INVESTIGATING THE VALUE OF INTEGRATED OPERATIONS PLANNING IN MANUFACTURING INDUSTRIES

Ph.D. Thesis

By

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DISCIPLINE OF MECHANICAL ENGINEERING

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INVESTIGATING THE VALUE OF INTEGRATED OPERATIONS PLANNING IN MANUFACTURING INDUSTRIES

A THESIS

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requirements for the award of the degree
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DISCIPLINE OF MECHANICAL ENGINEERING
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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **INVESTIGATING THE VALUE OF INTEGRATED OPERATIONS PLANNING IN MANUFACTURING INDUSTRIES** in the partial fulfillment of the requirements for the award of the degree of **DOCTOR OF PHILOSOPHY** and submitted in the **DISCIPLINE OF MECHANICAL ENGINEERING, INDIAN INSTITUTE OF TECHNOLOGY INDORE**, is an authentic record of my own work carried out during the time period from January 2014 to November 2019 under the supervision of Dr. Bhupesh Kumar Lad, Associate Professor, Discipline of Mechanical Engineering, Indian Institute of Technology Indore, India.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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Date: 13/08/2020

PREAMBLE

An organization is constituted by multiple functions which demonstrates strong interdependencies amongst each other. Leveraging these interdependencies can improve the performance of an entire manufacturing system. Integrated approach for operations planning is one such approach which closely examines such interdependencies between various functions and ameliorates the system's performance. However, due to factors like multiple decision variables, intricated parametric correlations, complex business dynamics, stochastic nature of business processes, and many others, a comprehensive integration of the manufacturing value chain is absent both in theory and practice.

A detailed literature review presented in this thesis confirms the need for significant advancement of the framework pertaining to integrated operations planning. Consequently, present thesis extensively contributes to the body of knowledge by developing advanced approaches for multifunction integration in realistic manufacturing environment. Such integrated approaches are comprehensively investigated for a broad range of industrial setups. The result so obtained confirms the value of integrated approaches over the conventionally done interrelated and independent planning approaches.

Beyond, extended solution space leading to prolonged time to arrive at the solution, coupled with the absence of an implementation framework is another reason which curtails the effectuation of integrated operations planning. Subsequently, to address the challenge related to balancing the timeliness and quality of solution, an agent based methodology is proposed. Further, the framework for systematic implementation of the integrated approach is presented through sequential development of the elementary integrated models.

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DEDICATION

I dedicate this work to the loving memory of my grandparents Late Shri Balkrishna C. Purohit and Late Smt. Rukmani Devi, whose endeavor for simplicity, commitment and affection will keep inspiring me and many others.

LIST OF PUBLICATIONS

Peer-reviewed Journals

1. **Purohit, B.S.** and Kumar Lad, B. *"*Production and Maintenance Planning: An Integrated Approach Under Uncertainties*", International Journal of Advance Manufacturing Technology **(IJAMT)*** (2016) 86: 3179. DOI:10.1007/s00170-016-8415-9 (SCI Impact Factor =2.601)
2. **Purohit, B. S.,** Kumar S., Lad, B.K., Manjrekar V. and Singh V. "Optimization of Multi-Item Operation Sequences and Batch Size for Non-Parallel Capacitated Machines: A Case Study", *International Journal of Performability Engineering **(IJPE)*** (2017) 13(5) DOI:10.23940/ijpe.17.05.p1.557568 (H* Index= 11)
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Manuscript Under Review

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Other:

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*H Index retain a similar definition as that of the impact factor.
Read more:
https://blog.scopus.com/posts/the-scopus-h-index-what-s-it-all-about-part-i

Proceedings in International Conferences

1. **Purohit,B.S**. and Lad,B.K. "Joint Optimization of Quality & Maintenance Plan: Towards a Lean Enterprise". *Proceedings of 6th International Conference on Advancements in Polymeric Materials*, February 20-22, 2015
2. Ringard,J.B., **Purohit,B.S.** and Lad,B.K. "Integrated Operations Planning for a Multi Component Machine Subjected to Stochastic Environment." *5th International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SIMULTECH 2015),* Colmar, Alsace, France
3. Kumar, S., **Purohit, B.S**. and Lad,B.K. "Integrated Approach for Job Scheduling and Multi-Component Maintenance Planning in a Production System". *5th International & 26th All India Manufacturing Technology, Design and Research Conference (AIMTDR 2014)* December 12th–14th, 2014, IIT Guwahati, Assam, India

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NOTATIONS

TCO	Total cost of operation
TSC	Total set-up cost
$TICC$	Total inventory carrying cost
$TCOPM$	Total cost of preventive maintenance
$TCOCM$	Total cost of corrective maintenance
$TBOC$	Total backorder cost
$TOTC$	Total overtime cost
$\lambda_{M_{zp}}$	Decision of sequencing when zth product is scheduled on Mth Machine in pth production run
α_{zp}	Batch size for zth product during pth production run
π_t	π_t is the makespan time
τ_M	Time at which Mth machine completes processing of all the products
ω_{ij}	Wait time for zth product on Mth machine
ST_{zp}	Set-up time for zth for pth production run
CT_{zp}	Cycle time is the with time for zth product during pth production run,
S_t	Scheduled delivery time
Q_p	Quantity produced of the pth product
$\bar{a}_m$	Maximum available time per machine
ψ_{jp}	Time at which jth operation of pth product is started
κ_{jp}	Time at which jth operation of pth product is completed
θ_{C_pM}	Machine allocation factor for pth product on Mth machine
Φ_{Mp}	Scheduled production factor;
RL_{zp}	Machine run length for zth product during pth production run

OQ_{ij}	Order quantity for raw material of i^{th} product in j^{th} month
FD_{ij}	Forecasted demand of i^{th} product in j^{th} month
SQR_i	Supplier quality rating for i^{th} product
MQR_i	Machine quality rating for i^{th} product
ST_{ij}	Sequence dependent set up time for i^{th} production run in j^{th} month
MLC	Manufacturing labor cost
IC_i	Inventory carrying cost of raw material for i^{th} product per unit per hour
T'_{ij}	Summation of manufacturing time and set-up time for i^{th} production run during j^{th} month.
PMF_{kpj}	Preventive maintenance factor for k^{th} component before p^{th} production run
CMF_{kpj}	Corrective maintenance factor for k^{th} component before p^{th} production run
NF_{kp}	Number of failures of k^{th} component during p^{th} production run
MT_{pj}	Machining time for p^{th} production run in j^{th} month
η_k	Scale parameter of k^{th} component
β_k	Shape parameter of k^{th} component
Ia_{kp}	Initial age of k^{th} component before p^{th} production
r_k	Restoration factor for k^{th} component
AD_{ij}	Demand of i^{th} product in j^{th} month
BO_{ij}	Backorder of i^{th} product in j^{th} month
IF_{qn}	Inspection factor for q^{th} characteristics after n^{th} production ru
TMC	Total maintenance cost
MLC	Manufacturing labor cost
R	Restoration facto for kth component
T_{cm_n}	Corrective maintenance time for the n^{th} production run

T_{pm_n}	Preventive maintenance time for the nth production run
FT	Fixed administrative time required to initiate any maintenance activity
T_A	Assembly/ disassembly time
RF	Rejection factor
IF	Inspection factor
V_{qn}	Measured value of qth characteristics of the part produced in nth production run,
ν_q	Time to inspect the qth quality characteristics
C_{DR}	Cost of detected rejections
C_{UDR}	Cost of undetected rejections
C_o	Cost of ordering
C_{rm}	Cost of material
SSF_{xyz}	Supplier selection factor for zth product for yth supplier in xth month
Q_{xyz}	Quantity ordered in xth month of zth product from yth supplier
SS_{zx}	Safety stock of zth product in xth month
TSC	Total Supply cost
UP_{yz}	Unit price for raw material of zth product from yth supplier
DF_{zy}	Discount factor for raw material of zth product from yth supplier
C_s	Cost of setup
C_m	Cost of machining
C_D	Cost of delayed delivery
C_B	Cost of backorders
I_{avg}	Average inventory of zth product for xth month
$T\bar{\bar{P}}C$	Total Penalty Cost
DC_{zxt}	Delay cost for tth customer for the zth product in xth month

ADD_{zxt}	Actual delivery date for z^{th} product in x^{th} month from t^{th} customer
CDD_{zxt}	Committed delivery date for z^{th} product in x^{th} month from t^{th} customer
ϵ_{xtz}	Number of backorders in x^{th} month for t^{th} customer for z^{th} product
P_{zt}	Per day penalty cost for delay of the z^{th} product for t^{th} customer
T_{ps}	Time when order for p^{th} product is made to s^{th} supplier
FC_{pm}	Fixed cost for preventive maintenance
FC_{CM}	Fixed cost for corrective maintenance
D_{np}	Detected rejections of n^{th} characteristics in p^{th} production run
U_{np}	Undetected rejections n^{th} characteristics in p^{th} production run
CDR	Cost of detected rejections
CDUR	Cost of undetected rejections
SM_{pn}	Specification met factor for n^{th} characteristics in p^{th} production run
V_{pn}	Measured value of n^{th} part in j^{th}.run
$TOTC$	Total overtime cost
TTO	Total time of operation
BWT	Basic work time

ACRONYMS

NP	Non-deterministic Polynomial
SO	Sub Objective
ELS	Economic Lot Scheduling
CLS	Capacitated Lot Sizing
DLS	Discrete Lot Sizing and Scheduling
GLS	General Lot Sizing and Scheduling
PFD	Personal, Fatigue and Delay
PFC	Process Flow Chart
GA	Genetic Algorithm
MOST	Maynard’s Operations Sequencing Technique
FCFS	First Come First Serve
SPT	Shortest Processing Time
LPT	Longest Processing Time
CM	Corrective Maintenance
PM	Preventive Maintenance
TTR	Time To Repair
RM	Raw Material
OT	Over Time
SA	Simulated Annealing
TS	Tabu Search
CTQ	Critical To Quality
USL	Upper Specification Limit
LSL	Lower Specification Limit

CHAPTER 1
INTRODUCTION

Current chapter introduces the topic of this dissertation and the provides an overview of the research theme. It elaborates the motivation behind selection of "Integrated operations planning" as the research area and highlights the key gaps in existing body of literature. Further, the identified gaps are translated into the objective and sub objectives which are realized in subsequent chapters. The chapter also provides a prelude about these chapters and overall structure of the thesis.

1.1 Preface

Manufacturing industry plays a key role in the economic growth and development (Haraguchi et al. 2017). For the same reason, the domain of manufacturing continues to receive significant attention from researchers and practitioners alike. This is also evident from the transformation of manufacturing industries which evolved from days of hand production to current trend of automated and agile manufacturing. This evolution is a result of the globalization, narrowing product lifecycle and diminishing margins, which has compelled the industry to constantly look for the ways to improve their performance.

In line with this, manufacturing industries continue to explore all the fronts through which their performance can be improved. Under such a competitive scenario, day to day activities plays a crucial role as the outcome of an industry is significantly dependent on the way ground level activities are planned and executed. This detailed level planning of the different functions of an organization is known as operations planning.

Operations is reckoned to be constituted by functions like production, maintenance, quality, material management etc. Each of these functions plays a critical role and have multiple decisions to be optimized. The result of all such optimized decisions is reflected in the performance of any organization.

Operation planning too has evolved over the period and have moved from an “Independent planning” to “Interrelated planning” and subsequently to “Integrated planning”. Independent planning refers to an approach in which each of the function is considered as independent function and all the related decisions are considered in silos.

However, it was later realized that the functions of operations exhibit strong correlation amongst each other and the decision relate to one function may significantly impacts the decision of other. For instance, to minimize the setups and maximize the machine utilization, production function may plan continuous production without providing ample hours for the upkeep of machines. This may negatively impact key indicators of maintenance function such as mean time to repair, number of breakdowns, preventive maintenance schedule adherence etc. Eventually it may also impact production and quality function alike as the poorly maintained machine is prone to produce defective parts, and frequent failures leads to production halts and delayed deliveries. It is thus evident that it resembles an atrocious cycle where planning of one function impacts the performance of other function which in turn impacts the performance of the same function for which the plan was primarily made. During the isolated treatment of these functions such interdependencies are tuned out and results into sub-optimal performance of the organization as a whole. While such independent viewpoint enriches the fundamental research, owing to the interdependencies amongst these functions, it does not ascertain the overall improvement in performance at the enterprise level.

To incorporate such dependencies “Interrelated approach” came into prominence in which the decisions of one function were used as a constraint for optimizing the decisions related to other functions. To exemplify, in the work of Tambe and Kulkani (2015), authors encompasses production schedule, preventive maintenance and quality control. It first independently identifies an optimal schedule for the batches to be processed and later maintenance and quality control decisions are optimized. Though the work considers interdependencies between the functions, this doesn’t ascertain that the maintenance schedule so arrived is optimal as an adherence to optimized production schedule becomes a constraint.

It demonstrates that though interrelated planning approach were better than independent approach, the dependencies between the functions were not fully utilized. This led to the development of "Integrated operations planning" approaches in which parameters of different functions are treated together and the decisions related to various functions are simultaneously optimized. It is thus more of coalescence of individual functions at parametric level for negotiating individual's overlapping objectives and align them to operational goals.

Subsequently, integrated approach stared gaining attention and more research was carried out to explore its potential. Through such work it was strongly demonstrated that integrated approaches lead to economic benefits and significant improvisation in the system performance compared to the conventionally done isolated approaches. For example, Cassady and Kutanoglu (2003) achieved 30% improvement in makespan. Similarly, Pandey et al. (2011) found an average improvement of 80% in expected cost per unit time through integration of production and maintenance decisions. Likewise, Zied et al. (2011) have obtained 6% improvement in total cost by combining inventory and maintenance.

These results manifests that integrated planning approach are seen as a promising approach for ameliorating system performance. However, through the review of the literature on the integrated planning, which is presented in subsequent chapters, few of the prominent gaps are identified. This indicates that there is a pressing need of further exploration in this area. This need becomes the motivation behind this work.

1.2 Problem Description

Despite of the perceived benefits of the integrated approach, it is observed that the independent planning approach still prevails in the shop floor. As a result, a round table discussion between the managers of the related function is often required to adjust such independently arrived operations plans and accommodate the requirements of the conflicting functions before implementation. The subjectivity involved in this process often lead to suboptimal performance of the manufacturing system. Moreover, such round table adjustments will be outmoded with increasing incursion of intelligent assets. Therefore, it has become imperative to replace the conventional operations planning scheme with more and more integrated approaches

In line with this, current work attempts to contribute towards development of framework for parametric level integration of various disjoint functions of a realistic manufacturing value chain and evaluate its value for manufacturing setups. The research problem of this dissertation is thus stated as "

"*Investigating the Value of Integrated Operations Planning in Manufacturing Industries"*

1.3 Gaps in literature

Keeping the problem statement in mind, a thorough literature review was done, the details of which are presented in subsequent chapters. Based on the insight gained from the literature and industrial practices, following gaps have been identified in the context of the problem at hand.

Gap 1: Integration of disjoint functions has been considered in a very simplistic environment. Aspects like multi component design of machine, the dependencies which exist between the components, multiple modes in which the component can fail, multiple quality characteristics of the product being made, stochastic nature of business processes, etc. are not simultaneously accommodated while developing the integrated models. Ignoring such aspect lead to a scenario which is idealistic but significantly differs from the actual characteristics floor and thus widens the breach between the theoretical models and their applicability on the floor.

Gap 2: The most prominent combination which comes across in the literature is one of the three combinations viz. production and maintenance, production and quality; and quality and maintenance Owing to the level of control, functions like production, maintenance are considered as internal function whereas and supply planning is considered as an external function as major part of its execution of dependent on external suppliers. Joint integration of such internal and external function is not reported in literature.

Gap 3: Considering the ramification involved in modeling stochastic nature of the processes and parametric dependencies between disjoint functions, the extent of integration is primarily restricted to two functions only. This deprives the existing models to have a holistic consideration which is required for the panoramic management of the entire value chain. It is thus required that the extent of integration be increased beyond two functions. This is another reason for which function like material supply planning needs to be encompassed while applying the integrated approach. This contemplation is required to align with the emerging trend of value chain thinking, where the supply planning is treated as enabler for value creation at the organizational level.

Gap 4: Considering the fact that operations planning decision needs to be implemented at the shop floor before the clientele changes and associated fluctuations, it is pivotal to develop a solution method which reduces the computational time. Existing literature reporting integration framework rarely emphasizes on the computational time elapsed to arrive at near optimal solution.

Gap 5: Even though shop floor engineers/managers agree with the relevance of integration, they are not able to implement it due to the lack of a formal framework and methodologies for the same.

1.4 Research scope & objective

Based on the identified gaps, the literature of integrated operations planning need to be advanced by:

- Relaxing unrealistic assumptions,
- Developing integrated approaches for real and complex manufacturing environments,
- Considering more operations functions for integration,
- Performing comprehensive investigation to generalize the value of integrated approache

Further, the integration of multiple operations functions comes with computational complexity which poses second challenge in terms of responsiveness of the value chain. For example, complex job scheduling problems are NP-hard i.e. non-deterministic polynomial-time hard (Tambe et al., 2013). Integraing other functions for scheduling further increaes the complexity and the solution time. On the other hand, extensive use of information technology is allowing customers and suppliers to directly interact with the manufacturing facility, which in turn necessitates a high level of responsiveness in the value chain to sustain in competitive economy. Therefore, quick response to dynamic conditions is important in captivating the advantages of the digitization in industries. Consequently, next essential advancement in the literature of integrated operations planning is to develop an autonomous decision-support system which provides fast response and uses the characteristics distributed intelligence/computation, communication, etc.

Based on the identified opportunities which still needs to be explored in the field of integrated operations planning, the objective of "Investigating the value of integrated operations planning in manufacturing industries" is attempted to be realized through the fulfillment of below mentioned sub-objectives (SO):

(1) SO1: Modeling a realistic environment by defying some of the assumptions present in the available literature,
(2) SO2: Comprehensive investigation of integrated operations planning approach to generalize the value of the same,
(3) SO3: Extending the scope of integrated operations planning by including functions that are external to a manufacturing organization,
(4) SO4: Developing the integrated operations planning for next generations smart factory.

These sub-objectives are realized through development of integrated models which translates the real-world complexities into mathematical formulations to optimize the operational metrices. Considering the complexity involved, functions were initially considered combinatorically and then extended to encompass the entire value chain. For instance, elementary models related to integration of Production and Maintenance, Maintenance and Quality, Production, Maintenance and Quality were first developed. Subsequently the entire value chain is integrated using these models. Each of the combinatorial model so developed was comprehensively evaluated under a broad range of manufacturing environment. For all such environment, parametric variability was induced to factor the stochastic nature of the associates processes. Subsequently, improvisation realized in the system performance was evaluated to establish the value of integrated operations planning approach.

1.5 Thesis outline

Above objectives are addressed in the thesis in five chapters. Table 1 presents the overview of the chapters and objectives addressed in the same.

Table 1.1: Overview of the thesis chapters

Chapters	Title	Functions considered	Illustrated with	Objectives Addressed
Chapter 2	Intra-function parametric integration: a case study	Integration of Batch size and Production schedule	Industrial case	SO1 and SO2
Chapter 3	Integration of production planning and maintenance planning	P+M	Numerical example	SO1 and SO2
Chapter 4	Integration of maintenance planning and quality planning	M+Q	Industrial case	SO1, SO2 and SO4
Chapter 5	Integration of production, maintenance and material supply planning	P+M+S	Numerical example	SO1, SO2, SO3
Chapter 6	Panoramic integration of the manufacturing value chain	P+M+Q+S	Industrial case	SO1, SO2, SO3 and SO4

P= Production, M= Maintenance, Q= Quality, S= Supply

Additionally, chapter 1 introduces the research problem and conclusion of the research work is presented in chapter 7.

