3-3)+(2-2)+(3-3)+(2-2)\}}{\left[\begin{array}{l} \{(1-1)+(0-0)+(1-1)+(4-1)+(3-3)+(2-2)+(3-3)+(2-2)\}+ \\ \{(1-1)+(0-0)+(7-1)+(5-4)+(3-3)+(2-2)+(3-3)+(2-2)\} \end{array} \right]}$$

$$= \frac{3}{3+6+1} = 0.3$$

A.3.6 TOPSIS type index of complexity (Euclidian distance)

The calculation for the TOPSIS type index of complexity by Euclidian distance for manufacturing system 'B' is demonstrated below. Here also, the data has been used from equations (3.8 and 3.9) as well as from equations (3.12, 3.13, 3.14 and 3.15) in chapter III.

$$\text{Index of complexity}_{\text{B}}^{\text{TOPSIS type (Euclidian distance)}}$$

$$= \frac{\sqrt{\sum_k \sum_l \left[J_{kl}^{B} - J_{kl}^{LECO} \right]^2}}{\left[\sqrt{\sum_k \sum_l \left[J_{kl}^{B} - J_{kl}^{LECO} \right]^2} \right] + + \left[\sqrt{\sum_k \sum_l \left[J_{kl}^{MOCO} - J_{kl}^{B} \right]^2} \right]}$$

$$= \frac{\sqrt{(1-1)^2+(0-0)^2+(1-1)^2+(4-1)^2+(3-3)^2+(2-2)^2+(3-3)^2+(2-2)^2}}{\left[\begin{array}{l} \sqrt{(1-1)^2+(0-0)^2+(1-1)^2+(4-1)^2+(3-3)^2+(2-2)^2+(3-3)^2+(2-2)^2} + \\ \sqrt{(1-1)^2+(0-0)^2+(7-1)^2+(5-4)^2+(3-3)^2+(2-2)^2+(3-3)^2+(2-2)^2} \end{array} \right]}$$

$$= \sqrt{0.1957} = 0.4423$$

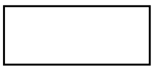
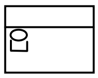
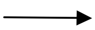
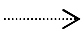
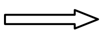
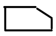
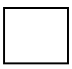
APPENDIX A.4

VALUE STREAM MAPPING

A value stream mapping (VSM) is a collection of all actions (value added as well as non-value-added) that are required to bring a product (or a group of products that use the same resources) through the production line, starting with raw material and ending with the customer (Rother and Shook, 1999). These actions consider the flow of both information and materials within the overall supply chain. The ultimate goal of VSM is to identify all types of waste in the value stream and to take steps to try and eliminate these (Rother and Shook, 1999). The main feature of this tool is that it can help in linking, visualizing and optimizing the material and information flow throughout the company's entire supply chain. VSM creates a common basis for the production process, thus facilitating more thoughtful decisions to improve the value stream (McDonald et al., 2002). VSM is a pencil and paper tool, which is created using a predefined set of standardized icons. This technique uses a standard library of symbols. The standard steps in implementing this tool are described below in brief.

- The first step is to choose a particular product or product family as the target for improvement.
- The next step is to draw a current state map that is essentially a snapshot capturing how things are currently being done.
- The third step in VSM is to create the future state map, which is a picture of how the system should look after the inefficiencies in it have been removed.

Library of symbols

	External sources (Suppliers/ customers)		Schedule box		Process
	Manual info flow		Push arrow		Electrronic info flow
	Kanban movement		Material movement to external source		Kanban symbol
	Data box		inventory		Supermarket