An overview of each chapter is as follows:

Chapter 2 reports an overture in form of a case study**,** wherein a preliminary model is developed which considers integration the decision function of a single function (production planning) thereby validating the value of integration in a stochastic environment. The findings from this work further motivate to investigate the value of integration of decision variable of multiple functions. **Chapter 3** aims to develop an integrated plan for production and maintenance of a multi component machine. It simultaneously determines production lot size, assembly specific preventive maintenance schedule and job sequencing for a multicomponent machine. The work considers an environment which is characterized by stochastic processes and uncertainties related to demand, supply, machine yield etc. Further, the approach is evaluated at multiple level of decision making such as long term, short term and immediate and for multiple key performance indicators such as machine availability, total number of failure and total cost of operations. Thus, the chapter helps in achieving sub objective 1 and 2 of the present research. **Chapter 4** aims to develop an integrated plan for maintenance and product inspection. It considers a multi-component machine and accommodates multiple dependencies (Stochastic, structural and economical) which exists between the constituent components of the machine. In addition, various potential failure modes in which these components can fail were modeled and the impact of such failures on multiple quality characteristics of the product was examined. Towards, the end of this chapter distributed approach is also presented as a solution method. Thus, the chapter helps in achieving sub objective 1,2 and 4 of the present research.

Chapter 5 advances the previous chapters by integrating material supply planning with production planning and inspection planning. It considers a stochastic environment where production and maintenance processes are imperfect and where there is significant dubiety related to demand and supply of material. As an outcome, the developed model optimizes order quantity for individual suppliers, job production sequence, production lot size and Preventive maintenance schedule. This chapter helps in achieving sub objective 1,2 and 3. **Chapter 6** considers an entire value chain from the perspective of integration. It aims at improving the performance a manufacturing firm by leveraging the interdependencies between four of the key functions namely production, maintenance, inspection and material planning. Causal linkages among these disjoint functions, the extent & constitution of integration, and the firm's performance are examined. Further, an agent based stochastic modelling approach is developed to balance the quality and timeliness of solution and an algorithm is formulated to negotiate and jointly optimize the conflicting decisions of these functions. It further evaluates various operations planning approaches against the proposed approach to demonstrate its superiority over the existing ones. This chapter helps in achieving all the sub objective of the present research

Chapter 7 concludes the research work by summarizing the research findings and contribution, and illustrates the future scope for the research.

1.6 Summary

The present thesis aims to advance the existing body of knowledge by developing a framework for multi-function integration for complex manufacturing environment and comprehensively investigating its value for various manufacturing environment. It further, proposes an agent based approach as an agile solution method. These approaches help in systematic expansion of integrated operations planning in diverse real-world manufacturing environments.

CHAPTER 2*

INTRA-FUNCTION PARAMETRIC INTEGRATION: A CASE STUDY

***Key Highlights**:*

Purpose: Current chapters aims to investigate the value of intra-function parametric integration. It considers production function of a complex manufacturing firm and integrate two of the critical decisions viz. production sequence and production batch size. Through this chapter, the complexities associated with the manufacturing environment are closely examined to incorporate them in subsequent chapters for inter- function integration.

Objective fulfilled: The current chapter helps in partially addressing sub objectives 1 (SO1) mentioned in chapter 1.

Findings: It is observed that after integration, an improvement of around 12.6 percent in makespan time could be realized. Parallelly, an improvement in the range of 2 to 17 percent was observed in terms of machine utilization.

***Originality and Contribution**:* Current work considers a real and complex manufacturing environment for integration in which around 17 products get produced through 23 machines. It is characterized by constraints related to process flow, minimum production quantity, available machine hours etc. Such constraints are complex to formulate and thus were relaxed in literature, resulting into a very simplistic environment for integration. Current work incorporates all such constraints and associated intricacies and thus advances the existing body of literature by defying the assumption made in past.

***Practical Implication**:* The framework proposed in this chapter leads to an improvement in the utilization of machines and facilitate the timely delivery of customer orders through the reduction in makespan time. The framework illustrated here can be easily adapted to any industrial environment without requiring any systemic changes in the operating system

**A part of the work presented in this chapter is published under the title "Optimization of Multi-item Operation Sequences and Batch Size for Non-Parallel Capacitated Machines: A Case Study". Purohit, B.S., Kumar, S., Manjrekar, V., Singh V., and Lad,B.K. in the International Journal of Performability Engineering (IJPE).*

2.1 Introduction

As mentioned in chapter 1, despite of the perceived benefits of the integrated approach its implementation at the shop floor is scarce. A part of this scarcity could be attributed to characteristic complexity of the manufacturing environment. Since, existing body of literature does not provide a framework through which complexities can be incorporated, the adaptation of the postulated majorly remains confined to hypothetical environments. To bridge this gap, current chapter attempts to factor all the complexities of a manufacturing environment and formulate them for the integrated planning.

Further, the intricacies of the problem will grow by manifold if the characteristic complexity of the manufacturing firm is considered along with the organization wide integration and simultaneously coupled it with all the decisions related to multiple functions. Considering the same, as a prelude, current chapter emphasises primarily on the production function and develop the framework for intra-function integration for a multi- machine environment. The observations related to complexities of the manufacturing setup are incorporated in subsequent chapters which deals the research problem at a single machine level.

Literature specific to the production scheduling is presented as under:

Zhu and Wilhelm (2006) comprehensively reviewed the literature related to simultaneous consideration of scheduling and lot sizing. It focuses on papers addressing a variety of machine configurations including single machine, parallel machine, flow shop, and job shop systems and reviews the optimization and heuristic solution methods used for each category. The work summarized the six prominent variations in which combined lot sizing and scheduling problems can be categorized. These variants are as follows:

i. Economic Lot Scheduling (ELS) in which the planning horizon is infinite;
ii. Capacitated Lot Sizing (CLS), in which jobs are scheduled in each period separately;
iii. Discrete Lot Sizing and Scheduling (DLS), which subdivides macro

periods of CLS into micro periods in which only one-part type may be processed at full capacity;

iv. Continuous Setup Lot Sizing adapts DLS, allowing at most one-part type each period but using less than full capacity;

v. Proportional Lot Sizing and Scheduling adapts CSL, allowing unused capacity to process a second part type in a period;

vi. General Lot Sizing and Scheduling (GLS) incorporates a user-defined parameter to restrict the number of lots per period.

The categories mentioned above covers almost all the possible forms in which the combined lot sizing and scheduling problems are dealt. Further, few of the common gaps which exists invariably in all such form is related to the objective function used for optimization. From the 26 articles reviewed,18 considered the makespan as the objective function. The disadvantage of this is that when the optimization is executed for minimizing the makespan, the advantage of staggered dates for customer delivery are not leveraged. This on the other hand can cause an impact on the finished goods inventory and also the cost which might be incurred in expediting the production. The work also highlights that the single-machine configuration has received the bulk of attention due to its relative simplicity. However, the approach through which the schedule is optimized may not necessarily hold good for a multi-machine environment due to the sequence dependent operations.

Work by Hazir & Kedad- Sidhoum (2014) is from the recent past which addresses the simultaneous optimization of batch size and production lot size with an aim to minimize sum of weighted earliness, tardiness penalties and setup costs. For a single machine, the work describes solving algorithms and imposes upper and lower bound to batch size for arriving at an optimized result. However, such restriction on batch size may confine the feasible solution space and scope of finding a better solution is narrowed down.

Mortezaei & Zulkifili (2013), also developed a model for scheduling and lot sizing which enables users to find optimal production quantity, sub-lot size, inventory levels etc. The model is tested for different scenarios using hypothetical numerical example but has considered few of the assumptions such as same process routes for all the products, negligible set up time, no precedence constraint etc. Further, the model considers only single day planning horizon and does not allows any backlogging. It can be observed that such observations lead to a significant deviation from the actual shop floor environment which, in reality, is much more complex.

Delporte and Thomas (1977) states that the problem of determining both lot sizes and repeating sequences for multiple products is difficult due to the combinatorial and continuous nature of the problem. Such are NP hard problems and most of the work that has been done on the problem has made various assumptions to simplify the problem. The main factor which differentiates the available literature is predominantly the heuristic applied. Besides, factors like simplified replication of the shop floor, consideration of few products, exclusion of stochastic nature of manufacturing and lack of practical implications, are found in majority of the available literature.

It is evident from literature mentioned above and more, that various algorithms which suggest solution for multiple versions of the integrating the scheduling and lot sizing problem are well acknowledged. But it also highlights that majority of the reported work considers multiples assumptions which are rarely observed on real shop floors. For example, product with slightest of commonality getting processed on same machine, all the jobs are considered to have same characteristics related to cycle time, setup time etc. Such an extent of similarity is rarely observed and is overly restrictive. Such assumptions lead to a simplistic replication of shop-floor and thus significantly deviate from real and complex manufacturing environment. It is also observed that the algorithms so developed are special-purpose algorithms i.e. each algorithm is developed for a specific environment to solve a particular problem. For instance, some algorithms are only applicable to single machines, some for two-machine problems while others for multiple parallel / related machines. Further, effectiveness of such algorithms in handling the extension of the addressed problems is acutely discussed (Dudek et al. 1992).

During exhaustive literature review, authors didn’t come across a real industrial application of integrated scheduling and lot sizing problem which is applied to an environment which has more than 10 machines. Further, such exact algorithms involve lengthy and complex equation, which requires thorough understanding of advanced mathematics and thus making it difficult for practitioners to interpret and apply (Peterson & Silver, 1985). Thus, practitioners prefer algorithms that are simpler, even though they may generate suboptimal solutions (Gaafar, 2006).

The review of the literaure mentioned above and more, also highlights the charactreisitc complexities of a manufacturing system. The same are summarized as under:

1. Capacitated Environment
2. Constraint of succesor and predecessor operation
3. Imperfect production process leading to stochastic process yield
4. Imperfect maintencae process leading to varying degree restoration of the machine age
5. Sequence dependent setup time
6. Complex architecture of end product leading to large number of assemblies, subassemblies and component
7. Constraint of delivery schedule
8. Constrain of minimum batch run length to ensure the optimality of production economy etc.

Likewise, as identified from the literature, the key parameters for integrated scheduling can be identified as under:

1. Production cycle time for the components on individual machines
2. Setup time of each component on each machine
3. Demand of the individual component
4. Operating process sequence
5. Number of availble machines
6. Number of components to be produced

Current chapter thus first attempts to address the above-mentioned gaps related to intra-function integration. The framework developed in this chapter and the understanding of the complexities of manufacturing set up is then extended to incorporate other functions for integration.

2.2 Industry background, description of industrial environment and problem summary

2.2.1 Industry background

Current study is based upon observations and findings derived from one of the manufacturing plant of a firm named AVTEC private limited. The plant manufactures power trains and precision engineered products for diverse applications in automotive and off highway industry.

2.2.2 Description of industrial environment

In its current form, the layout of the plant is broadly divided into multiple sections which are similar in terms of key manufacturing operations, kind of machines, process management etc. Therefore, instead of considering entire plant, a representative section is considered for current study. This representative section manufactures "Transmission Sets" and caters to the demand of multiple customers by producing multiple variants of transmission sets. Functionality wise, all such variants are same but minor changes occurs in few of the dimensions and material of constituent products. Even the manufacturing process for individual products doesn't call for any extra setup from variant to variants and thus for all the practical purposes these variants can be treated same. In addition, the plant also caters to the demand of spares of these individual products. The demand of spares is different for different products, which creates unevenness in the total quantity of individual products to be produced.

In order to meet customer demand, at its maximum capacity, the section under consideration can run for 3 shifts a day and 6 days per week. Considering appropriate allowances for Personal, Fatigue and Delay (PFD allowances), the maximum available time per day for production is 1162 minutes. However, depending on factors like demand, machine breakdowns, absenteeism, availability of raw material etc., the number of production days in a month may vary.

"Transmission Sets" produced are independent block comprising of sub-assemblies, intermediate assemblies, sub-products, parts etc. Most of these parts are bought out elements which are outsourced from multiple suppliers. The firm only focuses on production of 11 critical and precision engineered products, which eventually goes into final assembly of transmission. In absence of any one of these product, final assembly of transmission set cannot be completed and customer demand cannot be fulfilled. Thus, a set of all these 11 in-house produced products is collectively called as “Whole Set”. The raw material for these “Whole Sets” undergoes a wide range of machining operations including shaving, milling, shaping, machining, etc. which are carried out on multiple machines. The process flow for each of these products is predefined by the process engineers. However, the sequence in which these products are loaded on various machines can significantly affect production economies. A randomly planned production sequence may lead to either machine waiting for product which is getting processed on another machine or product waiting for machine which is busy processing another part. Considering complex process flow and production of multiple products on multiple machines, an optimized sequence of production holds prime importance for timely completion of “Whole Set” and fulfilling customer demand.

Likewise, production economies also get severely impacted by the decision related to production batch size. For example, a larger batch size of production of a product will hinder the timely production of remaining product. On the other hand, splitting the batch size into too smaller quantities will call for frequent set ups changes and will lead to decrease in available time for core manufacturing. This highlights the need of optimized production batch size for different products. Such optimized batch size may be unalike for different operations on different products and may bring a non- uniformity in quantity produced of different products. To streamline this, organization assembles the maximum number of whole sets which can be completed with the available quantity of various products produced. The remaining quantity of all the processed products is carried forward and deducted from demand of individual product for next time period.

While optimizing production sequence and batch size, organization faces various constraints such maximum available production hour, minimum lot size, precedence and antecedence of individual operations, etc.

2.2.3 **Problem summary**

Above mentioned description can be summarized as an environment of multiple non-parallel capacitated machines processing various products, each essential for final product and having an individual and unique process flow. Currently, the decision related to sequence of operations on individual machines and production batch size for each product on each machine is intuitive and influenced by production planner's limited domain knowledge. Such a person dependent planning approach may not be efficient and can negatively affect organization's performance. To develop a planning process, which is person independent and efficient, a data driven model based on systematic algorithm is essential. Further, since the nature of business is dynamic, it is expected that in future there may be change in process flow, number of machine, number of product etc. It is therefore required that the model should be generic and flexible enough to accommodate such variations. In addition, the model should also assist practicing managers in improving values for specific performance indicators such as makespan.

2.3 Model development and validation

2.3.1 **Model development**

As mentioned above, the organization's prime focus is to fulfil the customer demand of transmission sets in minimum possible time and thus organization's aim is to minimize the makespan of "Whole Sets". The makespan will vary with the sequence in which individual products are loaded on different machines. Thus, one of the decisions which concern the organization is regarding the sequence in which a product should be loaded to individual machines. The production batch size for each of these is another decision which impacts performance of the schedule. If "M" be the number of machines, "z" be number of products produced, "p" be the number of production runs, and "t" be the time period for planning, then these two decisions can be expressed as:

I. $Decision\ of\ Sequencing : \lambda_{M_{zp}}$, such that

$$\lambda_{M_{zp}} = \begin{cases} 1, & when\ z^{th}\ product\ is\ scheduled\ on\ M^{th} Machine\ \ in\ p^{th}\ \ production\ run \\ 0, & otherwise \end{cases}$$

II. $Decision\ of\ Batch\ Sizing : \alpha_{zp}$, such that

$\alpha_{zp} = Batch\ size\ for\ z^{th}\ product\ during\ p^{th} production\ run,$

And objective of minimizing makespan can be mathematically mentioned as:

$Objective$:

$$Minimize\ (\pi_t) = \ Minimize\ \{\text{Max}\ (\ \tau_M)\} \qquad (2.1)$$

Where,

$$\tau_M = \sum_{M=1}^{M=M} \sum_{p=1}^{p=p} \sum_{z=1}^{z=z} \{\lambda_{\text{M}_{\text{zp}}} \times [\omega_{zM} + ST_{zp} + (CT_{zp} \times \alpha_{zp})]\} \qquad (2.2)$$

Such that π_t is the makespan time , τ_M is the time at which Mth machine completes processing of all the products, ω_{zM} is the wait time for zth on Mth machine, ST_{zp} is the set up time and CT_{zp} is the cycle time is the with time for zth product during pth production run,

$Subject\ to$:

- Dispatch schedule constraint:

Organization follows policy of periodical dispatches, which are generally scheduled on weekly basis. This sets up a time constraint which can be written as:

$$\pi_t \leq S_t \qquad (2.3)$$

where S_t is the scheduled delivery time.

- Demand constraint:

Besides the constraint of timely shipment, there is another constraint for the quantity of “Whole sets” to be shipped in a particular time period. This translates in to constraint for minimum quantity to be produced, in order to fulfil the complete demand. The same can be written as:

$$\{Min.\left(Q_p\right)\} \geq D_t \ , \qquad (2.4)$$

where, Q_p is the quantity produced of the pth product

- Maximum Available Production Hour per Machine Constraint:

Considering the Personal, Fatigue and Delay allowance, maximum available time per machine $\bar{a}_m$ for production is 1162 minutes. Mathematically, same can be expressed as:

$$\bar{a}_m \leq 1162 \times d, \ \forall \ \text{m}, \text{m} \in [1,\text{M}] \quad (2.5)$$

- Precedent and Succeeding Operation Constraint:

Each product undergoes a series of operations before it gets completed for final assembly. The sequence in which these operations should be carried out is predefined in the “Process Flow Chart (PFC)” which is a structured document representing the sequential flow of activities. PFC clearly communicates the preceding and succeeding set of activities for all the operations and is arrived at by considering multiple parameters such as feasibility of operation, change in material property after each operation, dimensional tolerance etc. Deviation from process flow may lead to devastating effect on quality of final product. This renders the constraint of preceding and succeeding operation which can be written as:

$$\psi_{jp} \geq \kappa_{jp} , \quad (2.6)$$

where, ψ_{jp} is time at which j^{th} operation of p^{th} product is started and κ_{jp} time at which j^{th} operation of p^{th} product is completed

- Product multi -allocation constraint

To ensure that at any point of time, a product is not allocated simultaneously on multiple machines for production, a machine allocation factor(θ_{C_pM}) is introduced such that:

$$\sum_{p=1}^{p=M}(\theta_{C_pM}) \leq 1 , \quad (2.7)$$

Where,

$$(\theta_{C_pM}) = \begin{cases} 1, & if\ p^{th}\ product\ is\ processed\ on\ m^{th} Machine \\ 0, & otherwise \end{cases} \quad (2.8)$$

- Machine parallel production constraint:

Likewise, to ensure that at any point of time, a machine is not processing multiple parts simultaneously, a “Scheduled Production factor Φ_{Mp} such that:

$$\sum_{p=1}^{p=p}(\ \Phi_{Mp}) \leq 1, \qquad (2.9)$$

Where, $(\Phi_{Mp}) \ = \begin{cases} 1, & when\ M^{th} machine\ is\ processing\ p^{th}\ product \\ 0, & otherwise \end{cases}$

(2.10)

- Minimum batch run length constraint:

To avoid frequent machine set ups, it is required that for any particular batch, machine should have a run length (RL) for a minimum of one production shift. i.e.

$$\{\ Min. RL_{zp} \geq \left(\frac{1162}{3}\right) minutes \qquad (2.11)$$

2.3.2 Modal validation

In order to check correctness of the model, simulation runs for some intuitive scenarios were performed. These scenarios were generated by altering the number of machines, number of product in wholeset, time period etc. The results obtained were in line with the expected outcomes. For example, when the model was optimized for of 2 machines and 10 products in a simplified environment such as no job priorities, all jobs starting at first work centre etc., the results were aligned with conventional Johnson’s rule. In addition, using the real shop floor data, the modal is also critically examined and validated by process owners at AVTEC private limited.

2.4 Problem complexity, solution approach, data set and results

2.4.1 Problem complexity

Conventional production scheduling problem of “M Job-1 Machine” can have M! feasible solutions. In the current work, considering the distributed process flow of products, it is safe to assume that each of the 23 machines, on an average, processes 6 products. This leads to the total number of feasible solution for production sequence to be as high as $(6!)^{23}$. In addition, for every single production run on individual machine, there may be a variation in lot size which further increases the solution space by manifolds. Since the production manager needs to timely arrive at these decisions to start production, time to arrive at a solution also plays a critical role. Such a complex scenario therefore calls for carefully selected solution approach so that the results can be implemented on shop floor at earliest.

2.4.2 Solution approach

Problems like scheduling N jobs on a single machine, makespan minimization for parallel machines and economic lot size scheduling problem are known to be NP hard Problem (Pinedo and Hadavi 1992; Hsu, 1983). Since the current work considers a scenario which is the extension of those mentioned above, the same has been also considered as NP hard. It is therefore unlikely to obtain the optimal solution for current problem through polynomial-time-bounded algorithms. Considering the fact that heuristics can be tailored for such problems and their various extensions, (Jans and Degraeve, 2004), the same can be looked upon as a probable solution method. Also, for such complex scheduling problem, it is a general practice to find an appropriate heuristic rather than an optimal solution (Bilge et al., 2004; Ventura & Kim, 2003).

But considering the exceedingly large solution space even heuristics algorithms may not solve the problem effectively. Alternatively, meta-heuristics techniques such as taboo search, simulated annealing etc. can be applied. One such stochastic search algorithm called Genetic Algorithm (GA) is applied for current problem as its ability for performance and computational intensity has been demonstrated by various researchers. (Hyun et al., 1998; Cieniawski et al., 1995; Atyug et al., 2003). “@ RISK” optimizer, which uses Monte Carlo simulation based GA approach, is used for the same in this research and the details of the parameters are as shown in table 2.1.

Table 2.1 GA Parameters

Population Size	200
Number of Generations	100
Crossover Rate	0.1
Mutation Rate	0.5
Selection Scheme	Roulette wheel with elitist

2.4.3 **Data set**

The generalized modal is applied to real shopfloor using the below mentioned data set.

Table 2.2 lists all the 11 products which the firm produces to meet the collective requirement of wholesets and its spares. These products, based on their process flow, are routed through different machines. The list of all the machines is as mentioned in table 2.3. The process flow of a representative product is mentioned in table 2.4, which shows the sequence of operations, respective machines on which particular operation will be performed and corresponding cycle time and set up time as determined by Maynard's Operations Sequencing Technique (MOST).

Table 2.2 List of products processed in house for wholeset

Sr.	Raw part	Finished	Description	Short
1	BP7208Z02	BP7208Z	MAIN SHAFT	MS
2	BP7209Z/0-	BP7209Z	CLUSTER GEAR SHAFT	CGS
3	BP7207Z02	BP0766Z	TOP GEAR SHAFT;	TGS
4	BP7212Z/10	BP0773Z	GEAR ASSY; 2ND MAIN	G2M
5	BP7213Z/10	BP0774Z	GEAR ASSY; 3RD MAIN	G3M
6	BP7214Z/10	BP0775Z	GEAR ASSY 5TH MAIN	G5M
7	BP7211Z/10	BP0772Z	GEAR ASSY LOW MAIN	GLM
8	BP7204Z/0-	BP7204Z	GEAR;5TH,COUNTER	G5C
9	BP7205Z/12	BP7205Z	GEAR;COUNTER REVERSE	GRC
10	BP7206Z/10	BP0771Z	GEAR ASSY.;REVERSE IDLE,	GRI
11	BP7203Z/12	BP7203Z	GEAR;REVERSE,MAIN SHAFT	GRM

Table 2.3 Machine description

Machine	Description / Operations	Machine	Description / Operations
1	Deburring & Chamfering	13	Shaping
2	Helical Shaping	14	Hobbing
3	Gear shaving	15	Deburring and Chamfering
4	Shaving-1	16	Shaving -2
5	Gear tooth chamfering	17	Shaving -3
6	Turning -1	18	Gear Hobbing-3
7	Turning -2	19	Key way milling
8	Spline Rolling	20	Drilling
9	Soft Grinding	21	Spline Rolling-1
10	Gear Hobbing-1	22	Spline Rolling-2

Table 2.4 Representative Process Flow Chart (PFC) with cycle time and setup time

Main shaft					
S. No.	**Op. No.**	**Process Description**	**Machine**	**Set-up time (minutes)**	**Cycle time (minutes)**
1	30	turning operation- set up 1	turning -1	30	3.6
2	40	turning operation-set up 2	turning -2	30	4
3	50	soft grinding operation for section a1	soft grinding	30	1.3
4	60	soft grinding operation for section a2	soft grinding	30	1.6
5	70	spline hobbing operation	hobbing machine	90	2.23
	80	spline rolling of section a1	spline rolling	15	0.56
7	90	oil hole drilling operation	drilling machine	45	1.3
8	100	keyway milling operation	milling machine	45	1.86
9	120	spline rolling section d	spline rolling	90	2.66

These PFCs are executed on the shopfloor after collating the demand quantity of Transmission sets and demand quantity of spares of individual products. This demand quantity from customers regulates the dispatch and is represented in table 2.5 below.

Table 2.5 Dispatch commitment

Sr No	Product	Dispatch commitment		
		Sept'15	Oct '15	Nov'15
1	Engines (Var.1)	500	700	700
2	**Transmission for Customer**	**500**	**700**	**700**
3	**Transmission for Customer**	**2500**	**2500**	**2500**
4	Engines (Var.2)	350	300	300
5	Engines (Var.3)	48	TBD	TBD
6	AVTEC -Engines	10	20	20

2.4.4 Results

The model was optimized with above mentioned data set, to arrive at an improved value for batch size and production sequence. Table 2.6 shows a part of log of total time elapsed vis-à-vis progressive improvement in objective function (Goal Results). It demonstrates that the marginal improvement is diminishing as the time progresses. To trade-off between the quality of result and time elapsed, a termination condition is being imposed to end the optimization. It will stop when either of the below mentioned condition is fulfilled:

1. Best individual value doesn’t improve over 200 generations

2. Total improvement of the last 10 best solution is less than 0.1 percent

Such termination may not provide the global optimum and the solution can be improved further. However, the optimization results obtained here are within the confidence bound of 95 percent which provides an outlook for the quality of the learned local optimum against the global optimum.

Table 2.6 Representative log of progress trial

Trial no.	Iterations	Goal Result	Elapsed Time
14583	100	91154	24.63
38947	100	71569	62.58
62847	100	42265	101.56
77589	100	23458	122.05
92568	100	22596	162.2
96586	100	21908	169.45

The final result is collated in the form of "Integrated Operations Schedule", a representative part of which is displayed in table 2.7.

Table 2.7 Integrated production plan

PRODUCTION RUN	Machine 1		Machine 2		Machine 3	
1	Product	GRC	Product	G2M	Product	G5M
	Operation	20	Operation	40	Operation	20
	Batch Size	350	Batch Size	450	Batch Size	550
2	Product	GRM	Product	GRC	Product	GLM
	Operation	40	Operation	60	Operation	20
	Batch Size	450	Batch Size	450	Batch Size	550
3	Product	GRI	Product	TGS	Product	G5C
	Operation	40	Operation	80	Operation	30
	Batch Size	450	Batch Size	250	Batch Size	600

A close look at the table 2.7 illustrates that for the first production run on machine 1, the products GRC should be loaded for operation number 20 and the batch size should be 350. Likewise, G2M for operation number 40 and G5M for operation number 20 should be loaded on machine 2 and 3 respectively for their first production run and the respective batch size should be 450 and 550.

Considering the "Wholeset" requirement and constraint of process flow chart, conventional priority rules for scheduling like First Come First Serve (FCFS), Shortest Processing Time (SPT), Longest Processing Time (LPT) etc. cannot be applied in current scenario. However, the makespan arrived at by using proposed approach was compared against makespan of several other schedules, which were arrived at using different approaches. These approaches and corresponding makespan time is as shown in table 2.8 and summarized in figure 2.1.

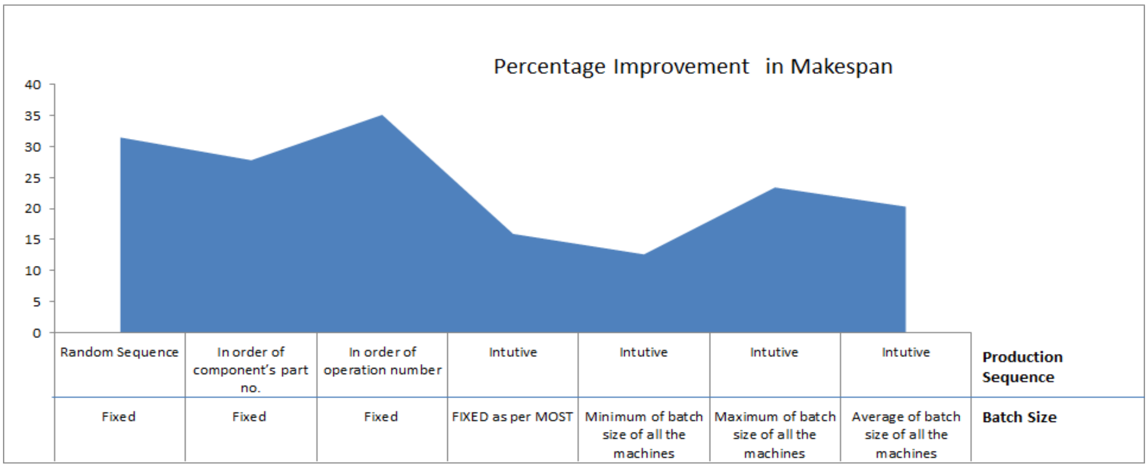


Figure 2.1 Percentage improvement in makespan

Table 2.8 Makespan for various approaches

Proposed approach Makespan = 21108.35

Conventional Approaches		Makespan for demand of September'15 (minutes)	Percentage Improvement using integrated approach
Batch size	Production sequence		
Fixed as per MOST	Random Sequence	30810.54	31.48
Fixed as per MOST	In order of product's part	29255.59	27.8
Fixed as per MOST	In order of operation	32548.63	35.14
Fixed as per MOST	Intuitive	25105.92	15.9
Minimum of batch	Intuitive	24158.35	12.6
Maximum of batch	Intuitive	27584.32	23.4
Average of batch size	Intuitive	26485.36	20.30

Pinedo (1995) indicates that a minimum makespan usually implies a high utilization of machines. The same has been reflected when the machine utilization of individual machine was compared before and after the application of proposed approach. The same is illustrated using figure 2.2 below.

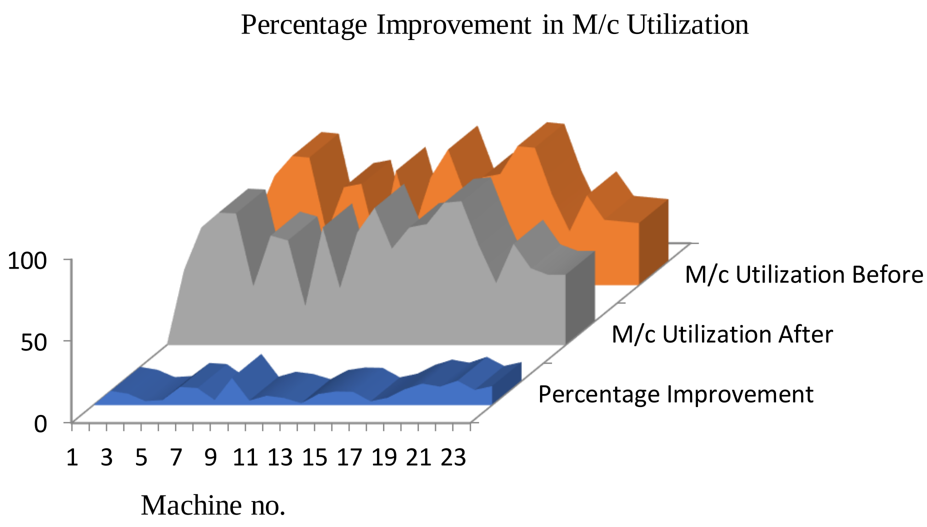


Figure 2.2 Improvement in machine utilization

It is evident that for all the machines, the utilization has increased and for some machines, the gain is as high as eleven percent. It can be thus stated that the schedule arrived by simulation based GA for joint optimization of scheduling and batch sizing has significantly outperformed the schedule arrived at by other approaches including the one which was previously applied by the organization.

2.5 Summary

In the current chapter, the integration of two of the key decision viz production scheduling and production batch size is presented. The work considers a real manufacturing environment and incorporates the complexities of the shopfloor.

The work demonstrates the improvement realized through the integration of the decision of the same function and thus becomes the motivation to extend the integration to other key functions. Through this work the characteristics nature of the shopfloor are captured which are subsequently incorporated in the coming chapters for integrating other pivotal function of the value chain.

CHAPTER 3*

INVESTIGATION OF THE VALUE OF INTEGRATED PRODUCTION AND MAINTENANCE PLANNING

Key Highlights

***Purpose**:* The purpose of this chapter is to develop an integrated production plan and maintenance plan. It aims to consider all the complexities of a manufacturing environment. Subsequently, it evaluates the value of integrated approach for a broad range of manufacturing environment to generalize its superiority over existing planning approaches. This chapter attempts to addresses the realization of Sub objective 1 and Sub objective 2.

Findings: It is observed that using the proposed approach the total cost of operations can be reduced in the range of 3 to 14 % depending on the operating environment. Additionally, for a specific environment, there was a significant reduction in the number of failures machine and the availability was increased to a level of 93%.

***Originality and Contribution**:* Current work defies the assumptions made in past by incorporating real world complexities related to stochastics nature of the process. It considers imperfect machining and maintenance processes and factors the impact of unplanned maintenance activities on the production and maintenance schedule. Such a comprehensive inclusion of all the real-world complexities and an extended comparative evaluation is not reported in past and thus is the originality and contribution of this chapter.

***Practical Implication**:* The integration of production and maintenance presented in this chapter synchronizes two disjoint functions. It deviates from the conventional time based / age based maintenance planning and proposes most appropriate opportunity to perform the maintenance while considering the production schedule. Due to such integration, there are minimum production halts for maintenance and production targets can be achieved with minimal stoppages. The work is therefore of great relevance to the operations managers who are continuously attempting to improve the operational efficiencies.

**A part of the work presented in this chapter is published under the title "Production and maintenance planning: an integrated approach under uncertainties". Purohit,B.S. and Lad,B.K. in the International Journal of Advanced Manufacturing Technology (IJAMT) and under the title "Integrated Approach for Job Scheduling and Multi-Component Maintenance Planning" Proceedings of 5th International & 26th All India Manufacturing Technology, Design and Research Conference (AIMTDR 2014) December 12th–14th, 2014.*

3.1 Introduction

The interdependency between production plan and maintenance plan is illustrated in chapter 1. Considering the significance of this interdependency, the same has been leveraged and various integrated models are reported in past. Review of literature specific to integration of production and maintenance is presented underneath through which prominent gaps are identified and attempted to address subsequently.

Focusing on integrated model, Kumar and Lad (2017) attempted to integrate production and maintenance with an aim of reducing the operating cost. The work considered a simplistic environment and made assumption such as statistically independent failure of machine, availability of machine at the start of production and many more. Further, the decision related to production planning was limited to the sequence of production only. Another important decision related to production plan i.e. production batch size was not considered. However, it is known that the production batch size influences the machine run time which in turn influences the machine wear and maintenance schedule. Exclusion of decision related to production batch size therefore does not ensure the effectiveness of the such integration.

Likewise, Von Hoyningen-Huen and Keismuller (2013) also considers integrated planning for a single machine subjected to stochastic failures and aims to minimize the average tardiness. Since the objective function used in this work is an indicator related to the production function, the optimization results were such that it emphasized more on the improvising the production function. In this process the optimal schedule for maintenance was compromised and the intent of integration was not fully realized. In addition, the work also does not differentiate between the preventive maintenance and corrective maintenance in terms of execution time and restoration of the machine condition. It also considers both of them as perfect maintenance process. Though the work demonstrates the reduction in the average tardiness, its practical implementation is curtailed as the environment under consideration was specific and hypothetical. Similarly, the work of Ghaleb et al. (2020) also considers integrated planning for a single machine and accounts the degradation of machine using Markovian chain.

On the other hand, Kouedue et al. (2014) performed joint analysis of the optimal policies for maintenance and production planning to minimize overall cost consisting of preventive and corrective maintenance costs, inventory holding cost, and backlog cost. For this, a two-level hierarchical decision-making approach is proposed. At the first level, the number of machine failure are evaluated; at the second level, the number of failures evaluated from the first level are used to arrive at the optimal production, preventive, and corrective maintenance policies. Here the machine's failure rate is considered to be dependent on the number of imperfect repairs, and as a result, the planning therefore becomes dependent on the number of failures. It can be thus noted that though the results propose the optimal schedule of production, parameters related to production are aptly considered. The work thus emphasizes more on maintenance with little focus on parameters related production planning lot sizing.

In majority of the literature, the objective of such integration was pertaining to the operating cost, or indicators like tardiness, completion time etc. However, Paprocka (2019) used efficiency of the production system. The work emphasized more first identifying the failure pattern through the real data to closely identify the failure pattern. While such approach provided more accurate results, such data might not be available for the new setups and thus may hamper the applicability of the proposed approach.

In line with the development of prognostic tools, Liu et al. (2018) leveraged the predictive maintenance for integrating it with the production schedule. The approach was presented through a case study and considered the health status and dummy age subjected to machine degradation is considered. However, more emphasis was on the maintenance part and production schedule was not aptly emphasized.

Realizing the fact that the integration of production and maintenance is considered in a simplistic environment, researchers sequentially added in more parameters and constraints to relate with real shopfloors. In this direction Xiang et al. (2014) formulated a joint production and maintenance planning problem in an environment subject to stochastic demand and random yields. It was targeted to find an integrated lot sizing and maintenance policy for the system. However, study lacks to consider the machine deterioration from reliability point of view. Also, machine is treated as a single component. Practical limitations like constraint on machine production capacity, due date from customer, variability in supply of raw material quality and impact of corrective maintenance were also missing. Chung et al. (2020) attempted to remove the assumption that hat the interval between maintenance activities is fixed or within a specified time frame. In the context of a wafer manufacturing industry, the irregularity on the maintenance schedule was highlighted.

Nourelfath and Châtelet (2012) have also developed integrated models and have accommodated inventory, multi components aspect along with their economic dependencies. It considers two possible causes for system failure: the independent failure of single components, and the simultaneous common cause failure of all components. The suggested preventive maintenance is a T-age group maintenance policy in which components are cyclically renewed all together. However, such policies may need equipment after predetermined time and may interrupt continuous production.

Considering the fact the manufacturing industry is characterized by stochastic nature and associated uncertainties, Seif et al. (2019) and Cui (2020), presented such integration in the light of such variabilities. The work considers a complex flow shop environment. However, the consideration of variability was only accounted for the maintenance related activities whereas, other variabilities such as demand fluctuation, machine yield, availability of material were not considered. Such variabilities also accounts for major deviation from the ideal process and thus are requires equal contemplation.

Work by Yildirim and Nezami (2014) also considers similar integration for an environment where product processing times are affected by machine degradation. Such degradation is repaired through preventive maintenance post which the can improve the job processing times also increases. The model investigates the impact of imperfect and "as-good-as-new" maintenance tainstrategies on production plan and total cost. This work considers few assumptions such as preventive maintenance can only be performed at the end of a period; in case of any failure during a job, processing will resume after the repair without any extra setup; and also that failures are detected instantly and repaired. However, after each failure and repair, before resuming the production the machine undergoes a trial production to ensure the effectiveness of production and this consumes some extra time. This time, in general, is accommodated in the maintenance activities itself but cannot be excluded when considering the optimization of production schedule.

While considering similar integration, Ahmadi (2019) took a multi- state production system which is also subjected to deterioration. The paper develops extensions of the existing modelling techniques from non-repairable systems to repairable production systems. The development includes estimation of a value function and so the behaviour prediction of revenue resulting from the system.

While a major focus on maintenance related integration was focused on the manufacturing industry, work similar to the one presented by Chansombat et al. (2019) can be considered to review such an integration problem from the perspective of service industry.

Based on the above-mentioned literature and more, it is apparent that majority of existing work is simplistic translation of industrial scenario which, in reality, is much more complex. Existing models also lack the comprehensive inclusion of uncertainties impacting the smooth execution of planned operations. An integrated model which demonstrates simultaneous incorporation of complexities like multicomponent machine, production of multiple product range, variation in forecast and actual demand, variations in raw material quality, etc. is missing in literature. It is therefore evident that before further integrating any other parameter, there is vast scope for broadening the level of integration between production and maintenance.