APPENDIX A.5

PERMANENT MULTINOMIALS

Permanent multinomial for original steel plant

$$
\begin{array}{l}
per(A) = \left[T_{16}T_{17}T_{15}T_{14}T_{13}T_{12}T_{11}T_{10}T_{9}T_{8}T_{7}T_{6}T_{4}T_{5}T_{1}T_{3}T_{2}\right]+ \\
\left[T_{1}T_{5}T_{4}T_{6}T_{7}T_{8}T_{9}T_{10}T_{11}T_{12}T_{13}T_{14}T_{15}T_{16}\left(e_{32}e_{217}e_{173}\right)+T_{3}T_{1}T_{5}T_{6}T_{7}T_{8}T_{9}T_{10}T_{11}T_{12}T_{13}T_{14}T_{15}T_{16}\left(e_{42}e_{217}e_{174}\right)\right]+ \\
\left[T_{1}T_{5}T_{4}T_{6}T_{7}T_{8}T_{9}T_{10}T_{11}T_{12}T_{13}T_{14}T_{15}\left(e_{32}e_{216}e_{1617}e_{173}\right)+T_{3}T_{1}T_{5}T_{6}T_{7}T_{8}T_{9}T_{10}T_{11}T_{12}T_{13}T_{14}T_{15}\left(e_{42}e_{216}e_{1617}e_{174}\right)\right]+ \\
\left[\begin{array}{l}
T_{1}T_{5}T_{4}T_{6}T_{7}T_{8}T_{9}T_{10}T_{11}T_{12}T_{13}T_{14}\left(e_{32}e_{215}e_{1516}e_{1617}e_{173}\right)T_{1}T_{5}T_{4}T_{6}T_{7}T_{8}T_{9}T_{10}T_{11}T_{12}T_{15}T_{14}\left(e_{32}e_{213}e_{1316}e_{1617}e_{173}\right)+ \\
T_{3}T_{1}T_{5}T_{6}T_{7}T_{8}T_{9}T_{10}T_{11}T_{12}T_{13}T_{15}\left(e_{42}e_{214}e_{1416}e_{1617}e_{174}\right)+T_{3}T_{1}T_{5}T_{6}T_{7}T_{8}T_{9}T_{10}T_{11}T_{12}T_{15}T_{14}\left(e_{42}e_{213}e_{1316}e_{1617}e_{174-}\right)+ \\
T_{3}T_{1}T_{5}T_{6}T_{7}T_{8}T_{9}T_{10}T_{11}T_{12}T_{13}T_{14}\left(e_{42}e_{215}e_{1516}e_{1617}e_{174}\right)+T_{1}T_{5}T_{4}T_{6}T_{7}T_{8}T_{9}T_{10}T_{11}T_{12}T_{13}T_{15}\left(e_{32}e_{214}e_{1416}e_{1617}e_{173}\right)
\end{array}\right]+ \\
\left[\begin{array}{l}
T_{1}T_{5}T_{4}T_{6}T_{7}T_{8}T_{9}T_{10}T_{11}T_{13}T_{15}\left(e_{32}e_{212}e_{1214}e_{1416}e_{1617}e_{173}\right)+T_{1}T_{5}T_{4}T_{6}T_{7}T_{8}T_{9}T_{10}T_{11}T_{15}T_{14}\left(e_{32}e_{212}e_{1213}e_{1316}e_{1617}e_{173}\right)+ \\
T_{3}T_{1}T_{5}T_{6}T_{7}T_{8}T_{9}T_{10}T_{11}T_{15}T_{14}\left(e_{42}e_{212}e_{1213}e_{1316}e_{1617}e_{174}\right)+T_{3}T_{1}T_{5}T_{6}T_{7}T_{8}T_{9}T_{10}T_{11}T_{13}T_{15}\left(e_{42}e_{212}e_{1214}e_{1416}e_{1617}e_{174}\right)+ \\
T_{1}T_{5}T_{4}T_{6}T_{7}T_{8}T_{9}T_{10}T_{11}T_{13}T_{14}\left(e_{32}e_{212}e_{1215}e_{1516}e_{1617}e_{173}\right)+T_{3}T_{1}T_{5}T_{6}T_{7}T_{8}T_{9}T_{10}T_{11}T_{13}T_{14}\left(e_{42}e_{212}e_{1215}e_{1516}e_{1617}e_{174}\right)
\end{array}\right]+ \\
\left[\begin{array}{l}
T_{1}T_{5}T_{4}T_{6}T_{7}T_{8}T_{9}T_{10}T_{13}T_{14}\left(e_{32}e_{211}e_{1112}e_{1215}e_{1516}e_{1617}e_{173}\right)+T_{1}T_{5}T_{4}T_{6}T_{7}T_{8}T_{9}T_{10}T_{15}T_{14}\left(e_{32}e_{211}e_{1112}e_{1213}e_{1316}e_{1617}e_{173}\right)+ \\
T_{3}T_{1}T_{5}T_{6}T_{7}T_{8}T_{9}T_{10}T_{13}T_{14}\left(e_{42}e_{211}e_{1112}e_{1215}e_{1516}e_{1617}e_{174}\right)+T_{3}T_{1}T_{5}T_{6}T_{7}T_{8}T_{9}T_{10}T_{13}T_{15}\left(e_{42}e_{211}e_{1112}e_{1214}e_{1416}e_{1617}e_{174}\right)+ \\
T_{3}T_{1}T_{5}T_{6}T_{7}T_{8}T_{9}T_{10}T_{15}T_{14}\left(e_{42}e_{211}e_{1112}e_{1213}e_{1316}e_{1617}e_{174}\right)+T_{1}T_{5}T_{4}T_{6}T_{7}T_{8}T_{9}T_{10}T_{13}T_{15}\left(e_{32}e_{211}e_{1112}e_{1214}e_{1416}e_{1617}e_{173}\right)
\end{array}\right]+ \\
\left[\begin{array}{l}
T_{3}T_{1}T_{5}T_{6}T_{7}T_{8}T_{9}T_{13}T_{14}\left(e_{42}e_{210}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{174}\right)T_{1}T_{5}T_{4}T_{6}T_{7}T_{8}T_{9}T_{13}T_{15}\left(e_{32}e_{210}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{173}\right)+ \\
T_{1}T_{5}T_{4}T_{6}T_{7}T_{8}T_{9}T_{13}T_{14}\left(e_{32}e_{210}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{173}\right)+T_{3}T_{1}T_{5}T_{6}T_{7}T_{8}T_{9}T_{13}T_{15}\left(e_{42}e_{210}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{174}\right)+ \\
T_{3}T_{1}T_{5}T_{6}T_{7}T_{8}T_{9}T_{15}T_{14}\left(e_{42}e_{210}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{174}\right)+T_{1}T_{5}T_{4}T_{6}T_{7}T_{8}T_{9}T_{15}T_{14}\left(e_{32}e_{210}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{173}\right)]
\end{array}\right]+ \\
\left[\begin{array}{l}
T_{3}T_{1}T_{5}T_{6}T_{7}T_{8}T_{15}T_{14}\left(e_{42}e_{29}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{174}\right)T_{1}T_{5}T_{4}T_{6}T_{7}T_{8}T_{13}T_{15}\left(e_{32}e_{29}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{173}\right)+ \\
T_{1}T_{5}T_{4}T_{6}T_{7}T_{8}T_{15}T_{14}\left(e_{32}e_{29}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{173}\right)+T_{3}T_{1}T_{5}T_{6}T_{7}T_{8}T_{13}T_{15}\left(e_{42}e_{29}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{174}\right)+ \\
T_{1}T_{5}T_{4}T_{6}T_{7}T_{8}T_{13}T_{14}\left(e_{32}e_{29}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{173}\right)+T_{3}T_{1}T_{5}T_{6}T_{7}T_{8}T_{13}T_{14}\left(e_{42}e_{29}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{174}\right)
\end{array}\right]+ \\
\left[\begin{array}{l}
T_{1}T_{5}T_{4}T_{6}T_{8}T_{13}T_{14}\left(e_{32}e_{27}e_{79}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{173}\right)+T_{3}T_{1}T_{5}T_{6}T_{7}T_{15}T_{14}\left(e_{42}e_{28}e_{89}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{174}\right)+ \\
T_{3}T_{1}T_{5}T_{6}T_{7}T_{13}T_{14}\left(e_{42}e_{28}e_{89}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{174}\right)+T_{3}T_{1}T_{5}T_{6}T_{7}T_{13}T_{15}\left(e_{42}e_{28}e_{89}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{174}\right)+ \\