In the subsequent section of this chapter, the above-mentioned gaps are bridged through development of a comprehensive integrated model for production and maintenance schedule. The approach presented in this chapter considers a manufacturing environment which considers the incidences which are stochastic in nature and also difficult to control, such as fluctuations in demand, uncertainty of supply, yield of machine etc. Incorporation of such real-world complexities enhances the adaptation of the proposed approach by the practicing manager and thus establishes the practical implication of this research.

3.2 Description of the representative manufacturing environment

To formulate the integration between production schedule and maintenance schedule, a machine consisting of multiple component is considered. Time to failure of these component follows two parameter Weibull distribution with a given shape (β) and scale parameter (η). Since Wiebull failure distribution can be used to model increasing, decreasing as well as constant failure rate, the same is used to characterize failure characteristics of component under consideration. Further, this machine may not be new and may have some accumulated age for its various component. In this research, some initial age (I_a) is considered for each component at the start of planning horizon. Machine may fail stochastically based on the time to failure distribution of component and initial age. Such random failure calls for Corrective Maintenance (CM) action which is considered as minimal, i.e. after each CM component are restored to as-bad-as it was at the time of repair. Time incurred for such corrective maintenance depends on time spent on identifying the fault, diagnosis, availability and readiness of repair resources etc. Such dependencies make it difficult to precisely estimate the exact time required to perform CM. Therefore, for each component, TTR_{cm} is considered as normally distributed, parameters (mean and standard deviation) of which can be obtained from maintenance log books. Preventive maintenance (PM) is proposed to reduce unplanned downtime losses. A PM action brings certain restoration to the machine. A restoration factor (R) is used to model the degree of repair of any such PM action. The restoration factor is a fraction which signifies how much life of the component can be restored after performing a maintenance activity. Time to perform preventive maintenance (TTR_{pm}) is fixed and known for each component.

The machine is used for processing demand of multiple products from various customers. Each of these products has its own fixed manufacturing time and is processed from a single but specific raw material. Considering work shift of 10 hours per day and 24 working days in a month, total man-hour per month for machine under consideration is 240. In case the monthly production target cannot be met within these 240 hours, production manager calls labor for overtime which costs double the normal labor cost. However, total number of overtime hours cannot be more than 5 per day. If the product is completed before month end, it can be directly shipped to customer and therefore no finished good inventory is counted. The raw materials for these products are supplied by unique suppliers. Due to the inherent process variability, lot received from suppliers contains some quantity which does not meet required specification and therefore cannot be used for manufacturing. These are termed as supplier rejections which affect quality rating of individual suppliers. Quality rating varies month over month, depending upon the process variability at supplier end and containment actions taken by him. Machine on which these raw materials get processed also produces defective parts due to chance causes and assignable causes and thus treated as imperfect machining process. Owing to imperfect machining process, all the products which are manufactured using machine may not met customer's quality requirements and thus called "NOT OK". In case of higher rejections, there might be shortage of "OK" products against the demanded quantity. This difference is reflected as backorders and costs manufacturer in the form of backorder cost for each such shortages. For such environment, where rejections are expected, material planner orders excess quantity of raw material to fulfil end customer's requirements while taking care of internal and external rejections.

Above mentioned description is translated mathematically to arrive at integrated operations plan which simultaneously determines

1. Job Sequence
2. Production lot size

3. Decision related to preventive maintenance of individual component so as to:

Minimize Total Cost of Operation such that $(TCO) = TSC + TICC + TCOPM + TCOCM + TBOC + TOTC$

Where TSC is Total Supply Cost, TICC is Total Inventor Carry Cost, TCOPM is Total Cost of Preventive Maintenance, TCOCM is Total Cost of corrective Maintenance, $TBOC$ is Total Backorder Cost, and $TOTC$ is Total Overtime Cost

Subjected to constraint of:

Total number of daily production hours <15

Number of production days in month < 24

Figure 3.1 briefly illustrates the above-mentioned scenario.

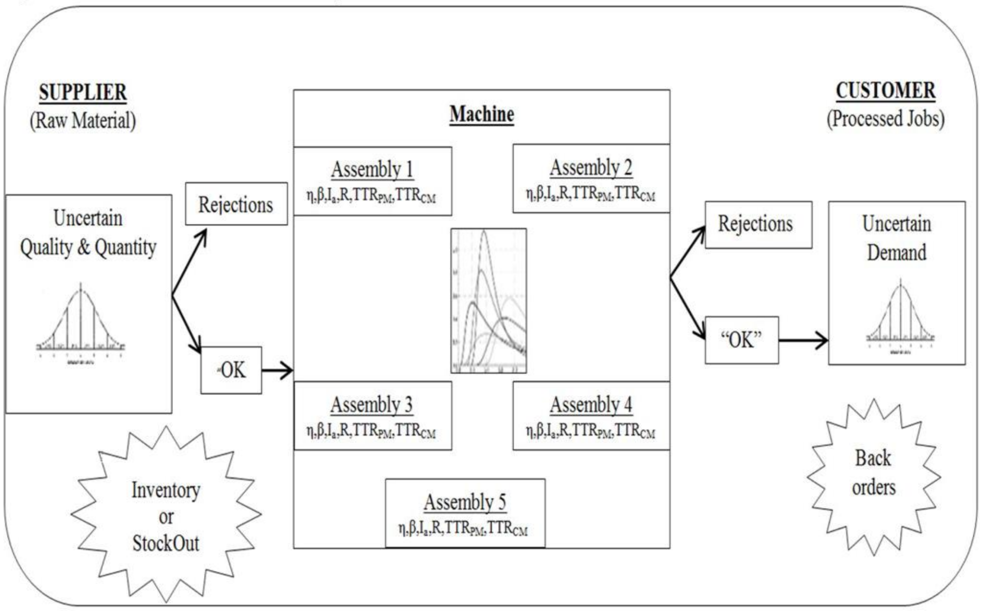


Figure 3.1 Description of industrial environment

3.3 Data set and formulation

A numerical example is taken to demonstrate the solution method in detail. The data set used is aligned with the industrial observations noted during process improvement studies performed by authors in a manufacturing industry.

Consider the machine with 5 components A1, A2, A3, A4 and A5. The characteristics of these component are as in table 3.1. Products to be manufactured on this machine are P1, P2, P3 and P4. Each product has different machining requirements and therefore need different machine setup in terms of tooling, clamping, lubrication etc. The changeover time of setup for each product thus depends on the previous setup and therefore current work considers sequence dependent set up time for each product. Product characteristics are as mentioned in table 3.2.

Raw material for these products is ordered in excess quantity as compared to demand. This is to accommodate normal rejections, both form supplier and machine. This order quantity depends upon average percentage of "OK" parts from each supplier and is referred as his supplier quality (SQR). Range of SQR varies from 1 to a fraction which is equal to predefined and mutually agreeable acceptable quality limit. When SQR falls below this limit, entire lot is rejected and supplier replaces it with new lot immediately at no extra cost. For current scenario, this average percentage for each supplier is taken as 97. However, this number varies depending on actual quantity of "OK" product and therefore considered as uniformly distributed in model. Also, while processing these products on machine, because of chance causes, normal rejections are inevitable and thus percentage of "OK" products from machine is also considered as uniformly distributed. The forecasted demand, which is used for rough cut production plan, and actual demand for these products are as in table 3.3.

Table 3.1 Component's failure and repair characteristics

Component	Preventive maintenance time in	Corrective		Initial Age in hours	Shape factor β	Size factor η	Restoration factor for PM
		Mean	Standard deviation				
Component	2	8	2	2000	2	1200	0.5
Component	2	6	1	2000	2.5	900	0.5
Component	2	10	2	2000	3	1100	0.5
Component	2	8	1	2000	1.5	600	0.5
Component	2	6	1	2000	1.8	1500	0.5

Table 3.2 Product characteristics

Product	Average percentage of "OK" units of raw material supply	Raw material inventory carrying cost (Rupees per unit per hour)	Manufacturing time (per unit per hour)	Back Order Cost (Rupees per month per unit)	Sequence dependent set- Preceding job			
					P_1	P_2	P_3	P_4
P_1	0.96	3	5	750	0.00	0.22	0.15	0.25
P_2	0.95	1.5	4	300	0.05	0.00	0.12	0.15
P_3	0.96	2.5	3	600	2.50	2.20	0.00	2.00
P_4	0.97	2	7	500	0.30	0.35	0.25	0.00

Table 3.3 Data set for demand

Month	Forecast of Demand				Actual Demand (Uniformly Distributed)			
	P_1	P_2	P_3	P_4	P_1	P_2	P_3	P_4
Jan'15	11	9	5	20	9-11	8-10	4-6	18-22
Feb'15	12	7	7	20	10-14	6-8	6-8	18-22
March'15	10	10	6	18	9-11	9-11	5-7	16-20

The demand is considered to be in between confidence bound interval. Uniform distribution being the simplest way to represent two sided bound, the same is considered to represent model capacity to handle stochastic demand.

To begin with, material planner orders raw material by considering forecasted demand, average supplier quality rating and average percentage rejections at machine. The raw material order quantity is thus calculated as:

$$OQ_{ij} = \left[FD_{ij} \,/\, (SQR_i \, X \, MQR_i)\right] \quad (3.1)$$

where OQ_{ij} = Order quantity for raw material of i^th^ product in j^th^ month, FD_{ij} is forecasted demand of i^th^ product in j^th^ month, SQR_i is average supplier quality rating for i^th^ product and MQR_i is machine quality rating for i^th^ product.

Ordered quantity is fully inspected and rejected quantity is separated leaving “OK” quantity which becomes available quantity for production. Production in-charge can process any quantity of raw material ranging from zero to quantity available. Therefore, this production lot size becomes a decision variable. However, as a management policy, there is also a constraint of maximum permissible backorder per month which refrains operations manager to let production quantity go beyond certain units in a month. For the current problem, this constraint is formulated as: Maximum backorders per month <5. Also, after each production run, decision for preventive maintenance activity becomes another decision variable. This decision influences total cost of operation by affecting cost of both corrective and preventive maintenance.

Total Cost of operations is calculated as:

$$TCO = TSC + TICC + TCOPM + TCOCM + TBOC + TOTC \qquad (3.2)$$

Where,

TCO = Total cost of operation

TSUC = Total set-up cost

TICC = Total inventory carrying cost

TCOPM = Total cost of preventive maintenance

TCOCM = Total cost of corrective maintenance

TBOC = Total backorder cost

TOTC = Total overtime cost

Model for calculating these cost components are discussed here under:

Set-up Cost: It is summation of set up cost for all the production runs and calculated as follows:

$$TSUC = \sum_{j=1}^{j=3} \sum_{i=1}^{i=4} [(ST_{ij}) \, X \, MLC] \qquad (3.3)$$

where ST_{ij} is sequence dependent set up time for ith production run in jth month. MLC is manufacturing labor cost which is taken as Rs. 100 per hour**.**

- **Inventory Cost**

Unlike other literature, instead of calculating average monthly inventory, current work calculates inventory after each production run. Such continuous measurement of inventory provides closer approximations. It is calculated as follows:

Initially, for any j^{th} month the available raw material quantities for i^{th} products is RM_{ij}. Subsequently, 4 variables h1, h2, h3 and h4 are considered.

For a particular month, their values depend on the product selected for manufacturing in first, second, third and fourth production run respectively. For example, for a particular month, if the sequence of production is product 3, product 4, product 1 and product 2 then h1, h2, h3, h4 will take values as 3,4,1 and 2 respectively.

Figure 3.2 shows the inventory level of raw material for different products, after each production run. As mentioned, let product 3 is selected for first production run. The quantity to be manufactured, i.e. q_3, will be transferred to production and thus will not be counted as RM Inventory. If T_3 is per unit machining time for product 3, then machining time, MT for production run 1 will therefore be $T_3.q_3$.

This, in addition to set-up time, will be the time for which raw material inventory, which is equal to $RM_{1j} + RM_{2j} + (RM_{1j}-q_3) + RM_{4j}$, is being carried during j^{th} month.

When extended for all the production runs of the month, Total inventory carrying cost (TICC) becomes:

$$TICC=\Big[\sum_{j=1}^{j=3}\{[\sum_{i=1}^{i=4}(RM_{ij}\ I_{Ci})(\sum_{i=1}^{i=4}T'_{ij}\ )] - [\,q_{h1j}IC_{h1}(T'_{h1j} + T'_{h2j} + T'_{h3j} + T'_{h4j})] - [q_{h1j}IC_{h2}(T'_{h1j} + T'_{h2j} + T'_{h3j} + T'_{h4j})] - [q_{h3j}\ IC_{h3}(T'_{h3j} + T'_{h2j} + T'_{h4j})] - [q_{h3j}\ IC_{h3}(T'_{h3j} + T'_{h4j})] + q_{h4j}IC_{h4}T'_{h4j}\}\ \Big] \quad (3.4)$$

where IC_i is inventory carrying cost of raw material for ith product per unit per hour and T'_{ij} represents summation of manufacturing time and set-up time for ith production run during jth month.

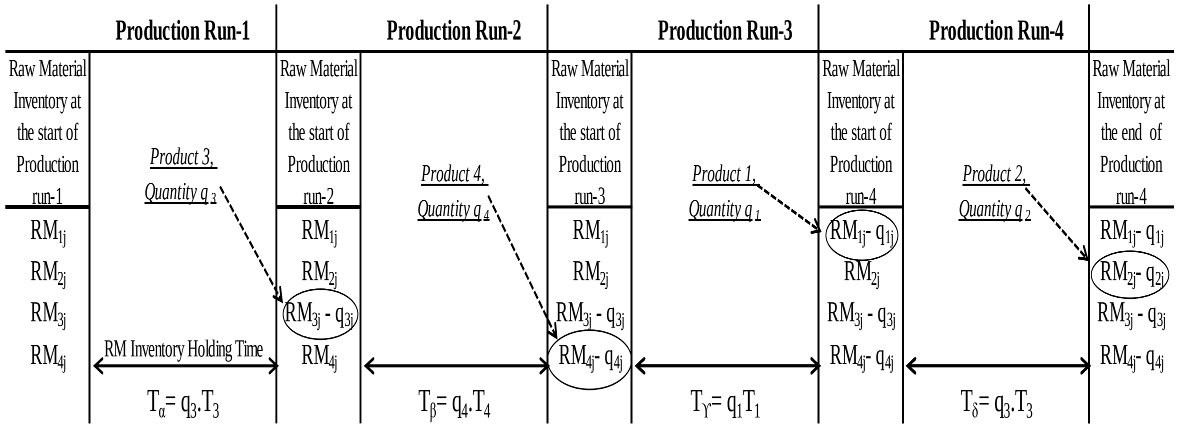


Figure 3.2 Inventory calculation

- **Maintenance Cost**

Total Maintenance cost is sum of cost preventive maintenance and corrective maintenance.

Total cost of preventive maintenance (TCOPM) is calculated as:

$$\text{TCOPM} = \sum_{j=1}^{j=3}\sum_{p=1}^{p=4}\sum_{k=1}^{k=5}[PMF_{kpj}\ x\ (TTRPM_k\ X\ MLC) \qquad (3.5)$$

where PMF_{kpj} is preventive maintenance factor for kth component before pth production run in jth month. Such that

$$PMF_{kpj} = \begin{cases} 0, & when\ PM\ is\ not\ performed \\ 1, & when\ PM\ is\ performed, \end{cases} \qquad (3.6)$$

$TTRPM_k$ is the time to perform preventive maintenance on kth component.

MLC is the labor cost which is kept as 150 rs per hour.

Similarly, total cost for corrective maintenance, TCOCM, is calculated as:

$$\text{TCOCM} = \sum_{j=1}^{j=3}\sum_{p=1}^{p=4}\sum_{k=1}^{k=5}\left(NF_{kpj} x\ TTRCM_k\ X\ MLC\right) \qquad (3.7)$$

where $TTRCM_k$ is time to perform corrective maintenance of k^th^ component. NF_{kpj} is number of failures of k^th^ component during p^th^ production run in j^th^ month.

NF_{kpj} is calculated using formula published by Lad and Kulkarni (2012)

$$NF_{kpj} = \left[\frac{\left((MT_{pj})+Ia_{kpj}\right)^{\beta_j}}{\eta_j}\right] - \left[\frac{(Ia_{kpj})}{\eta_j}\right]^{\beta_j} \tag{3.8}$$

where MT_{pj} is cycle time for p^th^ production run in j^th^ month, which is product of quantity produced, q_{pj} and time required for production single unit of i^th^ product.

η_k, and β_k are scale and shape parameter of k^{th} component respectively. If r_k is the restoration factor, Ia_{kpj} is the initial age of k^th^ component before p^th^ production run in j^th^ month, and which is calculated as :

$$Ia_{kpj} = \begin{cases} [(Ia_{k(p-1)j})+(MT)_{(p-1)j}] \times [1-(r_k \ X\, PMF_{kpj})] \\ \text{for all } p > 1 \\ [(Ia_{k(p)j-1})+(MT)_{(p)j-1}] \times [1-(\, r_k \, XPMF_{kpj})] \\ \text{for all } p = 1 \end{cases} \tag{3.9}$$

where r_k is the restoration factor for the k^th^ component.

- **Backorder Cost**

Total cost of backorder, (TBOC) is calculated as:

$$(TBOC) = \begin{cases} 0 \ , \\ for \left(AD_{ij} + BO_{i(j-1)}\right) \leq q_{ij} \\ \sum_{2=1}^{j=3} \sum_{i=1}^{i=4} [\left(AD_{ij} + BO_{i(j-1)} - q_{ij}\right) x \ BOC_i], \\ for \left(AD_{ij} + BO_{i(j-1)}\right) > q_{ij} \end{cases} \tag{3.10}$$

where, AD_{ij} and BO_{ij} is the demand and backorder of i^th^ product in j^th^ month. The next month's demand is amended by adding this backorder quantity. When j=1, $BO_{i(j-1)}$ becomes BO_{i0}, which is equal to zero, as backlog from previous planning horizon has already been considered as a part of demand for current month.

- **Overtime Cost**

Total Overtime cost (TOTC) is calculated for extra hours.
These extra hours can be calculated by subtracting total operational time from generally available operation time of 240 hours i.e. Overtime hours = Total time of operation – available operation time.

For a month, total time of operation (TTO) is summation of total time for CM time, total time for PM time, total manufacturing time and total set-up time

Mathematically $TTO = TTCM + TTPM + TST + TMT$

where,

TTCM (Total time for corrective maintenance)

$$=\left[\sum_{p=1}^{p=4} \sum_{k=1}^{k=5} PMF_{kpj}\ X\ \ TTRPM_k \right] \tag{3.11}$$

TTPM (Total time for preventive maintenance)

$$= \left[\sum_{p=1}^{p=4} \sum_{k=1}^{k=5} \left(NF_{kpj}\ X\ (TTRCM_k\right)\right] \tag{3.12}$$

$$\text{Total Set-up time (TST)} = \left[\sum_{i=1}^{i=4}\ ST_{ij}\right] \tag{3.13}$$

$$\text{Total machining time (TMT)} = \left[\sum_{i=1}^{i=4}\ \mathrm{q_i} T_i\right] \tag{3.14}$$

Therefore, over time hours for jth month equals

$$OT_j = \begin{cases} 0 & , \quad \left(TTO_j - 240\right) \le 0 \\ \sum_{2=1}^{j=3} TTO_j - 240 & , \quad \left(TTO_j - 240\right) > 0 \end{cases} \tag{3.15}$$

- **Total overtime cost**

$$\text{(TOTC)}=\sum_{j=1}^{j=3} OT_j\ X\ OTC, \tag{3.16}$$

where OTC is overtime cost per hour and equals to Rs.200 per hour.

3.4 Results

For a specific scenario where (R=0.5, Ia =2000 hrs.), the integrated model was simulated for optimizing total cost of operations (TCO). The representative log of progressive trial is mentioned in table 3.4 which describes the successive improvement in TCO and total time elapsed. It can also be noted that the improvement is diminishing as the log progresses, indicating that further solution improvement will take longer time and thus number of trials should be so selected so as to balance the benefits realized vis-a- vis the time elapsed.

Table 3.4 Log of progress trial

Trial no.	Iterations	Goal cell result (Mean)	Elapsed time (Minute)
568	100	117856	4.35
27455	100	102563	31.56
76584	100	295644	79.84
84879	100	304897	86.57
88780	100	305131	91.85

These optimization results obtained are within the confidence bound of 95 percent which provides an overview about the quality of the learned local optimum against the global optimum.

The final result is mentioned in the form of “Integrated Operations Schedule” in table 3.5. Table 3.5 communicates multiple planning decisions of conflicting nature. For example, it can be seen that for the first month, optimal production sequence is P1→ P3→ P2 and respective manufacturing quantities as 12 ,11 and 4 respectively. Decision regarding PM of specific component is binary in nature i.e. PM or No PM, and thus represented as “1” or “0” respectively (higlighted as , under “Component Maintenance Decision” column).

In brief, the result provides quantitative decision for a three month planning horizon for:

1. Lot size for manufacturing of specific product in specific month,
2. Sequence in which products needs to be manufactured,
3. Component on which preventive maintenance actions are to be performed after each production run.

For preventive maintenance, it highlights the opportunity only during the changeover of jobs on machine thus causing minimum disruptions to ongoing production

Table 3.5 Integrated operations plan

Month	Production run **1**							Production run **2**							Production run **3**						
Jan	Component					Production		Component Maintenance					Production		Component					Production	
	A1	A2	A3	A4	A5	Product	Quantity	A1	A2	A3	A4	A5	Product	Quantity	A1	A2	A3	A4	A5	Product	Quantity
	1	1	1	1	0	P1	12	0	1	0	0	1	P3	11	1	0	1	1	0	P2	4
Feb	Production run **1**							Production run **2**							Production run **3**						
	Component					Prodcution		Component Maintenance					Prodcution		Component					Production	
	A1	A2	A3	A4	A5	Product	Quantity	A1	A2	A3	A4	A5	Product	Quantity	A1	A2	A3	A4	A5	Product	Quantity
	0	0	1	0	0	P1	13	0	0	0	0	0	P2	0	0	0	0	0	1	P3	7
March	Production run **1**							Production run **2**							Production run **3**						
	Component					Prodcution		Component Maintenance					Prodcution		Component					Production	
	A1	A2	A3	A4	A5	Product	Quantity	A1	A2	A3	A4	A5	Product	Quantity	A1	A2	A3	A4	A5	Product	Quantity
	0	0	0	0	1	P2	11	0	1	0	0	0	P4	20	0	0	0	0	0	P3	5

3.5 Comprehensive evaluation

To generalize the superiority of integrated approach, it was exhaustively evaluated for approximately 2000 different scenarios. These different scenarios were generated by combinatorial selection of various alternatives related to performance indicator, decision level (Long term, Short term, Immediate) and process / equipment parameters. While long term planning refers to period of 6 months and beyond, short term refer to a period of 4 to 12 weeks, which accommodates moderate level of uncertainty whereas immediate refers to day to day activities and immediate actions. The details of these alternatives are as shown in table 3.6.

Table 3.6 Decision scenarios

Perfromance indicator	• Total cost of operation • Avarage machine availability • Total number of failure	
Decision level	Decision	Description of decision alternative
• Long Term	Production volume	- High: volume equal to machine's maximum production capacity - Medium : 66% of machine's maximum production capacity - Low: 33% of machine's maximum production capacity
• Short Term	Production and maintenance plan	- Production Plan: Level plan (Maintains output at a constant level throughout the planning horizon) Chase plan (Follows demand) - Maintenance plan: M1: Only CM (No PM) M2: CM + PM only at the start of planning horizon M3 : CM + PM at thestart of each month
• Immediate	Job sequencing rule	Priority rules: - Earliest Due Date (EDD) - Shortest Processing Time (SPT) - Longest Processing Time (LPT) - Random
Parameters	• Machine initial age (hours) : 0 ,2000, 10000 • Restoration factor: 0.3, 0.5, 0.8	

Table 3.7 summarizes the result for one such specific set which generates 72 different scenarios. In this set is TCO considered as performance indictor, initial age of all the component is considered as 2000 hours and restoration factor for preventive maintenance of all the component is taken as 0.5.

Table 3.7 Comparative results

Machine initial age **:2000** hours , Restoration factor = **0.5**								**Percentage improvement over best value**
KPI	Long Term Planning	Short Term Planning	Immediate Planning				**Integrated approach**	
			Scheduling	Maintenance				
				Only CM (M1)	PM at start of First Month Only (M2)	PM at start of Each Month Only		
TOTAL COST	High Volume	Level	EDD	495,138	427,773	419,094	305,131	13.70
		Chase		423,214	360,702	**353859 (Best)**		
		Level	SPT	500,197	439,901	426,058		
		Chase		427,573	366,286	360,112		
		Level	LPT	590,506	518,442	513,856		
		Chase		531,231	462,831	459,343		
		Level	Random	524,813	462,754	458,658		
		Chase		463,428	405,128	402,071		
	Medium Volume	Level	EDD	174,164	157,068	161,214	112,967	8.90
		Chase		139,388	**124072 (Best)**	128,516		
		Level	SPT	177,053	160,835	166,388		
		Chase		141,934	127,522	133,286		
		Level	LPT	207,406	188,703	193,498		
		Chase		177,272	159,890	164,807		
		Level	Random	185,316	169,874	175,789		
		Chase		154,226	140,147	146,034		

It can be observed from table 3.7 that in case of high volume, the minimum TCO using conventional approaches is observed when “Chase plan” is followed, scheduling is done using “Earliest Delivery Date” rule (EDD) and preventive maintenance is performed at the start of each month. This minimum value of TCO is compared with that obtained using integrated approach. Integrated approach shows a percentage improvement of over 13 percent. Similarly, 8.9 and 2.6 percent improvement is obtained for medium and low volume cases respectively.

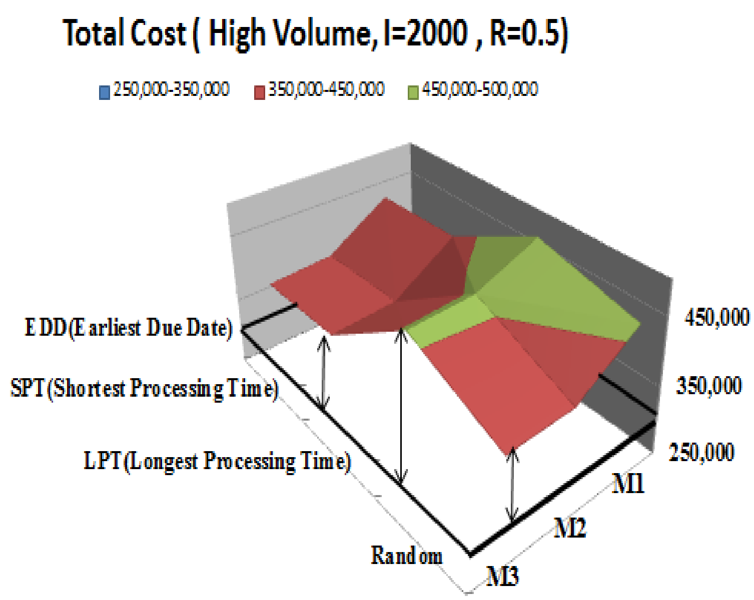


Figure 3.3 Total cost of operation under various planning approaches

Figure 3.3 shows the comparison of all the possible combination for high volume case with integrated approach. The black line represents the total cost using integrated approach

The arrows highlight the difference between the values obtained using conventional and integrated approach. For any point on the surface, it can be observed that, the black line is always below the surface. This demonstrates that integrated approach always provides lesser TCO. Similar results were observed when TCO surface for low and medium volume was plotted.

For different production volume (high/medium/low), the evaluation was further extended for different initial age of machine and restoration factor of preventive maintenance. Percentage improvement using integrated approach over best value amongst conventional policies is plotted in figure 3.4(a), 3.4(b) and 3.4(c). The result shows that as compared to conventional approaches, integrated approach provides substantial percentage improvement for TCO for all the scenarios. However, the improvements are more significant when the initial age of the machine is high and/or restoration factor for preventive maintenance is low. Also, the approach is most beneficial for the situation when production volume is high.

Evaluation was further extended and effectiveness of the integrated approach is also analysed with respect to other performance indicators like average machine availability and total number of breakdowns. Figure 3.5 and 3.6 illustrates the outcome of these comparative evaluations. Only the case of high volume is illustrated as it was identified as most promising situation for the application of integrated approach.

The results show that machine availability under conventional approaches is less than that obtained under integrated approach. Similarly, there is significant reduction in number of machine failures when integrated approach is used. It is thus evident that irrespective of environment, parameters and constraints, integrated approach outperforms conventional approaches.

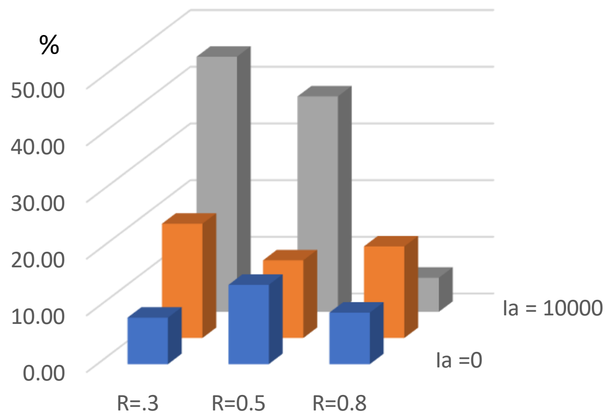


Figure 3.4 (a) Percentage improvement in total cost for high production volume environment

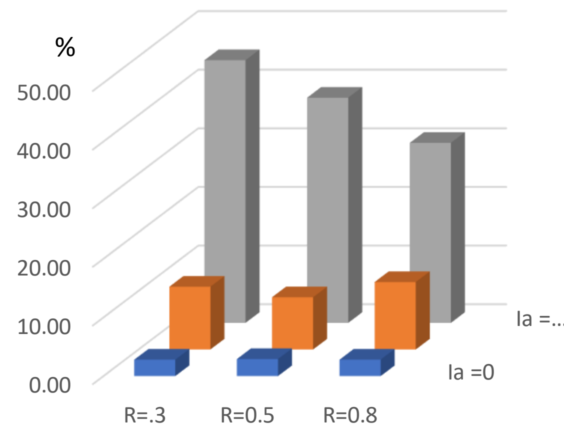


Figure 3.4 (b) Percentage improvement in total cost for medium production volume environment

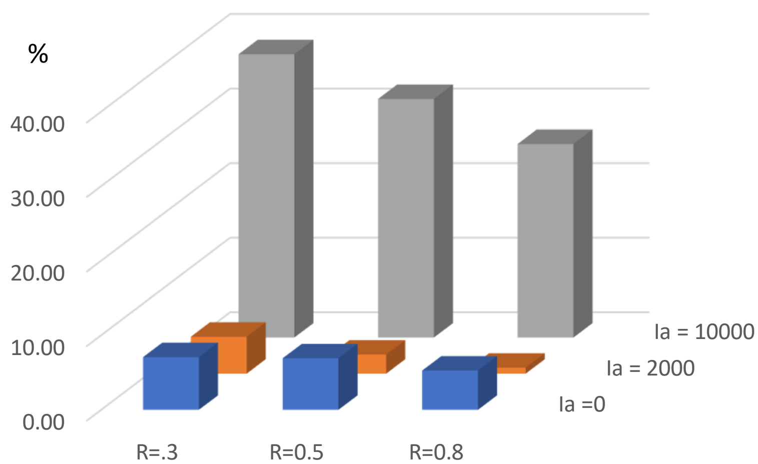


Figure 3.4 (c) Percentage improvement in total cost for low production volume environment

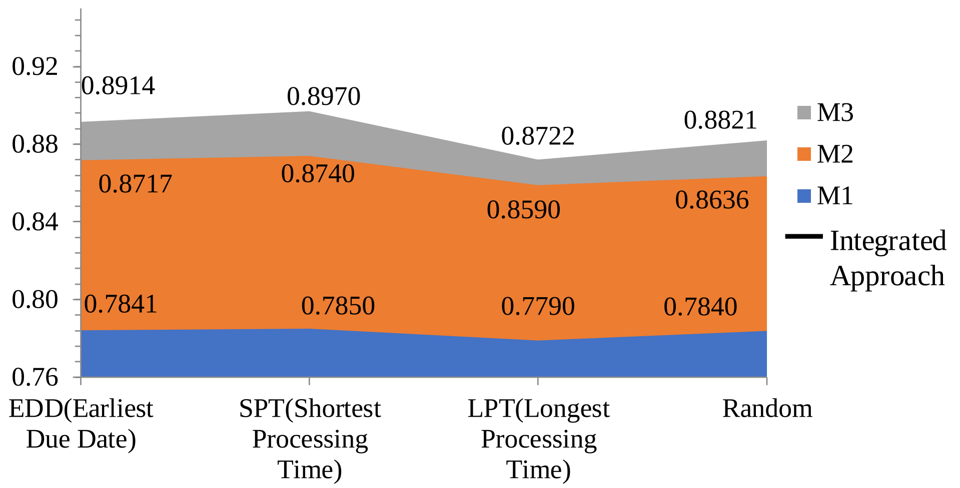


Figure 3.5 Average machine availability under various planning approaches

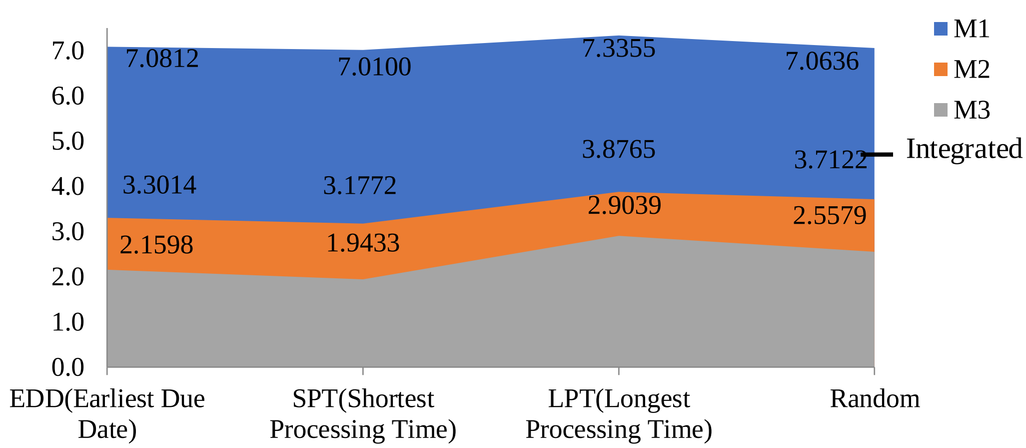


Figure 3.6 Total number of machine failures under various planning approaches

3.6 Summary

This chapter successfully demonstrates the approach for integrating production plan and maintenance plan for a complex manufacturing environment. The environment considered is characterized by multiple products, variations in demand, uncertainties related to supply and quality of raw material, yield of machine, etc. For a multicomponent machine, it simultaneously optimizes production schedule, preventive maintenance schedule and manufacturing lot size. As a result, a deviation from conventional time / age based preventive maintenance is proposed by identifying the opportunity during the changeover of jobs. On time scale, such opportunities are not necessarily equidistant and thus provide non-uniform but more realistic optimal maintenance cycle. This in turn makes the implementation of proposed schedule easier as it causes minimum disruptions to ongoing production.

Through a comprehensive evaluation, it is further concluded that irrespective of environment, parameters and constraints, proposed approach outperforms all the existing approaches. However, the improvement is more substantial for high production volumes environment. In addition, it is observed that as machine reaches to its end of life, the failure probability increases and the opportunities for the preventive maintenance also increase by manifolds. Integrated approach is found to be very promising in such environment as it examines all the possible opportunities for the preventive maintenance and identifies the most appropriate one while synchronizing it with the production schedule to minimize the halts and thus facilitates in keeping the operating cost at minimum.

CHAPTER 4*

INTEGRATION OF MAINTENANCE AND QUALITY PLANNING

Key Highlights

Purpose*:* The purpose of this chapter is to develop a framework for jointly arriving key decisions related to machine tool maintenance and product inspection. The approach considers realistic environment, like multi-component Work Centre, multiple dependent failure modes and multiple Critical To Quality (CTQ) characteristics. It also aims to propose a solution method to address the challenges related to responsiveness and computational involvedness in integrated shop floor planning approach in a realistic manufacturing environment.

Objectives fulfilled**:** The approach attempts to address sub-objectives 1, 2, and 4 (SO1, SO 2 and SO4) of the thesis, as mentioned in Chapter 1.

Findings: It is manifested that integration of maintenance and quality planning leads to an improvement in system performance. In specific to operating cost, an improvement in the range of 2.3% to 14.55 % was realized for different manufacturing environment. Additionally, using a distributed approach an improvement in the solution time of around 12 percent was realized against around 9% increase in objective function value i.e. operating cost.

Originality and Contribution: In this work, all the three dependencies (stochastic, structural, economic) which exists between the machine component from failure and repair view point are simultaneously considered. Further, the work considers the impact of various failure modes on multiple quality characteristics of the product.

**A part of the work presented in this chapter is published in Proceedings of 6th International Conference on Advancements in Polymeric Materials, February 20-22, 2015` under the title of "Joint Optimization of Quality & Maintenance Plan: Towards a Lean Enterprise" and is communicated in the Journal of Quality in Maintenance Engineering under the title "Integrated Maintenance and Product Inspection Planning for a Multi-Component Work Centre"*

Such a comprehensive incorporation of various dependencies was not considered earlier in integrated maintenance and quality planning literature.

Practical Implications*:* Using the proposed approach the most appropriate opportunities for carrying out preventive maintenance and products' quality inspection can be identified. It therefore leads to elimination of the redundant inspection and maintenance activities on the floor and improves the productivity of the system. The applicability of the proposed approach was investigated through a case study of vertical transportation industry.

4.1 Introduction

The interdependency of machine maintenance and product quality is discussed in chapter 1 of this thesis. Realizing the importance of this interdependency, many researchers have addressed the same in their research. A review of such formulations/model is presented underneath to highlight the prominent gaps in existing body of literature.

Work by Tambe et al. (2013) considered a maintenance model for a multi-component system in which maintenance decisions are optimized and the system availability requirements were treated as constraint. The approach developed in this work considers the effect of component failures on the quality of product being manufactured as well as the production schedule on the machine. It considered unplanned breakdowns as an opportunity to do the maintenance activities for other components and takes the advantage of economic dependency in a multi-component system. However, the work accounted for single product and its single quality characteristics for analysis. However, majority of the products, in reality, are inspected for multiple quality characteristics and therefore such consideration of single characteristics is a significant deviation from actual shop floor scenario.

Alfares et al. (2005) also formulated an integrated model for maintenance and quality. It considers an environment in which, when the production system deteriorates, the system shifts to an out-of-control state and begins to produce a proportion of defective items, necessitating corrective maintenance. The work considers realistic aspects, such as varying demand and production rates to determine the production and inspection schedules. However, in this work also, a significant number of assumptions were made such as production of a single item, constant rate for demand, error-free and instantaneous maintenance and inspection activities etc. The work also assumes that the machine does not produce any defective during the initial few minutes of the production cycle. Nevertheless, in practice the initial few minutes of the start of production are considered to be most vulnerable due to changeover of material, machine set- up and personnel. The work also assumes that when the machine deteriorates, it could only be identified through the inspection of the parts produced. However, in reality there could be multiple failure modes, one of them being the mode in which the entire functioning of the machine is arrested. In addition to all such assumptions, one of the biggest gaps of this work is that scheduled maintenance inspections are performed at equal intervals. Restricting the maintenance to such equal interval may lead to ignorance of the opportunities which are not equidistant on the time scale but are more beneficial in terms of reducing the sudden breakdowns and improving the machine availability.

Realizing the fact that equal interval for maintenance and inspection may not be optimal, Njike et al. (2012) develop an optimal stochastic control model. The model differs from other models in that, instead of age-dependent machine failure, it considers only defective products as feedback to arrive at optimal inspection policy. This consideration allows merging all failure parameters into a single one. Further with this approach, using a numerical example, an overall reduction in the operating cost was demonstrated. However, the other assumptions of producing a single product, and having a single CTQ existed in this work also.