T_{3}T_{1}T_{5}T_{6}T_{8}T_{13}T_{14}\left(e_{42}e_{27}e_{79}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{174}\right)+T_{1}T_{5}T_{4}T_{6}T_{7}T_{13}T_{14}\left(e_{32}e_{28}e_{89}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{173}\right)+ \\
T_{1}T_{5}T_{4}T_{6}T_{8}T_{13}T_{15}\left(e_{32}e_{27}e_{79}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{173}\right)+T_{3}T_{1}T_{5}T_{6}T_{8}T_{13}T_{15}\left(e_{42}e_{27}e_{79}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{174}\right)+ \\
T_{1}T_{5}T_{4}T_{6}T_{8}T_{15}T_{14}\left(e_{32}e_{27}e_{79}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{173}\right)+T_{1}T_{5}T_{4}T_{6}T_{7}T_{13}T_{15}\left(e_{32}e_{28}e_{89}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{173}\right)+ \\
T_{1}T_{5}T_{4}T_{6}T_{7}T_{15}T_{14}\left(e_{32}e_{28}e_{89}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{173}\right)+T_{3}T_{1}T_{5}T_{6}T_{8}T_{15}T_{14}\left(e_{42}e_{27}e_{79}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{174}\right)]+
\end{array}\right]+ \\
\left[\begin{array}{l}
T_{1}T_{5}T_{4}T_{7}T_{13}T_{14}\left(e_{32}e_{26}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{173}\right)+T_{3}T_{1}T_{5}T_{7}T_{13}T_{14}\left(e_{42}e_{26}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{174}\right)+ \\
T_{1}T_{5}T_{4}T_{7}T_{13}T_{15}\left(e_{32}e_{26}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{173}\right)+T_{1}T_{5}T_{4}T_{7}T_{15}T_{14}\left(e_{32}e_{26}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{173}\right)+ \\
T_{1}T_{5}T_{4}T_{8}T_{13}T_{15}\left(e_{32}e_{26}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{173}\right)+T_{1}T_{5}T_{4}T_{8}T_{15}T_{14}\left(e_{32}e_{26}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{173}\right)+ \\
T_{3}T_{1}T_{5}T_{8}T_{13}T_{14}\left(e_{42}e_{26}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{174}\right)+T_{1}T_{5}T_{4}T_{8}T_{13}T_{14}\left(e_{32}e_{26}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{173}\right)+ \\
T_{3}T_{1}T_{5}T_{7}T_{15}T_{14}\left(e_{42}e_{26}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{174}\right)+T_{3}T_{1}T_{5}T_{7}T_{13}T_{15}\left(e_{42}e_{26}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{174}\right)+ \\
T_{3}T_{1}T_{5}T_{8}T_{15}T_{14}\left(e_{42}e_{26}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{174}\right)+T_{3}T_{1}T_{5}T_{8}T_{13}T_{15}\left(e_{42}e_{26}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{174}\right)+
\end{array}\right]+ \\
\left[\begin{array}{l}
T_{3}T_{1}T_{8}T_{13}T_{14}\left(e_{42}e_{25}e_{56}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{174}\right)T_{3}T_{1}T_{8}T_{13}T_{15}\left(e_{42}e_{25}e_{56}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{174}\right)+ \\
T_{1}T_{4}T_{7}T_{13}T_{14}\left(e_{32}e_{25}e_{56}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{173}\right)+T_{1}T_{4}T_{7}T_{13}T_{15}\left(e_{32}e_{25}e_{56}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{173}\right)+ \\
T_{1}T_{4}T_{7}T_{15}T_{14}\left(e_{32}e_{25}e_{56}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{173}\right)+T_{3}T_{1}T_{7}T_{15}T_{14}\left(e_{42}e_{25}e_{56}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{174}\right)+ \\
T_{1}T_{4}T_{8}T_{13}T_{14}\left(e_{32}e_{25}e_{56}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{173}\right)+T_{1}T_{4}T_{8}T_{13}T_{15}\left(e_{32}e_{25}e_{56}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{173}\right)+ \\
T_{1}T_{4}T_{8}T_{15}T_{14}\left(e_{32}e_{25}e_{56}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{173}\right)+T_{3}T_{1}T_{7}T_{13}T_{15}\left(e_{42}e_{25}e_{56}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{174}\right)+ \\
T_{3}T_{1}T_{8}T_{15}T_{14}\left(e_{42}e_{25}e_{56}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{174}\right)+T_{3}T_{1}T_{7}T_{13}T_{14}\left(e_{42}e_{25}e_{56}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{174}\right)+
\end{array}\right]+ \\
\left[\begin{array}{l}
T_{3}T_{8}T_{15}T_{14}\left(e_{42}e_{21}e_{15}e_{56}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{174}\right)+T_{3}T_{8}T_{13}T_{15}\left(e_{42}e_{21}e_{15}e_{56}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{174}\right)+ \\
T_{3}T_{8}T_{13}T_{14}\left(e_{42}e_{21}e_{15}e_{56}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{174}\right)+T_{4}T_{7}T_{13}T_{14}\left(e_{32}e_{21}e_{15}e_{56}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{173}\right)+ \\
T_{4}T_{7}T_{13}T_{15}\left(e_{32}e_{21}e_{15}e_{56}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{173x}\right)+T_{4}T_{7}T_{15}T_{14}\left(e_{32}e_{21}e_{15}e_{56}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{173}\right)+ \\
T_{3}T_{7}T_{13}T_{15}\left(e_{42}e_{21}e_{15}e_{56}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{174}\right)+T_{3}T_{7}T_{13}T_{14}\left(e_{42}e_{21}e_{15}e_{56}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{174}\right)+ \\
T_{4}T_{8}T_{13}T_{14}\left(e_{32}e_{21}e_{15}e_{56}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{173}\right)+T_{4}T_{8}T_{13}T_{15}\left(e_{32}e_{21}e_{15}e_{56}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{173}\right)+
\end{array}\right]
\end{array}
$$

(A.5.1)

Permanent multinomial for restructured steel plant

$$
\begin{aligned}
&Per\ (A') = \left[T_1T_5T_4T_6T_7T_8T_9T_{10}T_{13}T_2T_3T_{15}T_{14}T_{12}T_{11}T_{16}T_{17}\right] + \\
&\left[\begin{aligned}
&T_1T_5T_4T_6T_7T_8T_9T_{10}T_{15}T_{14}T_{11}T_3T_2T_{16}T_{17}\left(e_{1312}e_{1213}\right) + T_1T_5T_4T_6T_7T_8T_9T_{13}T_2T_3T_{15}T_{14}T_{12}T_{16}T_{17}\left(e_{1011}e_{1110}\right) + \\
&T_1T_5T_4T_6T_7T_8T_9T_{10}T_{13}T_2T_3T_{15}T_{14}T_{12}T_{11}\left(e_{1617}e_{1716}\right) + T_1T_5T_4T_6T_7T_8T_9T_{10}T_{13}T_2T_3T_{14}T_{11}T_{16}T_{17}\left(e_{1512}e_{1215}\right) + \\
&T_{15}T_{14}T_3T_2T_{13}T_{10}T_9T_8T_7T_6T_4T_5T_1T_{16}T_{17}\left(e_{1211}e_{1112}\right) + T_1T_5T_4T_6T_7T_8T_9T_{15}T_{11}T_3T_2T_{13}T_{10}T_{16}T_{17}\left(e_{1412}e_{1214}\right)
\end{aligned}\right] + \\
&\left[T_1T_5T_4T_6T_7T_8T_9T_{10}T_{13}T_{15}T_{14}T_{12}T_{11}T_{16}\left(e_{32}e_{217}e_{173}\right) + T_1T_5T_6T_7T_8T_9T_{10}T_{13}T_3T_{15}T_{14}T_{12}T_{11}T_{16}\left(e_{42}e_{217}e_{174}\right)\right] + \\
&\left[\begin{aligned}
&\left\{\begin{aligned}
&T_1T_5T_4T_6T_7T_8T_9T_3T_2T_{16}T_{17}T_{15}T_{14}\left(e_{1312}e_{1213}\right)\left(e_{1110}e_{1011}\right)T_1T_5T_4T_6T_7T_8T_9T_{10}T_{11}T_3T_2T_{15}T_{14}\left(e_{1312}e_{1213}\right)\left(e_{1617}e_{1716}\right) + \\
&T_1T_5T_4T_6T_7T_8T_9T_{13}T_2T_3T_{15}T_{14}T_{12}\left(e_{1011}e_{1110}\right)\left(e_{1617}e_{1716}\right) + T_1T_5T_4T_6T_7T_8T_9T_{10}T_{11}T_{13}T_2T_3T_{14}\left(e_{1512}e_{1215}\right)\left(e_{1617}e_{1716}\right) + \\
&T_1T_5T_4T_6T_7T_8T_9T_{13}T_2T_3T_{14}T_{16}T_{17}\left(e_{1512}e_{1215}\right)\left(e_{1011}e_{1110}\right) + T_{15}T_{14}T_3T_2T_{13}T_{10}T_9T_8T_7T_6T_4T_5T_1\left(e_{1211}e_{1112}\right)\left(e_{1617}e_{1716}\right) + \\
&T_1T_5T_4T_6T_7T_8T_9T_3T_2T_{13}T_{16}T_{17}T_{15}\left(e_{1412}e_{1214}\right)\left(e_{1011}e_{1110}\right) + T_1T_5T_4T_6T_7T_8T_9T_{15}T_{11}T_3T_2T_{13}T_{10}\left(e_{1412}e_{1214}\right)\left(e_{1617}e_{1716}\right)
\end{aligned}\right\} + \\
&\left\{T_1T_5T_4T_6T_7T_8T_9T_{10}T_{13}T_{15}T_{14}T_{12}T_{11}\left(e_{32}e_{216}e_{1617}e_{173}\right) + T_1T_5T_6T_7T_8T_9T_{10}T_{13}T_3T_{15}T_{14}T_{12}T_{11}\left(e_{42}e_{216}e_{1617}e_{174}\right)\right\}
\end{aligned}\right] + \\
&\left[\begin{aligned}
&[T_1T_5T_4T_6T_7T_8T_9T_{11}T_{14}T_{16}T_{10}T_{15}\left(e_{1312}e_{1213}\right)\left(e_{32}e_{217}e_{173}\right) + T_1T_5T_6T_7T_8T_9T_{10}T_{11}T_3T_{14}T_{16}T_{15}\left(e_{1312}e_{1213}\right)\left(e_{42}e_{217}e_{174}\right) + \\
&T_1T_5T_4T_6T_7T_8T_9T_{13}T_{15}T_{14}T_{12}T_{16}\left(e_{1011}e_{1110}\right)\left(e_{32}e_{217}e_{173}\right) + T_1T_5T_6T_7T_8T_9T_{13}T_3T_{15}T_{14}T_{12}T_{16}\left(e_{1011}e_{1110}\right)\left(e_{42}e_{217}e_{174}\right) + \\
&T_1T_5T_4T_6T_7T_8T_9T_{10}T_{13}T_{14}T_{11}T_{16}\left(e_{1512}e_{1215}\right)\left(e_{32}e_{217}e_{173}\right) + T_1T_5T_6T_7T_8T_9T_{10}T_{13}T_3T_{14}T_{11}T_{16}\left(e_{1512}e_{1215}\right)\left(e_{42}e_{217}e_{174}\right) + \\
&T_{15}T_{14}T_{13}T_{10}T_9T_8T_7T_6T_4T_5T_1T_{16}\left(e_{1211}e_{1112}\right)\left(e_{32}e_{217}e_{173}\right) + T_{15}T_{14}T_3T_{13}T_{10}T_9T_8T_7T_6T_5T_1T_{16}\left(e_{1211}e_{1112}\right)\left(e_{42}e_{217}e_{174}\right) + \\
&T_1T_5T_4T_6T_7T_8T_9T_{15}T_{11}T_{13}T_{10}T_{16}\left(e_{1412}e_{1214}\right)\left(e_{32}e_{217}e_{173}\right) + T_1T_5T_6T_7T_8T_9T_{15}T_{11}T_3T_{13}T_{10}T_{16}\left(e_{1412}e_{1214}\right)\left(e_{42}e_{217}e_{174}\right)
\end{aligned}\right] + \\
&\left[\begin{aligned}
&\left\{T_1T_5T_4T_6T_7T_8T_9T_{13}T_2T_3T_{14}\left(e_{1512}e_{1215}\right)\left(e_{1011}e_{1110}\right)\left(e_{1617}e_{1716}\right) + T_1T_3T_2T_{13}T_5T_4T_6T_7T_8T_9T_{15}\left(e_{1412}e_{1214}\right)\left(e_{1011}e_{1110}\right)\left(e_{1617}e_{1716}\right)\right\} + \\
&\left\{\begin{aligned}
&T_1T_5T_4T_6T_7T_8T_9T_{10}T_{11}T_{15}T_{14}\left(e_{1312}e_{1213}\right)\left(e_{32}e_{216}e_{1617}e_{173}\right) + T_1T_5T_6T_7T_8T_9T_{10}T_{15}T_{11}T_3T_{14}\left(e_{1312}e_{1213}\right)\left(e_{42}e_{216}e_{1617}e_{174}\right) + \\
&T_1T_5T_4T_6T_7T_8T_9T_{13}T_{15}T_{14}T_{12}\left(e_{1011}e_{1110}\right)\left(e_{32}e_{216}e_{1617}e_{173}\right) + T_1T_5T_6T_7T_8T_9T_{13}T_3T_{15}T_{14}T_{12}\left(e_{1011}e_{1110}\right)\left(e_{42}e_{216}e_{1617}e_{174}\right) + \\
&T_1T_5T_4T_6T_7T_8T_9T_{10}T_{11}T_{13}T_{14}\left(e_{1512}e_{1215}\right)\left(e_{32}e_{216}e_{1617}e_{173}\right) + T_1T_5T_6T_7T_8T_9T_{10}T_{11}T_{13}T_3T_{14}\left(e_{1512}e_{1215}\right)\left(e_{42}e_{216}e_{1617}e_{174}\right) + \\