Work by Lam and Banjevic (2015), propose a decision policy for scheduling the quality inspections optimized myopically over the next inspection interval. In traditional practices, regular inspections are considered at fixed intervals. The work considers the possibility of generating savings through the number of inspections carried out. As such, it uses a proportional approach for modelling the occurrence of defectives. The cost and time of inspections are incorporated into model, and optimal decision for one interval is made. This process is repeated for each decision point, resulting in a decision policy that produces an optimal time for the next inspection. However, in this work, all the characteristics to be inspected are treated equally and inspection policy is unified for all the CTQs. Nevertheless, of the various characteristics for which the product is inspected, each may have different parameters and thus such a common inspection schedules for all such CTQs may not suffice.

On the other hand, the literature which only focuses on the maintenance optimization, bring forth a very important aspect of maintenance planning which needs considerable attention. This aspect is related to the machine architecture. Machine architecture is defined by the constituent's components of the machine and various dependencies which these components exhibit from the failure and repair view point. It also relates multiple failure modes of different components with different impact on the product's quality characteristics. However, most of the existing approaches which optimize maintenance plan ignore this aspect and therefore this aspect is never considered while integrating the maintenance and quality. It is for the same reason that the research considering the machine architecture is only available in the area of maintenance optimization and not in the literature related to the integrated planning. Few of the key literature prominently emphasises on significance of such dependencies arsing due to the machine architecture are mentioned as under.

An overview of the dependencies which exist between machine components is provided by Laggoune et al. (2010) Subsequently, work by Cho and Parlar (2010) extends this overview and elaborates three different kinds of dependencies namely stochastic, structural and economic dependency. It is further highlighted by Nowakowski and Werbińka(2009) that, consideration of various dependencies is essential for closer approximation of machine behaviour and in absence of such consideration true maintenance requirement of the machine cannot be estimated with confidence.

Owing to the complexity related to these dependencies, majority of the existing literature has dealt with them individually. For example, Zhou et al. (2012) considered a multicomponent system and planned PM activities while considering production schedule and its variation caused by unpredictable market fluctuations. To an extent it is aligned in the direction of accommodating economic dependencies between the components. Economic dependency was also considered by Nourelfath and Châtelet (2012) in which they have stochastic and economic dependencies for simultaneous consideration of preventive maintenance and production plan. The extended work, however, was more of horizontal expansion where inventory was also considered along with production and maintenance but owing to problem complexity only economic dependency between the components was examined. On the other hand, Nakagawa and Murthy (1993) considered stochastic dependencies, for a two-unit system where failure of one unit causes failure of another unit with a pre-defined probability. Cost models were developed and the model was extended by providing a distribution pattern to the damage of a unit when another one fails. Likewise, work by Xing (2007) handled the stochastic dependencies for the system reliability analysis and highlighted that Markov modelling may not provide optimal solution considering it a state space explosion problem.

This manifests that simultaneous consideration of all the dependencies between the machine components is absent in literature. For the same reason, these dependencies are not being incorporated while integrating maintenance with any other function, including quality. This becomes one of the most prominent gaps to be bridged in integrated maintenance and quality planning. Besides, as identified from the literature above, integration of quality and maintenance is generally explored considering very simplistic example as it assumes machine as single component with single failure mode. Also, only single quality characteristics of the product is considered for analysis. Additionally, instead of considering probabilistic nature of processes like maintenance, manufacturing etc., the same has been modelled from a deterministic perspective. Such assumption accumulates and leads to vast deviation from the realistic environment and thus restricts is applicability

It can be arrived at the point that the function viz maintenance and quality has their own complexities which still needs to be incorporated in the existing models. Integrating these functions together with these complexities will further increase the complexities by manifolds and will lead also to increase in time to arrive at the solution, but at the same time will contribute towards the development of more realistic approach which finds it way easy towards the implementation.

Through the consideration of a real manufacturing environment and incorporation of all the associated complexities mentioned above, current chapter bridges the identified gaps in literature by developing a comprehensive integrated model for production and maintenance planning.

4.2 Description of representative manufacturing environment

The development of the approach for integration of maintenance and inspection plan is presented through a representative industrial setting. However, it is emphasized here that the approach is generic and can be easily tuned for any specific industrial case. The description of the environment is as under:

The firm processes heavy metallic sheets which subsequently form a part of larger assemblies for vertical transportation industry. The firm processes gigantic parts in terms of weight (30 Kg. to 70 Kg.) and dimensions (1100 mm to 1400mm width and 1400 mm to 2400 mm breadth). Considering massive and voluminous nature of parts and the precision level involved, it is convenient for the firm to deploy machine which can individually and accurately perform series of manufacturing and associated operations like material movement, job alignment, punching, shaving, cutting, polishing etc. Such multi-tasking machines are capital intensive and are referred as "Work Centre".

The parts so produced are of tight tolerances and high dollars values and thus have high cost of rejection. These parts need to be inspected, as in absence of inspection; there lies a prominent risk of passing a defective product to the customer. These parts are inspected for three different characteristics which are critical to product quality and referred as CTQ. The job will be rejected if any of the CTQ characteristics is not met. Organization follows fixed interval inspection frequency, in which every fifth part is inspected for all the three CTQs. But it has resulted into escape of defective product. To overcome such incidences, 100 % inspection is one of the options but since each inspection consumes cost and is considered as non-value added activity, a carefully selected inspection plan is required.

Work Centre is constituted by multiple components, each one having its own reliability and maintainability characteristics. Proper maintenance of these components brings certain restoration and is necessary as poorly maintained components loses their reliability and may lead to devastating situation like sudden break down, extended downtime, costly repair activities and poor product quality. On the other hand, frequent maintenance also leads to production halts and cuts down on productivity. This highlights the need for an efficient preventive maintenance plan which facilitates upkeep of Work Center for continuous production of dimensionally and visually acceptable parts.

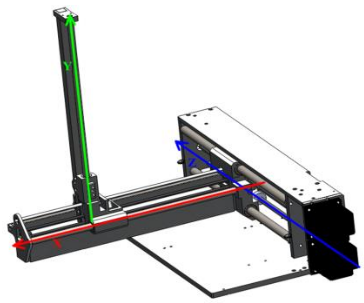
Currently, organization performs regular preventive maintenance (PM) activities after every 20^{th} production run. Despite of an effective PM plan, the component may still fail stochastically, for which Corrective Maintenance (CM) action is performed. Further, such failures can occur in multiple failure modes, the details of these failure modes are as shown below in Table 4.1.

Table 4.1 Failure mode description

Failure Mode	Description
M1-Functioning Arrest	Work Centre stops operating
M2- Mean Shift	When mean dimension of produced parts shifts
M3- Sigma Spread	When the standard deviation of the sample increase
M4- Both Mean and sigma	When M2 & M3 happens together

For each component, failure mode M1 (sudden stop) can be immediately detected and thus immediate CM is performed. However, in case of all other modes, the failure will only be detected after the part inspection. Also, failure mode may not immediately result into rejection because of tolerance range for the part. In addition, all the rejection may not be because of component failure as normal rejection are inherited in all the manufacturing processes. For this, whenever a rejection is found during an inspection, the inspection of two consecutive parts is also performed. If any of these two parts is found rejected then all the parts produced since last inspection are checked and simultaneously appropriate minimal CM action (Kijima 1989) will be conducted.

To demonstrate the approach, the current work focuses on a specific assembly of Work Centre called "Contour Arm". This assembly contains multiple components including suction cups, front and rear diverters, oscillating clamp, etc. However, from the product quality perspective, the most important components were found to be "Axial Rails" as the machining trajectory and final dimension of critical characteristics of the product is dependent on these rails. The three rails in the assembly are Height Rail (C1), Breadth Rail (C2) and Length Rail (C3). Various dependencies exist amongst these components namely, structural dependency, economic dependency and stochastic dependency. These dependencies in the context of "Contour Arm" are further elaborated below.



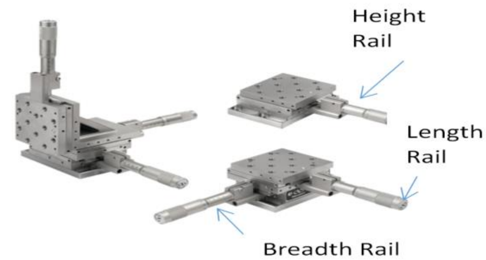


Figure 4.1(a) Schematic view of contour arm

Figure 4.1(b) Components of contour arm

a) Stochastic Dependency:

An approximate illustration of the assembly is shown in the figure 4.1 (a) and illustration of components is shown in figure 4.1 (b). It can be noted that height rail (Y-Axis) is independent whereas the length and breadth rails are coupled which results into "Stochastic dependency" amongst them. It is observed that whenever the length rail fails in mode M2 or M4, there is failure mode M2 incurred in breadth rail also. However, the vice versa was not observed.

b) Structural Dependency:

Length and breadth rail are kept intact in an assembly structure. This implies that to perform any maintenance action on either of the two rails, entire assembly structure needs to be dissembled, and thus these components are "Structurally dependent".

c) Economic Dependency:

Every time a maintenance task is to be performed, a job order needs to be prepared and a fixed administrative cost is associated with it. Combining the maintenance actions will therefore result in lower cost than individual activities, which brings in "Economic dependency". It is thus beneficial to perform the maintenance jointly and minimize this fixed administrative cost.

4.3 Model development

As the problem focuses on two of the operations functions of an organization, it is important to develop a combined performance index for the same. In the present chapter Total Cost of Operations (TCO) is used as a combined measure to see the effectiveness of these two interdependent operations policies. TCO consists of maintenance cost, inspection cost and rejection cost. These costs are affected by inspection and preventive maintenance schedules. TCO thus becomes the objective function and is represented as:

$$TCO = f\begin{Bmatrix} (IF_{qn}, PMF_{k_n}); \begin{pmatrix} time\ to\ repair, number\ of\ failures, \\ number\ of\ rejections \end{pmatrix}; \\ (cost\ and\ other\ deterministict\ parameters) \end{Bmatrix} \quad (4.1)$$

In the above equation variables in the first bracket are the decision variables. Such that,

i. IF_{qn} : Inspection factor for qth characteristics after n^{th} production run

$$= \begin{cases} 0, \ if \quad inspection\ for\ \mathrm{q^{th}} \\ characteristics\ is\ not\ performed\ after \\ n^{th} production\ run \\ 1, \ if\ inspection\ is\ performed\ \ for\ \mathrm{q^{th}} \\ characteristics\ is\ not\ performed\ after \\ n^{th} production\ run \end{cases} \quad (4.2)$$

ii. PMF_{k_n}: Preventive Maintenance factor for k^{th} component after n^{th}production run

$$= \begin{cases} 0, \ if\ the\ \ Inspection\ for\ \mathrm{q^{th}} \\ characteristics\ is\ not\ performed\ after \\ n^{th} production\ run \\ 1, \ if\ Inspection\ is\ performed\ \ for\ \mathrm{q^{th}} \\ characteristics\ is\ not\ performed\ after \\ n^{th} production\ run \end{cases} \quad (4.3)$$

After each production run, the decision related to part inspection is binary in nature. i.e. "Inspect the part" or "No Inspection of the part." If the number of CTQs to be checked during an inspection be "q" then each part inspection decision is associated with 2^q alternatives. Further, if the number of components in the machine is "m" then after each production run the decision related to PM of individual components can be taken in 2^m ways, i.e. "PM of specific component" or "No PM of a specific component." Clubbing these decisions related to inspection and preventive maintenance, the total no. of decisions which can be taken after each production run is $(2)^{q+m}$ and thus for "N" production run, this sums up to $[(2)^{q+m}]^N$ alternatives. This makes the problem combinatorial in nature.

The parameters mentioned in second bracket of equation 1 are stochastic in nature and are modelled using appropriate distributions. For example, past data indicated that the times-to-failures follow two parameters Weibull distribution. Accordingly, the numbers of failures are calculated. Likewise, since the Time to Repair (TTR) depends on time spent on identifying the fault, diagnosis, availability and readiness of repair resources, etc. It is difficult to estimate the exact time required to perform maintenance action. Based on the past repair time data, a uniform distribution is considered to model the uncertainty associated with time for corrective maintenance.
Similarly, the occurrence of rejection is also stochastic in nature. Rejection occurs either due to chance causes or assignable causes. In current work, rejection due to assignable causes are linked with the failure mode M2, M3 and M4, which in turn are modelled using Weibull distribution and probability of occurrence of specific failure mode. During such failures, the dimension of critical characteristics goes out of specification limit leading to rejection of parts. On the other hand, chance causes are modelled considering the normal distribution. The mean and standard deviation for this normal distribution are derived from inspection records.

The third bracket in the equation 1 consists of the cost and other deterministic parameters specific to particular manufacturing setup. The details of such parameters can be found on following sections. In a particular manufacturing setup if some of these parameters are not know with certainty then appropriate probability distribution may be used to model them.

The individual component of objective function i.e. maintenance cost, inspection cost and rejection cost are discussed in following sub sections 4.1, 4.2 and 4.3 respectively.

4.3.1 Maintenance Cost Model

Total Maintenance Cost (TMC) for "N" production run is the sum of preventive maintenance cost and corrective maintenance cost for each of the n^{th} production run and can be stated as:

$$TMC = [\sum_{n=1}^{n=N} T_{cm_n} + T_{pm_n}] \times MLC_m \qquad (4.4)$$

Where T_{cm_n} is the corrective maintenance time for the n^{th} production run, T_{pm_n} is the preventive maintenance time and MLC_m is the labor cost.

While developing the maintenance cost models, all the dependencies are incorporated in the calculation of T_{cm_n} (see sub subsection 4.3.1.1) and T_{pm_n} (4.3.1.2)

4.3.1.1 Corrective maintenance cost model

Corrective maintenance time under various circumstances can be mathematically written as in equation 5, where, FT is the fixed administrative time required to initiate any maintenance activity, T_A is the assembly/ disassembly time and TTR_{k_m} is the time required for corrective maintenance of k^{th} component when it fails in m^{th} failure mode. Φ_{k_n} is the preventive maintenance factor of k^{th} component, T_{pm_k} is the time for preventive maintenance for k^{th} component and CMF_{k_n} is the corrective maintenance factor for k^{th} component during n^{th} production run.

$$T_{cm_n} = \begin{cases} [FT + T_A + \{ (TTR_{c1_m}) + (TTR_{c2_m}) + (IF_{c3_n} \times T_{pm_{(c3)}})\}] \times Nf_{c1_n}, \\ \quad when\ CMF_{c_1} = 1\ and\ failure\ mode\ = M2\ or\ M4 & (a) \\ [FT + T_A + \{ (TTR_{c1_m}) + (IF_{c2_n} \times T_{pm_{(c2)}}) + (IF_{c3_n} \times T_{pm_{(c3)}})\}] \times Nf_{c1_n}, \\ \quad when\ CMF_{c1} = 1\ and\ failure\ mode\ = M1\ or\ M3 & (b) \\ [FT + T_A + TTR_{c2_m} + (IF_{c3_n} \times T_{pm_{(c3)}}) + (IF_{c1_n} \times T_{pm_{(c1)}})] \times Nf_{c2_n}, when\ CMF_{c_2} = 1 & (c) \\ [FT + TTR_{c3}] \times Nf_{c3_n}, when\ CMF_{c3} = 1\ and\ (IF_{c1_n} + IF_{c2_n} = 0) & (d) \\ [FT + TTR_{c3} + (IF_{c1_n} \times T_{pm_{(c1)}}) + (IF_{c2_n} \times T_{pm_{(c2)}}) + T_A] \times Nf_{c3_n}, \\ \quad when\ CMF_{c_3} = 1\ and (IF_{c1_n} + IF_{c2_n} \geq 1) & (e) \end{cases}$$

The elaboration of the equation 4.5 (a-e) is as under:

- When component c1 fails ($CMF_{c_1} = 1$) in mode M2 or M4, due to the stochastic dependency, component c2 also fails thus both the components undergo corrective maintenance ingesting CM repair time as TTR_{c1_m} and TTR_{c2_m}. Further, since both of them are intact in the same structure, to consider the structural dependency, time for assembly, T_A, is only accounted once. In addition, while performing the corrective maintenance on component c1 and c2, component c3 may or may not be planned for preventive maintenance, which is determined by the preventive maintenance factor for component c3 i.e. IF_{c3}. Likewise, in all the scenarios, the fixed administrative time, FT, is considered only once and is shared amongst all the components which go for maintenance. This accommodates the economic dependencies amongst the components. *{Equation 4.5 (a)}*

- When component c1 fails ($CMF_1 = 1$) in mode M1 or M3, it does not impact any other component and thus only c1 goes for corrective maintenance and ingesting CM repair time as TTR_{c1_m} . However, c2 and c3 can be preventively maintained which depends on individual PM factors i.e. IF_{c2} and IF_{c3} respectively. Here the assembly/disassembly time is also considered once to accommodate structural dependency. *{Equation 4.5 (b)}*
- When component c2 fails ($CMF_{c_2} = 1$), it does not stochastically impact any other component and thus corrective maintenance is only performed on c2. However, preventive maintenance can be performed on c1 and c3 which depends on individual PM factors i.e. IF_{c1} and IF_{c3} respectively. Here also, the structural and economic dependencies are accommodated by considering the assembly/disassembly time and fixed time appropriately. *{Equation 4.5 (c)}*
- When component c3 fails ($CMF_{c_3} = 1$) , along with corrective maintenance of c3, c1 and c2 may or may not undergo preventive maintenance. In specific case, where none of the components go for preventive maintenance, the time elapsed in maintenance activity accounts only fixed time and time or corrective maintenance of c3 is considered. *{Equation 4.5 (d)}.*
- For the scenario in which c1, or c2 or both may undergo preventive maintenance, considering the structural dependency between c1 and c2, time for assembly/ disassembly of the structure is considered only once. *{Equation 4.5 (e)}*

$\mathrm{Nf}_{\mathrm{k_n}}$ mentioned in equation 5 is the conditional number of failures of kth component in nth production run. As cited by Lad and Kulkarni (2012) for minimal corrective repair, the conditional number of failures of the kth component at any time "t" can be written as:

$$\mathrm{Nf}_{\mathrm{k_n}} = \int_0^t \mathrm{F}(\mathrm{t}|\mathrm{t}_{\mathrm{k_n}})\mathrm{dt} \quad (4.6)$$

Considering machining time, MT, and component's age before n^th^ production run, t_{k_n}, the above equation can be simplified and number of failure during n^th^ production run can be calculated as:

$$Nf_{k_n} = \left[\frac{(MT + t_{k_n})^{\beta_k}}{\eta_k}\right] - \left[\frac{t_{k_n}}{\eta_k}\right]^{\beta_k} \quad (4.7)$$

where η_k and β_k are the scale and shape parameters of the k^th^ component. t_{k_n} can be evaluated as :

$$t_{k_n} = [t_{k_{n-1}} + CT] \times [1 - \left(r_k \times CMF_{k_{n-1}}\right)] \quad (4.8)$$

The restoration factor for the k^th^ component, r_k, is used to model the degree of repair of preventive maintenance action, and is a fraction which signifies how much life of the component can be restored after performing the maintenance activity.

CMF_{k_n} , used in equation (4.5), is the corrective maintenance factor. It equals to zero when corrective maintenance is not performed and equals one otherwise. Corrective maintenance is performed in two cases. First, when machine breaks down and stops operating and second when the machine starts producing faulty parts. Such situation is identified when two consecutive parts are inspected and both the parts get rejected. Mathematically, this can be written as:

$$CMF_{k_n} = \begin{cases} 0, \\ when\ corrective\ \ maintenance\ \ is\ not\ performed \\ 1, \\ when\ machine\ breaksdown\ and\ stop\ operating \\ 1\ , \\ when\left(\sum_{q=1}^{q=Q}\{RF_{q(n-1)} + RF_{q(n-2)}\}\right) > 1\ \ and \\ \left(\ \sum_{q=1}^{q=Q}\{IF_{q(n-1)} + IF_{q(n-2)}\}\right) > 1 \end{cases} \quad (4.9)$$

Where $RF_{q(n-1)}$ and $IF_{q(n-1)}$ is the rejection factor and inspection factor for qth characteristics during (n-1)th production run such that,

$$RF_n = \begin{cases} 0, & USL \geq V_{qn} \geq LSL \\ 1, & USL < V_{qn} \text{ or } V_{qn} < LSL \end{cases} \qquad (4.10)$$

USL and LSL are upper specification limit and lower specification limit of the CTQ.