&T_{15}T_{14}T_{13}T_{10}T_9T_8T_7T_6T_4T_5T_1\left(e_{1211}e_{1112}\right)\left(e_{32}e_{216}e_{1617}e_{173}\right) + T_{15}T_{14}T_3T_{13}T_{10}T_9T_8T_7T_6T_5T_1\left(e_{1211}e_{1112}\right)\left(e_{42}e_{216}e_{1617}e_{174}\right) + \\
&T_1T_5T_6T_7T_8T_9T_{11}T_3T_{13}T_{10}T_{15}\left(e_{1214}e_{1412}\right)\left(e_{42}e_{216}e_{1617}e_{174}\right) + T_1T_5T_4T_6T_7T_8T_9T_{15}T_{11}T_{13}T_{10}\left(e_{1412}e_{1214}\right)\left(e_{32}e_{216}e_{1617}e_{173}\right) +
\end{aligned}\right\}
\end{aligned}\right] + \\
&\left[\begin{aligned}
&T_1T_3T_5T_6T_7T_8T_9T_{14}T_{15}T_{16}\left(e_{1312}e_{1213}\right)\left(e_{1011}e_{1110}\right)\left(e_{42}e_{217}e_{174}\right) + T_1T_3T_2T_5T_4T_6T_7T_8T_9T_{14}T_{15}\left(e_{1617}e_{1716}\right)\left(e_{1312}e_{1213}\right)\left(e_{1011}e_{1110}\right) + \\
&T_1T_5T_4T_6T_7T_8T_9T_{15}T_{14}T_{16}\left(e_{1312}e_{1213}\right)\left(e_{1110}e_{1011}\right)\left(e_{32}e_{217}e_{173}\right) + T_1T_5T_4T_6T_7T_8T_9T_{13}T_{14}T_{16}\left(e_{1512}e_{1215}\right)\left(e_{1011}e_{1110}\right)\left(e_{32}e_{217}e_{173}\right) + \\
&T_1T_5T_6T_7T_8T_9T_{13}T_3T_{14}T_{16}\left(e_{1512}e_{1215}\right)\left(e_{1011}e_{1110}\right)\left(e_{42}e_{217}e_{174}\right) + T_1T_5T_4T_6T_7T_8T_9T_{15}T_{13}T_{16}\left(e_{1412}e_{1214}\right)\left(e_{1011}e_{1110}\right)\left(e_{32}e_{217}e_{173}\right) + \\
&T_1T_3T_{13}T_{16}T_5T_6T_7T_8T_9T_{15}\left(e_{1412}e_{1214}\right)\left(e_{1011}e_{1110}\right)\left(e_{42}e_{217}e_{174}\right)
\end{aligned}\right] + \\
&\left[\begin{aligned}
&T_1T_5T_4T_6T_7T_8T_9T_{15}T_{14}\left(e_{1312}e_{1213}\right)\left(e_{1011}e_{1110}\right)\left(e_{32}e_{216}e_{1617}e_{173}\right) + T_1T_3T_5T_6T_7T_8T_9T_{14}T_{15}\left(e_{1312}e_{1213}\right)\left(e_{1011}e_{1110}\right)\left(e_{34}e_{416}e_{1617}e_{174}\right) + \\
&T_1T_5T_4T_6T_7T_8T_9T_{13}T_{14}\left(e_{1512}e_{1215}\right)\left(e_{1011}e_{1110}\right)\left(e_{32}e_{216}e_{1617}e_{173}\right) + T_1T_5T_6T_7T_8T_9T_{13}T_3T_{14}\left(e_{1512}e_{1215}\right)\left(e_{1011}e_{1110}\right)\left(e_{42}e_{216}e_{1617}e_{174}\right) + \\
&T_1T_5T_4T_6T_7T_8T_9T_{13}T_{15}\left(e_{1412}e_{1214}\right)\left(e_{1011}e_{1110}\right)\left(e_{32}e_{216}e_{1617}e_{173}\right) + T_1T_5T_6T_7T_8T_9T_3T_{13}T_{15}\left(e_{1412}e_{1214}\right)\left(e_{1011}e_{1110}\right)\left(e_{42}e_{216}e_{1617}e_{174}\right)
\end{aligned}\right] + \\
&\left[\begin{aligned}
&T_{15}T_{13}T_8T_7T_6T_4T_5T_1\left(e_{32}e_{29}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{173}\right) + T_{15}T_{14}T_8T_7T_6T_4T_5T_1\left(e_{32}e_{29}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{173}\right) + \\
&T_{15}T_3T_{13}T_8T_7T_6T_5T_1\left(e_{42}e_{29}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{174}\right) + T_{15}T_{14}T_3T_8T_7T_6T_5T_1\left(e_{42}e_{29}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{174}\right) + \\
&T_{14}T_{13}T_8T_7T_6T_4T_5T_1\left(e_{1215}e_{1011}e_{910}e_{29}e_{32}e_{173}e_{1516}e_{1617}e_{1112}\right) + T_{14}T_3T_{13}T_8T_7T_6T_5T_1\left(e_{42}e_{29}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{174}\right)
\end{aligned}\right] + \\
&\left[\begin{aligned}
&T_{15}T_{14}T_8T_4\left(e_{32}e_{21}e_{15}e_{56}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{173}\right)T_{15}T_3T_{13}T_8\left(e_{42}e_{21}e_{15}e_{56}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{174}\right) + \\
&T_{15}T_{14}T_3T_8\left(e_{42}e_{21}e_{15}e_{56}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{174}\right) + T_{15}T_3T_{13}T_7\left(e_{42}e_{21}e_{15}e_{56}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{174}\right) + \\
&T_{15}T_{14}T_3T_7\left(e_{42}e_{21}e_{15}e_{56}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{174}\right) + T_{15}T_{13}T_7T_4\left(e_{32}e_{21}e_{15}e_{56}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{173}\right) + \\
&T_{15}T_{14}T_7T_4\left(e_{32}e_{21}e_{15}e_{56}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1213}e_{1316}e_{1617}e_{173}\right) + T_{15}T_{13}T_8T_4\left(e_{32}e_{21}e_{15}e_{56}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1214}e_{1416}e_{1617}e_{173}\right) + \\
&T_{14}T_{13}T_7T_4\left(e_{32}e_{21}e_{15}e_{56}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{173}\right) + T_{14}T_{13}T_8T_4\left(e_{32}e_{21}e_{15}e_{56}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{173}\right) + \\
&T_{14}T_3T_{13}T_7\left(e_{42}e_{21}e_{15}e_{56}e_{68}e_{89}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{174}\right) + T_{14}T_3T_{13}T_8\left(e_{42}e_{21}e_{15}e_{56}e_{67}e_{79}e_{910}e_{1011}e_{1112}e_{1215}e_{1516}e_{1617}e_{174}\right)
\end{aligned}\right]
\end{aligned}
\tag{A.5.2}
$$

Permanent multinomial for original packaging equipment industry

$$
\begin{aligned}
&\mathrm{per}(P) = [S_1S_2S_3S_5S_4S_6S_7S_8S_9S_{10}S_{11}S_{12}S_{13}S_{14}] + \\
&[S_1S_2S_3S_5S_4S_6S_7S_8S_9S_{10}S_{11}S_{14}(e_{1312}e_{1213}) + S_1S_2S_3S_5S_4S_6S_7S_8S_9S_{11}S_{13}S_{14}(e_{1210}e_{1012}) + \\
&S_1S_2S_3S_5S_4S_6S_9S_{10}S_{11}S_{12}S_{13}S_{14}(e_{78}e_{87}) + S_1S_2S_3S_5S_4S_7S_9S_{10}S_{11}S_{12}S_{13}S_{14}(e_{68}e_{86}) + \\
&S_1S_2S_3S_7S_6S_4S_9S_{10}S_{11}S_{12}S_{13}S_{14}(e_{58}e_{85})] + \\
&[S_1S_2S_3S_5S_6S_7S_8S_9S_{12}S_{13}S_{14}(e_{1110}e_{104}e_{411})] + \\
&[\{S_1S_2S_3S_5S_4S_6S_9S_{11}S_{13}S_{14}(e_{78}e_{87})(e_{1210}e_{1012}) + S_1S_2S_3S_7S_6S_4S_9S_{10}S_{11}S_{14}(e_{58}e_{85})(e_{1312}e_{1213}) + \\
&S_1S_2S_3S_5S_4S_6S_9S_{10}S_{11}S_{14}(e_{1312}e_{1213})(e_{78}e_{87}) + S_1S_2S_3S_5S_4S_7S_9S_{10}S_{11}S_{14}(e_{68}e_{86})(e_{1312}e_{1213}) + \\
&S_1S_2S_3S_5S_4S_7S_9S_{11}S_{13}S_{14}(e_{68}e_{86})(e_{1210}e_{1012}) + S_1S_2S_3S_6S_4S_9S_7S_{11}S_{13}S_{14}(e_{58}e_{85})(e_{1210}e_{1012})\} + \\
&\{S_9S_6S_5S_3S_2S_1S_{11}S_{12}S_{13}S_{14}(e_{47}e_{78}e_{810}e_{104}) + S_9S_7S_5S_3S_2S_1S_{11}S_{12}S_{13}S_{14}(e_{46}e_{68}e_{810}e_{104}) + \\
&S_9S_7S_6S_3S_2S_1S_{11}S_{12}S_{13}S_{14}(e_{45}e_{58}e_{810}e_{104})\}] + \\
&[S_1S_2S_3S_5S_6S_9S_{12}S_{13}S_{14}(e_{78}e_{87})(e_{1110}e_{104}e_{411}) + S_1S_2S_3S_5S_6S_7S_8S_9S_{14}(e_{1312}e_{1213})(e_{1110}e_{104}e_{411}) + \\
&S_1S_2S_3S_6S_9S_7S_{12}S_{13}S_{14}(e_{58}e_{85})(e_{1110}e_{104}e_{411}) + S_1S_2S_3S_5S_7S_9S_{12}S_{13}S_{14}(e_{68}e_{86})(e_{1110}e_{104}e_{411})] + \\
&[S_9S_6S_5S_3S_2S_1S_{11}S_{14}(e_{1312}e_{1213})(e_{78}e_{810}e_{104}e_{47}) + S_9S_7S_5S_3S_2S_1S_{11}S_{14}(e_{1312}e_{1213})(e_{68}e_{810}e_{104}e_{46}) + \\
&S_9S_7S_6S_3S_2S_1S_{11}S_{14}(e_{1312}e_{1213})(e_{45}e_{58}e_{810}e_{104})] + [S_1S_2S_3S_5S_6S_9S_{14}(e_{78}e_{87})(e_{1110}e_{104}e_{411})(e_{1312}e_{1213}) + \\
&S_1S_2S_3S_5S_7S_9S_{14}(e_{68}e_{86})(e_{1110}e_{104}e_{411})(e_{1312}e_{1213}) + S_1S_2S_3S_7S_6S_9S_{14}(e_{58}e_{85})(e_{104}e_{411}e_{1110})(e_{1312}e_{1213})] + \\
&[S_3S_5S_4S_6S_7S_8S_{11}(e_{12}e_{29}e_{910}e_{1012}e_{1213}e_{1314}e_{141})] + \\
&[S_3S_5S_6S_7S_8S_9(e_{12}e_{24}e_{411}e_{1110}e_{1012}e_{1213}e_{1314}e_{141}) + S_5S_4S_6S_7S_8S_{11}(e_{12}e_{23}e_{39}e_{910}e_{1012}e_{1213}e_{1314}e_{141})] + \\
&[\{S_3S_5S_4S_6S_{11}(e_{78}e_{87})(e_{12}e_{29}e_{910}e_{1012}e_{1213}e_{1314}e_{141}) + S_3S_5S_4S_7S_{11}(e_{68}e_{86})(e_{12}e_{29}e_{910}e_{1012}e_{1213}e_{1314}e_{141}) + \\
&S_3S_7S_6S_4S_{11}(e_{58}e_{85})(e_{12}e_{29}e_{910}e_{1012}e_{1213}e_{1314}e_{141})\} + \\
&\{S_9S_6S_5S_3S_{11}(e_{12}e_{24}e_{47}e_{78}e_{810}e_{1012}e_{1213}e_{1314}e_{141}) + S_9S_7S_5S_3S_{11}(e_{12}e_{24}e_{46}e_{68}e_{810}e_{1012}e_{1213}e_{1314}e_{141}) + \\
&S_9S_7S_6S_3S_{11}(e_{12}e_{24}e_{45}e_{58}e_{810}e_{1012}e_{1213}e_{1314}e_{141}) + S_5S_6S_7S_8S_9(e_{12}e_{23}e_{34}e_{411}e_{1110}e_{1012}e_{1213}e_{1314}e_{141})\}] + \\
&[\{S_3S_5S_6S_9(e_{78}e_{87})(e_{12}e_{24}e_{411}e_{1110}e_{1012}e_{1213}e_{1314}e_{141}) + S_5S_4S_6S_{11}(e_{78}e_{87})(e_{12}e_{23}e_{39}e_{910}e_{1012}e_{1213}e_{1314}e_{141}) + \\
&S_3S_5S_7S_9(e_{68}e_{86})(e_{12}e_{24}e_{411}e_{1110}e_{1012}e_{1213}e_{1314}e_{141}) + S_3S_7S_6S_9(e_{58}e_{85})(e_{12}e_{24}e_{411}e_{1110}e_{1012}e_{1213}e_{1314}e_{141}) + \\
&S_7S_6S_4S_{11}(e_{58}e_{85})(e_{12}e_{23}e_{39}e_{910}e_{1012}e_{1213}e_{1314}e_{141}) + S_5S_4S_7S_{11}(e_{68}e_{86})(e_{12}e_{23}e_{39}e_{910}e_{1012}e_{1213}e_{1314}e_{141})\} + \\
&\{S_9S_6S_5S_{11}(e_{12}e_{23}e_{34}e_{47}e_{78}e_{810}e_{1012}e_{1213}e_{1314}e_{141}) + S_9S_7S_5S_{11}(e_{12}e_{23}e_{34}e_{46}e_{68}e_{810}e_{1012}e_{1213}e_{1314}e_{141}) + \\
&S_9S_7S_6S_{11}(e_{12}e_{23}e_{34}e_{45}e_{58}e_{810}e_{1012}e_{1213}e_{1314}e_{141})\}] + \\
&[S_5S_6S_9(e_{78}e_{87})(e_{12}e_{23}e_{34}e_{411}e_{1110}e_{1012}e_{1213}e_{1314}e_{141}) + S_5S_7S_9(e_{68}e_{86})(e_{12}e_{23}e_{34}e_{411}e_{1110}e_{1012}e_{1213}e_{1314}e_{141}) + \\
&S_6S_9S_7(e_{58}e_{85})(e_{12}e_{23}e_{34}e_{411}e_{1110}e_{1012}e_{1213}e_{1314}e_{141})]
\end{aligned}
\tag{A.5.3}
$$