V_{qn}, which is measured value of q^{th} characteristics of the part produced in n^{th} production run, approximately takes normally distributed values such that its probability density function f(x|μ,σ) equals to $\left[\frac{e^{\frac{(x-\mu)^2}{2\sigma}}}{\sigma\sqrt{2\pi}}\right]$ where μ and σ are mean and standard deviation of observed values for product CTQ.

4.3.1.2 Preventive maintenance cost model

Various scenarios which can exist depending upon the combination of components undergoing PM, are elaborated as under. The time for preventive maintenance, T_{pm_n}, for each of them is mathematically translated into equation 4.11 subsequently.

- When none of the component undergoes preventive maintenance and corrective maintenance, total time for maintenance is zero. *{Equation 4.11(a)}*
- When either of c1, c2 or c3 or both c2 and c3 goes for preventive maintenance, total maintenance time is considered as sum of the component's preventive maintenance time, fixed time and assembly/ disassembly time which is counted once to accommodate structural as well as economic dependencies. *{Equation 4.11(b)}*

- When the only preventive maintenance of component c1 is performed, the total time elapsed is fixed time and the c1's preventive maintenance time. *{Equation 4.11(c)}*

$$T_{pm_n} = \begin{cases} 0, \quad when \; \sum_{k=c1}^{k=c3} PMF_{kn} = 0 \quad (a) \\ FT + \begin{bmatrix} \left(TTR_{pm_{(c1)n}} \times PMF_{c1_n}\right) + T_A + \\ \left(TTR_{pm_{(c2)n}} \times PMF_{c2_n}\right) + \left(TTR_{pm_{(c3)n}} \times PMF_{c3_n}\right) \end{bmatrix}, \\ \quad when \; \sum_{k=c2}^{k=c3} PMF_{kn} \geq 1 \quad (b) \\ FT + \left(TTR_{pm_{c1}} \times PMF_{c1_n}\right), \quad otherwise. \quad (c) \end{cases} \tag{4.11}$$

4.3.2 Inspection Cost Model

If ν_q is the time to inspect the qth quality characteristics and LC is the labor cost in hours, then the inspection cost for N production runs can be calculated as:

$$Inspection\ Cost = \left\{\sum_{n=1}^{n=N} \sum_{q=1}^{q=Q} \left(IF_{nq} \times \nu_q\right)\right\} \times LC \tag{4.12}$$

4.3.3 Rejection Cost Model

The model considers both detected as well as undetected rejection for cost calculation.

$$Detected\ Rejection\ Cost = \left(\sum_{n=1}^{n=N} IF_n \times RF_n\right) \times C_{DR} \tag{4.13}$$

where C_{DR} is unit "Detected Rejection" Cost.

$$UnDetected\ Rejection\ Cost = \left\{\sum_{n=1}^{n=N} [(1 - IF_n) \times RF_n]\right\} \times C_{UDR} \tag{4.14}$$

where C_{UDR} is unit "Un-Detected Rejection" Cost.

The above mentioned optimization model is subjected to the following constraints:

- Total monthly maintenance cost should not exceed 1.5 percent of the total monthly revenue.
- Total monthly rejection cost should not exceed 0.5 percent of total monthly revenue.

4.4 Data set

The problem was approached with initial data collection related to Work Centre. Analysis of failure history demonstrated that failure characteristics of the key components under consideration best follow a two-parameter Weibull distribution. Further, component characteristics were analyzed and reported as in table 4.2 and product specifications are as mentioned in table 4.3.

Table 4.2 Component's failure and repair characteristics

Compone-nt	Shape parameter Eta (θ)	Scale paramete r Beta (β)	Completed run hours at the time of study	PM time (Hr.) T_{pm}	PM restoration factor (r)	Failure mode (M)	Probability of failure mode	CM time	
								Mean	Sigma
CK-M305 Length Rail	1092	1.047	150	1	0.5	M1	0.152	4.22	2.0
						M2	0.304	2.12	1.2
						M3	0.512	2.17	1.0
						M4	0.032	3.03	2.1
CK-M377 Breadth Rail (C2)	896	1.18	150	2		M1	0.124	5.48	3.3
						M2	0.437	5.67	3.9
						M3	0.35	3.78	23
						M4	0.089	4.17	2.3
BTQX-1508 Height Rail	967	1.16	150	2		M1	0.241	5.08	3.1
						M2	0.247	4.96	2.8
						M3	0.458	3.13	1.0
						M4	0.054	4.07	2.5

Table 4.3 Product specification

Critical to Quality Characteristics	Dimension (mm)
Length (CTQ 1)	2050.00 ±2.50
Breadth (CTQ 2)	1350.00 ±1.85
Edge Bend Radius (CTQ 3)	45.00 ±0.75

4.5 Results

Figure 4.2 provides an overview of results of integrated approach in terms of decision variables, objective function i.e. Total Cost of Operations (TCO) in rupees and comparison with existing approaches. In all, three different approaches are compared with the proposed approach, the details of which are elaborated here under.

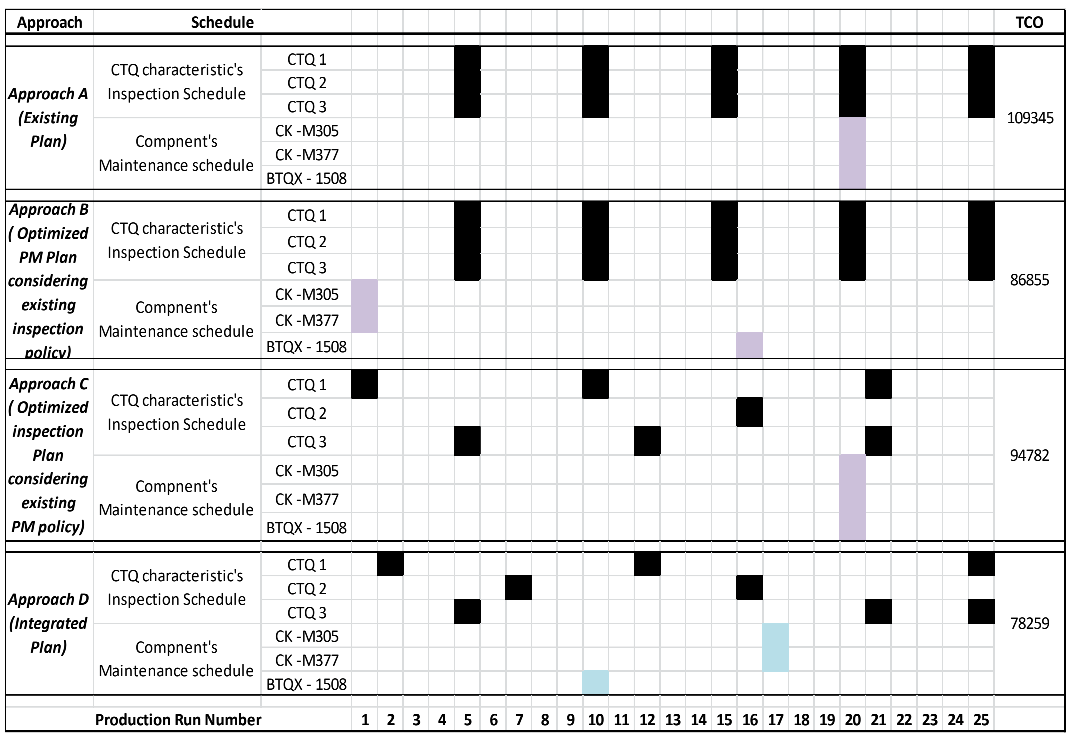


Figure 4.2 Integrated Operations Plan

Approach "A" is the existing approach used by the industry in which every fifth product is inspected for all the CTQs and at every 20^{th} production run machine goes for PM of all the components. In approach "B" and "C" the optimization is applied only to PM schedule and inspection schedule respectively, keeping the plan for the other function fixed as in approach "A". Approach "D" is the proposed approach in which PM schedule and the inspection schedule are integrated. The comparison of cost and time elapsed in arriving at the solution for each of these approaches is as summarized in figure 4.3, which clearly highlights that though the time elapsed in arriving at the solution is higher, integrated approach outperforms other approaches in improvising the objective function.

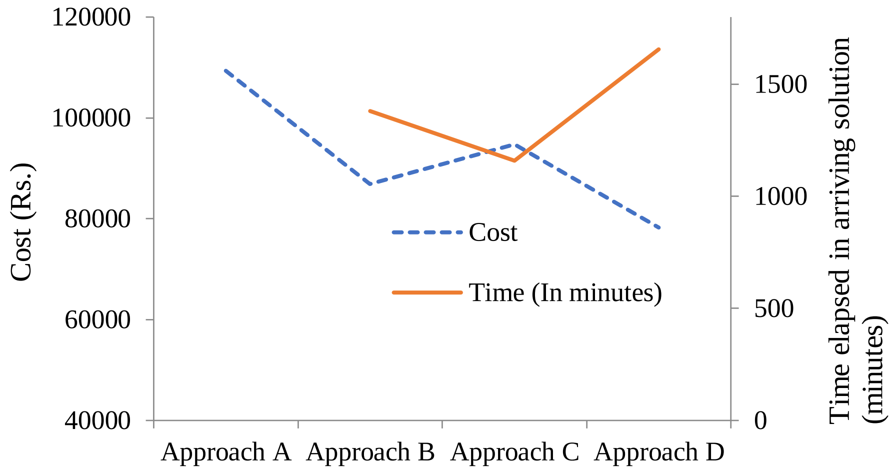


Figure 4.3 Cost and Time*Comparison for various approaches

* Time for approach "A" is not shown as it is the "Fixed Interval based approach" evolved through the experience

Further, to establish the superiority of the proposed approach, the same is evaluated for broad range of manufacturing set-ups. These setups differ in the condition of machine, effectiveness of preventive maintenance activities and cost related to inspection and rejection.

In the first place, from the maintenance perspective, three environments are considered viz. new, old and very old machine. Likewise, three levels of effectiveness of PM was considered viz. high (R=0.8), medium (R=0.5) and low (R= 0.2). Further, for the fixed interval policy, various combinations of fixed interval for machine maintenance and product inspection were studied. In all, 324 scenarios were evaluated, a representative section of which is as shown in table 4.4 (New machine; R=0.8). Lowest TCO obtained under the fixed interval policy for each of environment was compared against TCO for integrated approach. It can be observed that the integrated approach becomes belittling when machine is new and restoration factor for PM is high. On the other extreme, as the establishment ages and wear/deterioration of machine parts increases, the restoration gained through the maintenance activities drops, as it becomes progressively difficult to refurbish the machine's condition beyond a certain extent. Under such conditions, the improvisation realized in the objective function is maximum (around eighteen percent).

Table 4.4 TCO for various combination of PM and inspection frequency

New Machine, R = 0.8	Inspection Frequency						Integrated Approach
PM Frequency	Every Part (100%)	Every 5^{th} Part	Every 10^{th} Part	Every 20^{th} Part	Every 50^{th} Part	Every 100^{th} Part	
PM After 5^{th} Part	**88922 (Min TCO)**	92138	94282	95036	93986	96312	**86855**
PM After 20^{th} Part	114300	119345	119030	120409	124046	126522	
PM After 50^{th} Part	174058	167524	165963	163883	178496	182752	
PM After 100^{th} Part	205804	198607	194127	193819	204309	209705	
NO PM	225148	214779	207274	204342	220166	233114	

Subsequently, the evaluation was extended for new machine and very old machine by varying cost of inspection and rejections, along with the restoration factor. In addition, equivalence of simulation run time was also examined.

In specific, for each of the machine condition (new and very old) and each of the degree of restoration factor (R=0.2, 0.5 and 0.8) the evaluation was extended to cover four different environments elaborated as below:

- Inspection and rejection cost up by twenty five percent of the actual inspection and rejection cost
- Inspection and rejection cost down by twenty five percent of the actual inspection and rejection cost
- Inspection and rejection cost up by fifty percent of the actual inspection and rejection cost
- Inspection and rejection cost down by fifty percent of the actual inspection and rejection cost

The results for cost comparison are as summarized in figure 4.4 (a,b,c) and result for simulation run time are as in figure 4.5.

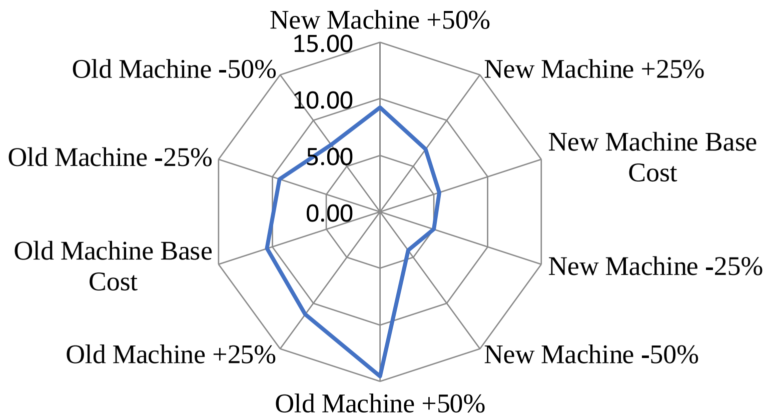


Figure 4.4 (a) Percentage Improvement in Objective Function for R=0.2

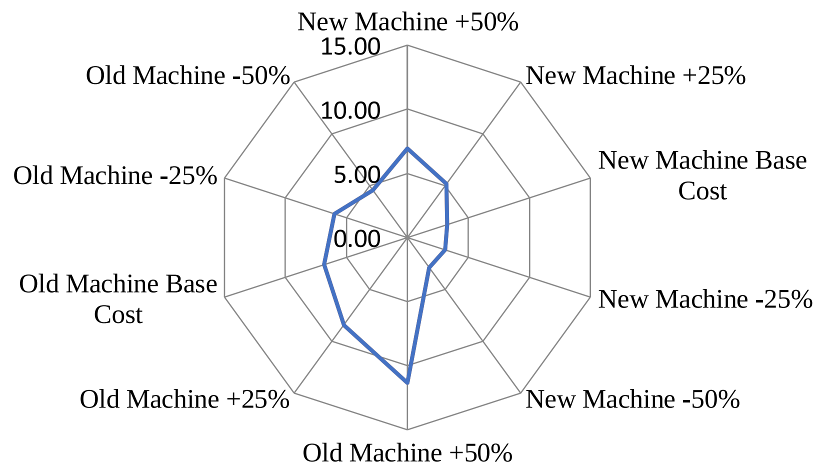


Figure 4.4 (b) Percentage Improvement in Objective Function for R=0.5

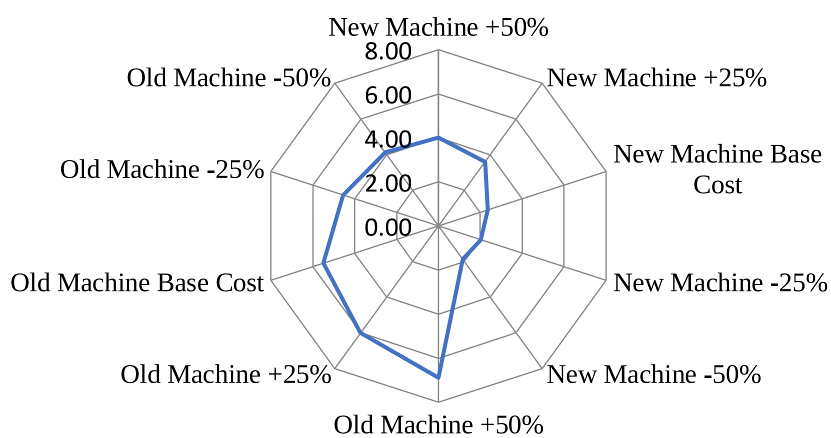


Figure 4.4 (c) Percentage Improvement in Objective Function for R=0.8

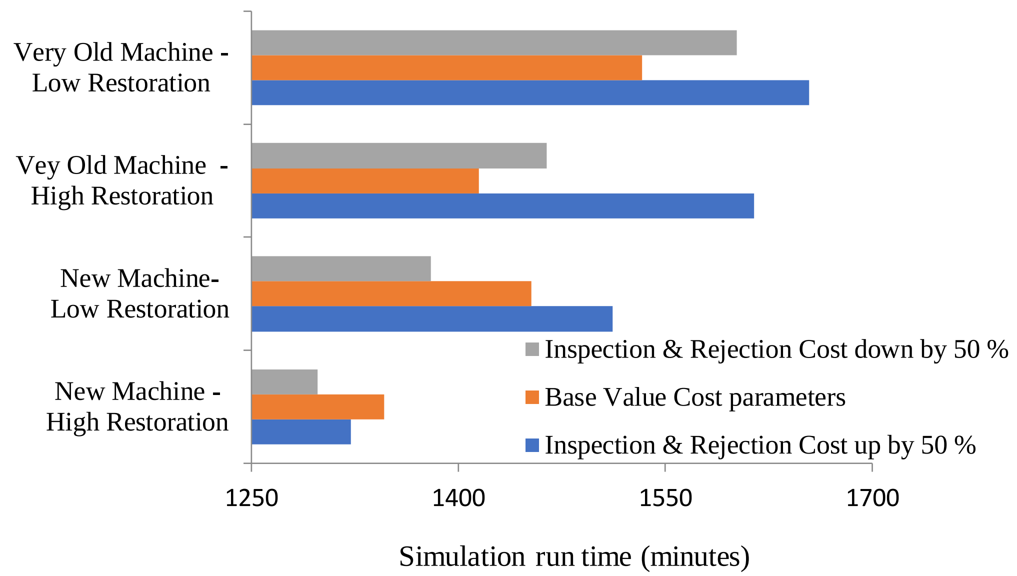


Figure 4.5 Comparison of simulation run time for various operating environments

Figure 4.4 reflects that integrated approach further outperforms against the conventional approach in all the extended cases. However, the percentage improvisation in objective function is highest when the quality cost is high. The environment in which quality cost is high can be related to the industries producing precision engineered products in high volume, such as those manufacturing, automotive gears, high pressure control valves etc. Such industries require capital intensive Work Centre capable of operating in narrow tolerances. This also regulates the use of convoluted metrological support such coordinate measuring machines. This subsequently results into maintenance cost and quality cost are becoming comparable and necessitating the use of integrated approach.

Figure 4.4 further reflects that when the quality cost is low, the percentage improvement realized is minimal and effect of integration is diminishing. Such kind of environment prevails in the High Volume – Low precision industries where the dollar value of the product is insignificant and thus inspection instruments are also generic. Example of such as industries are the one producing catalogued products such as nuts, bolts, etc.

Figure 4.5 depicts a representative scenario for the simulation run time elapsed for high and low value of restoration factor (R=0.8 and R=0.2) for new machine and very old machine when quality cost parameters are altered. It can be observed that when the machine is erstwhile and the effectiveness of the PM is also low, the simulation run time to arrive at near optimal solution is higher. This can be attributed to the more number of opportunities encountered for PM coupled with a panoptic dispersion of inspection activities to optimize the overall cost. Similarly, the effect of quality parameters like cost of inspection and rejection on solution time can also be observed form figure 4.6. This reflects that process parameters do impacts the simulation time which is bound to increase with the problem complexity. This leads toward the requirement for more agile solution approach. An agent based approach is proposed in the nest section for the same.

4.6 Development of distributed approach as a solution method

As mentioned in the previous section, in a dynamic environment, it is required to arrive at solution with minimal time and thus agile solution methods needs to be developed to enhance the applicability of the integrated approach. Current section draws a basic framework to address the agility requirement by developing an agent based planning approach to distribute the computational efforts involved in integrated approach.

Owing to the capability of agent based approach to reduce the response time, its application for developing industrial systems to address manufacturing enterprise integration, enterprise collaboration, manufacturing planning, shop floor control has been continuously growing (Fikar et al. 2018).