Permanent multinomial for case I of restructuring in packaging equipment industry

$$per(P') = [S_1S_2S_3S_5S_4S_6S_7S_8S_9S_{10}S_{11}S_{12}S_{13}S_{14}]+$$
$$[S_1S_2S_3S_5S_4S_6S_7S_8S_9S_{10}S_{11}S_{14}(e_{1312}e_{1213})+$$
$$S_1S_2S_3S_5S_4S_6S_9S_{10}S_{11}S_{12}S_{13}S_{14}(e_{78}e_{87})+S_1S_2S_3S_5S_4S_7S_9S_{10}S_{11}S_{12}S_{13}S_{14}(e_{68}e_{86})+$$
$$S_1S_2S_3S_7S_6S_4S_9S_{10}S_{11}S_{12}S_{13}S_{14}(e_{58}e_{85})]+$$
$$[S_1S_2S_3S_5S_6S_7S_8S_9S_{12}S_{13}S_{14}(e_{1110}e_{104}e_{411})]+$$
$$[\{S_1S_2S_3S_7S_6S_4S_9S_{10}S_{11}S_{14}(e_{58}e_{85})(e_{1312}e_{1213})+$$
$$S_1S_2S_3S_5S_4S_6S_9S_{10}S_{11}S_{14}(e_{1312}e_{1213})(e_{78}e_{87})+S_1S_2S_3S_5S_4S_7S_9S_{10}S_{11}S_{14}(e_{68}e_{86})(e_{1312}e_{1213})\}+$$
$$\{S_9S_6S_5S_3S_2S_1S_{11}S_{12}S_{13}S_{14}(e_{47}e_{78}e_{810}e_{104})+S_9S_7S_5S_3S_2S_1S_{11}S_{12}S_{13}S_{14}(e_{46}e_{68}e_{810}e_{104})+$$
$$S_9S_7S_6S_3S_2S_1S_{11}S_{12}S_{13}S_{14}(e_{45}e_{58}e_{810}e_{104})\}]+$$
$$[S_1S_2S_3S_5S_6S_9S_{12}S_{13}S_{14}(e_{78}e_{87})(e_{1110}e_{104}e_{411})+S_1S_2S_3S_5S_6S_7S_8S_9S_{14}(e_{1312}e_{1213})(e_{1110}e_{104}e_{411})+$$
$$S_1S_2S_3S_6S_9S_7S_{12}S_{13}S_{14}(e_{58}e_{85})(e_{1110}e_{104}e_{411})+S_1S_2S_3S_5S_7S_9S_{12}S_{13}S_{14}(e_{68}e_{86})(e_{1110}e_{104}e_{411})]+$$
$$[S_9S_6S_5S_3S_2S_1S_{11}S_{14}(e_{1312}e_{1213})(e_{78}e_{810}e_{104}e_{47})+S_9S_7S_5S_3S_2S_1S_{11}S_{14}(e_{1312}e_{1213})(e_{68}e_{810}e_{104}e_{46})+$$
$$S_9S_7S_6S_3S_2S_1S_{11}S_{14}(e_{1312}e_{1213})(e_{45}e_{58}e_{810}e_{104})]+[S_1S_2S_3S_5S_6S_9S_{14}(e_{78}e_{87})(e_{1110}e_{104}e_{411})(e_{1312}e_{1213})+$$
$$S_1S_2S_3S_5S_7S_9S_{14}(e_{68}e_{86})(e_{1110}e_{104}e_{411})(e_{1312}e_{1213})+S_1S_2S_3S_7S_6S_9S_{14}(e_{58}e_{85})(e_{104}e_{411}e_{1110})(e_{1312}e_{1213})]+$$
$$[S_3S_5S_4S_6S_7S_8S_{11}(e_{12}e_{29}e_{910}e_{1012}e_{1213}e_{1314}e_{141})]+$$
$$[S_3S_5S_6S_7S_8S_9(e_{12}e_{24}e_{411}e_{1110}e_{1012}e_{1213}e_{1314}e_{141})+S_5S_4S_6S_7S_8S_{11}(e_{12}e_{23}e_{39}e_{910}e_{1012}e_{1213}e_{1314}e_{141})]+$$
$$[\{S_3S_5S_4S_6S_{11}(e_{78}e_{87})(e_{12}e_{29}e_{910}e_{1012}e_{1213}e_{1314}e_{141})+S_3S_5S_4S_7S_{11}(e_{68}e_{86})(e_{12}e_{29}e_{910}e_{1012}e_{1213}e_{1314}e_{141})+$$
$$S_3S_7S_6S_4S_{11}(e_{58}e_{85})(e_{12}e_{29}e_{910}e_{1012}e_{1213}e_{1314}e_{141})\}+$$
$$\{S_9S_6S_5S_3S_{11}(e_{12}e_{24}e_{47}e_{78}e_{810}e_{1012}e_{1213}e_{1314}e_{141})+S_9S_7S_5S_3S_{11}(e_{12}e_{24}e_{46}e_{68}e_{810}e_{1012}e_{1213}e_{1314}e_{141})+$$
$$S_9S_7S_6S_3S_{11}(e_{12}e_{24}e_{45}e_{58}e_{810}e_{1012}e_{1213}e_{1314}e_{141})+S_5S_6S_7S_8S_9(e_{12}e_{23}e_{34}e_{411}e_{1110}e_{1012}e_{1213}e_{1314}e_{141})\}]+$$
$$[\{S_3S_5S_6S_9(e_{78}e_{87})(e_{12}e_{24}e_{411}e_{1110}e_{1012}e_{1213}e_{1314}e_{141})+S_5S_4S_6S_{11}(e_{78}e_{87})(e_{12}e_{23}e_{39}e_{910}e_{1012}e_{1213}e_{1314}e_{141})+$$
$$S_3S_5S_7S_9(e_{68}e_{86})(e_{12}e_{24}e_{411}e_{1110}e_{1012}e_{1213}e_{1314}e_{141})+S_3S_7S_6S_9(e_{58}e_{85})(e_{12}e_{24}e_{411}e_{1110}e_{1012}e_{1213}e_{1314}e_{141})+$$
$$S_7S_6S_4S_{11}(e_{58}e_{85})(e_{12}e_{23}e_{39}e_{910}e_{1012}e_{1213}e_{1314}e_{141})+S_5S_4S_7S_{11}(e_{68}e_{86})(e_{12}e_{23}e_{39}e_{910}e_{1012}e_{1213}e_{1314}e_{141})\}+$$
$$\{S_9S_6S_5S_{11}(e_{12}e_{23}e_{34}e_{47}e_{78}e_{810}e_{1012}e_{1213}e_{1314}e_{141})+S_9S_7S_5S_{11}(e_{12}e_{23}e_{34}e_{46}e_{68}e_{810}e_{1012}e_{1213}e_{1314}e_{141})+$$
$$S_9S_7S_6S_{11}(e_{12}e_{23}e_{34}e_{45}e_{58}e_{810}e_{1012}e_{1213}e_{1314}e_{141})\}]+$$
$$[S_5S_6S_9(e_{78}e_{87})(e_{12}e_{23}e_{34}e_{411}e_{1110}e_{1012}e_{1213}e_{1314}e_{141})+S_5S_7S_9(e_{68}e_{86})(e_{12}e_{23}e_{34}e_{411}e_{1110}e_{1012}e_{1213}e_{1314}e_{141})+$$
$$S_6S_9S_7(e_{58}e_{85})(e_{12}e_{23}e_{34}e_{411}e_{1110}e_{1012}e_{1213}e_{1314}e_{141})]$$

(A.5.4)

Permanent multinomial for case II of restructuring in packaging equipment industry

$$per\left(P^{''}\right)=\left[S_1S_2S_3S_{14}S_{13}S_{12}S_{11}S_9S_8S_4S_6S_5S_7\right]+$$
$$\left[S_{14}S_{11}S_9S_8S_4S_3S_2S_1S_6S_5S_7\left(e_{1213}e_{1312}\right)\right]+$$
$$\left[S_1S_2S_3S_{14}S_{13}S_9S_8S_6S_5S_7\left(e_{1112}e_{124}e_{411}\right)\right]+$$
$$[S_3S_{11}S_4S_6S_5S_7\left(e_{12}e_{29}e_{98}e_{812}e_{1213}e_{1314}e_{141}\right)+S_3S_9S_8S_6S_5S_7\left(e_{12}e_{24}e_{411}e_{1112}e_{1213}e_{1314}e_{141}\right)]+$$
$$[S_{11}S_4S_6S_5S_7\left(e_{12}e_{23}e_{39}e_{98}e_{812}e_{1213}e_{1314}e_{141}\right)+S_9S_8S_6S_5S_7\left(e_{12}e_{23}e_{34}e_{411}e_{1112}e_{1213}e_{1314}e_{141}\right)]$$

(A.5.5)

APPENDIX A.6

ALGORITHM FOR GRAPH THEORETIC MODELING

An algorithm to develop graph theoretic model for any manufacturing organization is presented below. It can be implemented by any manufacturing firm for comprehensive analysis and understanding of interaction cycles in the manufacturing system for possible improvement.

Step i Identification of different subsystems and interactions among them.

Step ii Representation of subsystems and interactions among them as a block diagram and a graph.

Step iii Development of permanent matrix.

Step iv Evaluation of the permanent function for the permanent matrix and obtaining the permanent multinomial.

Step v Graphical representation of the terms of the permanent multinomial as sub-graphs.

Step vi Identification of the sources of repetitive interaction cycles for possible reduction in complexity in interaction structure.

Step vii Structural comparison of the restructured systems with respect to the original systems using coefficients of dissimilarity as well as newly developed complexity indices.

Step viii Taking appropriate decisions for obtaining maximum benefit from restructuring exercises for developing lean manufacturing systems.

PUBLICATIONS BASED ON PRESENT STUDY

Published

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BRIEF BIOGRAPHY OF THE CANDIDATE

Varinder Singh is a lecturer in the Mechanical Engineering group at the Birla Institute of Technology and Science, Pilani, KK Birla Goa campus, Goa, India. He has over 9 years of teaching experience and has taught various courses in mechanical engineering like Production Planning and Control, Management of Production Systems, Plant layout and Design, Quality Control, Assurance & Reliability, Computer Integrated Manufacturing, Prime Movers and Fluid Machines, Thermodynamics, Engineering Graphics and Workshop Practice. Besides teaching in the institute, he was also involved in teaching the practicing engineers at TATA Power through on-line mode under the Work Integrated Learning Program of the institute. He has also contributed as Practice School-II faculty at BOSCH Ltd, Verna, Goa.

He completed his undergraduate study at Guru Nanak Dev Engineering College, Ludhiana and obtained B. E. degree of Punjab Technical University, Jalandhar, Punjab, India in 2000 in mechanical engineering. He obtained M. E. degree in Manufacturing Systems Engineering from Birla Institute of Technology and Science (BITS), Pilani, Rajasthan, India, in 2002. His current research interests are towards development of new methods for analysis of lean manufacturing systems, analysis of restructuring using graph theoretic and other MADM methodologies.

BRIEF BIOGRAPHY OF THE SUPERVISOR

Dr. Pravin Singru is an Associate Professor and currently heading the Mechanical Engineering Department at BITS Pilani, K K Birla Goa Campus. He obtained his M. Tech. from IIT, Kharagpur and Ph.D. from Visvesvaraya National Institute of Technology, Nagpur. His doctoral thesis was on "Dynamic and Vibration Response of Pulleys of a Belt Drive". Dr. Singru has more than 21 years of teaching experience. He teaches courses in the area of Mechanics of solids, Kinematics and Dynamics of Machines, Vibrations & MEMS. Dr. Singru has been associated with BITS Pilani administration as Member of selection committee for non-teaching staff, Faculty In charge (Workshop), Nucleus Member of Placement and Practice School Division, Member of Task Force for Mission 2012. He is actively involved in the curriculum redesign of Mechanical Engineering Program of BITS Pilani University. He has been guiding six research scholars for their research leading to Ph.D. degree of the Institute. He has published 17 research papers in International Journals and 36 papers in National & International Conferences. He is reviewer of 5 International Journals. He has organized Indo-Russian work shop on Topical Problems in Solid Mechanics, sponsored by DST and Russian Academy of Sciences, Nov, 2008. He has delivered talks on invitation from various Institutions in India. Dr. Singru is Coordinator of National center for MEMS design with a grant of Rs. 30 lakhs. Under his leadership, department has received Rs. 80 lakhs grant from DST under FIST Scheme. He has recently organized an international conference titled “Emerging Technologis-Micro to Nano (EMTM2N-2013)” in February 2013.