Agents are autonomous computational systems and capable of applying fixed rules to reasoning and planning capabilities. Thus, each agent not only solves its local problems to maximize its local objectives but also works together with other agents to attain a global objective.

A brief literature related to Agent based planning is as below:

Zhang and Anosike (2012) presented an agent-based modeling and control approach with a particular focus on the distributed simulation mechanism. Russell et al. (2010) stated that Multi-Agent System (MAS) can provide a new way for solving distributed, dynamic and hard problems. Where, an agent is defined as anything that can be viewed as perceiving its environment through sensors and acting upon that environment through actuators. This capability makes multi-agent entities a good candidate to handle the distributed, dynamic, and complex problems. However, MAS is rarely employed for manufacturing environments and machine scheduling domain. One of the rare studies in this domain is presented by Khelifati and Benbouzid-Sitayeb (2011). They proposed a distributed approach which is using multi-agent paradigm for scheduling independent jobs and maintenance operations in the flow-shop sequencing problem. The approach introduces a dialogue between two communities of agents (production and maintenance) leading to a high level of cooperation. It also provides a framework in order to react to the disturbances occurring in the workshop. Duan et al. (2012) proposed a negotiation-based optimization method for scheduling of a manufacturing system. There are two main agent types in their paper which are manufacturers and suppliers. In their paper, Erol et al. (2012) proposed multi-agent based approach for machine scheduling together with the automated guided vehicles in a flexible manufacturing environment. The approach works under a real-time environment and generates feasible schedules using negotiation/bidding mechanisms between agents. This approach is tested on off-line scheduling problems from the literature. Lou et al. (2012) presented a multi-agent based proactive-reactive scheduling for job-shop scheduling problem. In the proactive scheduling, the objective is to generate a robust predictive schedule against known uncertainties. While in the reactive scheduling, the objective is to dynamically rectify the predictive schedule to adapt to unknown uncertainties viz., the reactive scheduling stage is actually complementary to the proactive scheduling stage. Case study showed that this scheduling mechanism generates more robust schedules than the classical scheduling mechanism. Henchiri and Ennigrou (2013) proposed a multi-agent model based on hybridization of TS method and Particle Swarm Optimization (PSO) in order to solve flexible job-shop scheduling problem. The objective was to minimize the makespan. The model was composed of Resource agents and an Interface agent. On each Resource agent, TS based local optimization process was placed to execute local diversification techniques. A global optimization process based on PSO has been integrated at the Interface agent. Polyakovskiy and M'Hallah (2014) proposed a MAS based heuristic to solve weighted earliness tardiness parallel machine problem where jobs have different processing times and distinct due dates. The MAS has three types of agents: I, G, and M. The I-agents are free jobs that need to be scheduled, whereas the G-agents are groups of jobs already assigned to machines. The M-agent acts as the system's manager of the independent intelligent I-agent and G-agent, which are driven by their own goals, fitness assessments, and context-dependent decision rules

For the entities involved in the current problem, three agents are developed namely maintenance agent, process inspection agent and coordination and negotiation agent. Each of the agents is selfish as they are made self-interested and aims only to optimize the specific goal attributed to them. For instance, primary objective of maintenance agent is to minimize the maintenance cost. Similarly, primary objective of the process inspection agent is to optimize inspection cost. Independent optimization is carried out by both agents individually; post which each of the agents generates and ranks the sets consisting of multiple preferred solutions in order of improvement realized in objective.

Since these two individual agents operate in environments that are only partly known and predictable, it is therefore required that the set of optimized decisions arrived by them should be negotiated between overall goal and individual agent's goals. For this a third agent called coordination and negotiation agent is designed. This agent optimizes the conflicting decisions through negotiation which is influenced by the value of the objective function and proceeds by accepting the plan, rejecting it or proposing next alternative plan. This plan is then evaluated for its feasibility and an alternative plan is generated until a stage where it is not possible to estimate the best alternative to a negotiated plan subject to acceptability of other agents. The final negotiated plan supports agents in satisfying their own objectives by matching the best counterpart plan.

The negotiation mechanism is elaborated through the following flow chart as below:

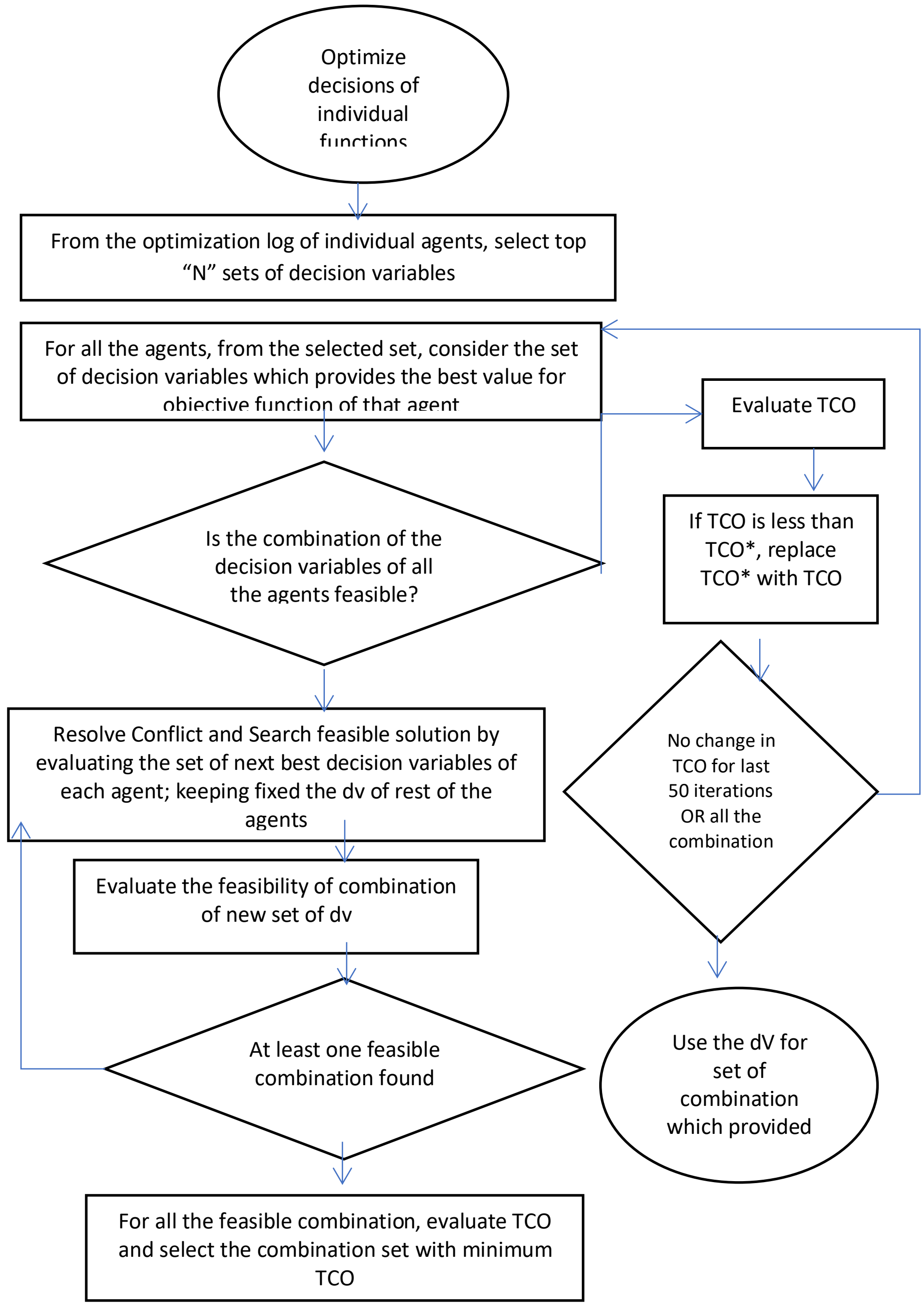


Figure 4.6 Flow chart for the negotiation mechanism

4.7 Comparative evaluation

To evaluate the distributed approach against the centralized approach, a comparative evaluation was performed. Three cases were evaluated for the distributed planning approach which differed in the numbers of solutions considered for negotiation from each agent. The results are as in table 4.5.

Table 4.5 Comparative evaluation of the centralized and distributed planning approach

Planning Approach		Time elapsed (In min)	Objective function	Percentage improvement in result using Integrated approach	Percentage reduction in solution time
Integrated Planning (Centralized)		1656	78529	NA	NA
Integrated Planning (Distributed)	Distributed Approach (20 Solutions)	844	104865	-24%	49%
	Distributed Approach (50 Solutions)	1109	98485	-16%	33%
	Distributed Approach (100 Solutions)	1457	92088	-9%	12%

The table illustrates the percentage change in objective function as well as the percentage improvement in the solution time for various scenarios considered. For instance, when only top 20 solutions were considered from each agent, the time to arrive at the solution is around 49% less as compared to the time elapsed when the centralized approach was applied. However, the value of objective function i.e. overall cost was around 24 % higher. Since the objective function is to minimize the overall cost, this percentage change is depicted as a negative number. Likewise, when top hundred solutions were considered for both the agents, time elapsed was 12 % lower than the centralized approach, however, the overall cost was only 9 % higher. It can thus be concluded that the distributed approach provides the solution in lesser time as compared to all the other approaches, but the quality of solution is inferior to that of the centralized approach. It can be also observed that as the number of solution considered for negotiation in the distributed approach increases, the solution quality approaches that of the centralized integrated approach. It can thus be arrived at that as the problem complexity increases; the distributed approach is more promising for balancing the timeliness and quality of solution.

4.8 Summary

In current chapter, an integrated approach for preventive maintenance and process quality inspection is proposed for a multi-component machine. The formulation of the approach is complex as it is based on minimum assumptions and replicates a real manufacturing environment characterized by factors like multiple failure modes of components, impact of these failure modes on various quality characteristics, stochastic nature of maintenance activities, multiple dependencies amongst components, etc. It is demonstrated that the integrated approach outperforms conventional approach of independent planning. Moreover, a comprehensive evaluation of the integrated suggests that simultaneous consideration of maintenance and quality becomes more important for the environment characterized by older machine, less effective PM activities and high cost of rejection and inspection. To make the proposed approach more applicable and responsive, a novel integrated yet distributed approach is also proposed as a solution method for next-generation manufacturing system. It is further observed that solution provided by the distributed approach is quick but sub standardized as compared to the centralized approach. However, the breach in the quality of the solution between the two approaches becomes undistinguished as complexity of the environment grows and distributed approach provides the solution in much lesser time to respond to dynamic business requirements.

The work addresses the realization of Sub objective 1, Sub objective 2 and Sub objective 4 mentioned in chapter 1.

CHAPTER 5*

INTEGRATION OF PRODUCTION, MAINTENANCE AND MATERIAL SUPPLY PLANNING

Key Highlights

Purpose: Existing body of literature is mainly confined to the integration of two functions. This chapter aims to extend the magnitude of integration and develops a framework for integrating three disjoint functions. It integrates production plan, maintenance plan and raw material supply plan. It subsequently evaluates the value of such integration and generalizes its superiority. This chapter thus attempts to addresses the realization of Sub objective 1, Sub objective 2 and Sub objective 3.

Findings: The proposed approach is examined over a broad range of manufacturing environment and as a result, an improvement in the total cost of operation in the range of 5.23 to 15.28 percent was observed. It was also observed that the integration of the supply planning function is more beneficial when the variability associated demand and lead time of raw material supply is high.

Originality and Contribution: In the current wok, the correlation between the material supply plan and maintenance plan is established. This correlation was overlooked in existing body of literature, but is an important input for optimizing the plan of each of these functions. Through the incorporation of supply planning function, current work extends the existing integrated models to include the function which extends beyond the shop floor. Such an integration of more than two function which considers material supply planning is not reported in past and thus becomes the novelty and contribution of current chapter.

Practical Implication: The work brings forth a very significant relation between the maintenance plan and the material supply plan. This correlation can be utilized in optimizing the allocation of raw material orders to the suppliers in a way that the down time of the machines is synchronized and the waiting time for the material to get

A part of the work presented in this chapter is published under the title "Machine tool reliability: an operational perspective". Purohit, B.S. Jean-Baptiste Ringard,and Lad,B.K. in the Life Cycle Reliability and Safety Engineering (LRSE) and under the title "Integrated Operations Planning for a Multicomponent Machine Subjected to Stochastic Environment" Proceedings of 5th International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SIMULTECH-2015),21-23 July 2015.

processed is minimized. This can result into significant improvement in the production economy and can thus of prime relevance to operation managers.

5.1 Introduction

While reviewing the literature related to integration, it was noted that there is a scarcity of literature in which the supply planning function is considered for integration. As mentioned in chapter 1, it could be attributed to the fact that in case of material supply planning; a significant part of the execution like order processing, shipment etc. is dependent on supplier of the material and the extent of control over execution of supply planning function is relatively less. From this perspective, to an extent, supply planning can be considered as an external function.

Considering the fact that the integrated approach is in its evolution phase, the initial focus of researchers is in developing the approach for the functions for which the interdependencies are well establish. And thus, there is abundance of literature mentioning the integration of production and maintenance, maintenance and quality, and production and quality. However, material supply planning being a critical function of an organization, it too needs significant contemplation towards its integration with the other functions. Such an encompassment of the supply planning function helps in panoramic management of the value chain and is also necessary to align the integration with the emerging trend in which the manufacturing supply chain is treated as enabler for value creation at the organizational level (Simatupang et al 2017; Kaehkonen and Lintukangas 2013; Wankhade and Kundu, 2018).

Frohlich and Westbrook (2001) also confirmed in their research that owing to the complexity of multi-function integration, the focus of researchers in the initial phase of is confined to integration of internal functions over external functions. On the other hand, as pointed out by Eloranta, and Hameri, few of the empirical studies have focused on either upstream integration or downstream integration, each to the exclusion of the other. Review of the articles in which such integration of supply planning function is attempted are mentioned underneath:

Work by Goyal and Deshmukh (2010) is amongst the closest which integrates supply planning with a production system. The work highlights the fact that when the raw materials are used in production, the procurement policies are dependent on the schedule and the batch size for the product. Hence, it is necessary to unify the procurement and production policies. However, conventionally, the policies for procurement and production are not integrated. Aligned with this requirement, a coordinated approach between the procurement and production policies id formulated in this work. The model proposed here is a traditional inventory model for a single product, multistage batch environment aiming at the minimization of total variable cost and thereby determining the batch sizes for the product and raw material order sizes. The proposed approach is demonstrated through a numerical data set and the result further establishes the need to extending the integrated approach to encompass function like material planning with production.

Kanyalkar and Adil (2007) integrated production planning with procurement and distribution plans in a multi-site environment. This paper develops a mixed integer linear goal programming model for an integrated multi-item, multi-plant procurement, production and distribution problem. As against the normal procedure of the multi-step production planning, which uses different formulations for different levels of decisions, this work uses a single formulation, which gives the solution for both levels in a single step. At the same time unlike the single step production-planning method it does not need detailed information for an entire planning horizon. The integration is of significant practical relevance for the companies having multi-location manufacturing and distribution facilities and multiple dock/supplier locations supplying raw material to the plants.

Pal et al. (2011) also attempts to addresses the problem of integrated procurement, production and shipment planning for a value chain, spanning over three echelons which are supplier, manufacturer and retailer. It integrated supplier order scheduling with a production-shipment planning process. A model to minimize operating cost for a manufacturer is developed, which supplies finished products to retail centers with a chase strategy to match supply with demand. It leverages the information of demand, holding costs and storage capacities of the retailers to schedule its production and procurement. The work was carried out at a tactical level and has opened the direction in which integration could be extended to the longer periods wherein selection of suppliers that best matches the business goals of the could be made through the integration of production plans.

Work by Torabi and Hassini (2009) also considers the integration of material planning with production and considers a real case of an automobile company. This study proposes a multi-objective, multi-site production planning model integrating procurement and distribution plans in a multi-echelon supply chain network with multiple suppliers, multiple manufacturing plants and multiple distribution centers. The model incorporates four important conflicting objectives simultaneously: minimization of the total cost of logistics, maximization of the total value of purchasing, minimization of defective items and minimization of late deliveries. The work establishes the fact that in value chain master planning problems, a paramount characteristic need to be addressed. This characteristic is regarding the conflicting objectives where it is often difficult to align the goals of the different functions within the organization. Extending the integration to incorporate more function thus becomes a promising solution.

From the literature mentioned above and more, it can be concluded that w though supply planning function is considered for integration, its integration is limited between two functions which are production and distribution. While factors like nature of the store items (perishable / non -perishable / shelf life), stock out costs, lead time, number of suppliers, demand volatility etc. are important for optiimzng the material planning function, a very critical function is missed which bridges the flow between the production and distribution. This function is maintenance planning. It is observed that the characteristics of the machine, on which the plan arrived after integration of supply planning function will be executed, are not considered. Parameters of machine related to failure and repair are critical as these determines the availability of the machine and regulates the production and distribution plan. All the work reporting integration of supply planning function have missed to this aspect and thus belittles the benefit that could be realized through such integration. The holistic consideration of other peripheral function is thus required. In addition, the observation made in earlier chapters related to simplistic environment, evaluation of the proposed model for other manufacturing environment, generalization of the value of the proposed approach, use of hypothetical data etc. continues to be there in the models attempting to incorporate supply planning function for integration. Current chapter aims to bridge all these gaps is subsequent sections.

5.2 Description of representative manufacturing environment

The integration of supply plan with production and maintenance plan is demonstrate through a value chain one end of which is represented by customers and other end is represented by suppliers of raw materials of the products. Since the maximum transformation in the product is carried out by performing a machining operation, the machine is considered as the central element of this value chain. In order to meet the customer's demand, at its maximum capacity, the machine under consideration can run for 3 shifts a day and 6 days per week. This machine under consideration is constituted by multiple components which are reliability wise connected in series and are independent from each other. Since Weibull failure distribution can be used to model increasing, decreasing as well as constant failure rate, the same is assumed to characterize failure characteristics of components of the machine. The machine processes the raw materials which are supplied by a set of previously screened raw material suppliers. To mitigate the risk related to availability of raw material, the manufacturer follows multi sourcing policy, according to which there can be more than one supplier who can provide same raw material. The decision related to selection of particular supplier/ suppliers and their respective order quantity is predominantly based on cost, quality and delivery parameters. In addition, considering capacity, availability and variability in transportation lead time, decision on appropriate safety stock is also vital for balancing the cost related to inventory and stock-outs. Optimizing these decisions is of prime importance from supply planning perspective.

These raw materials are processed on the machine in order of their priority which is influenced by delivery dates requested by customers and other parameters such as penalty cost for late deliveries, inventory carrying cost etc. There can be many customers and each one can demand multiple products in different quantity and at different time. The delivery of these products is primarily dependent on the availability of the machine, which in turn is influenced by factors like maintenance scheduling and breakdowns. These breakdowns can be minimized if the machine undergoes periodic Preventive Maintenance (PM) as each PM activity, to some extent restores the condition of the machine. The extent of this restoration is measure by Restoration Factor (RF). High restoration factor signifies more efficient PM process and thus longer machine life. Despite of these PM activities, machine may still encounter random breakdown, which are then addressed by Corrective Maintenance (CM) activities. Since CM is unplanned, it tends to consume more time which also reduces machine availability for production. To reduce such random breakdown, timely PM is practiced which also consume available production time. Under such scenarios, efficient maintenance scheduling becomes a key concern.

In addition, from manufacturing perspective, optimal sequencing of jobs and their manufacturing lot sizes are the decisions which contribute towards the efficient execution of the production plan, whose performance is measured by indicators like number of tardy jobs, missed orders etc. Tardy jobs results in delayed deliveries for which manufacturer has to bear penalty cost. Similarly, in situations where demanded quantity could not be completed, manufacturer has to bear backorder cost. It is assumed that these back orders are not carried forward for the next month and thus considered as lost orders. In addition, the environment in which above value chain operates is complex and is characterized by various uncertainties such as variation in demand, machine yield, raw material quality, transportation lead time and time required for corrective maintenance, to name a few. The above mentioned description is illustrated in figure 5.1.

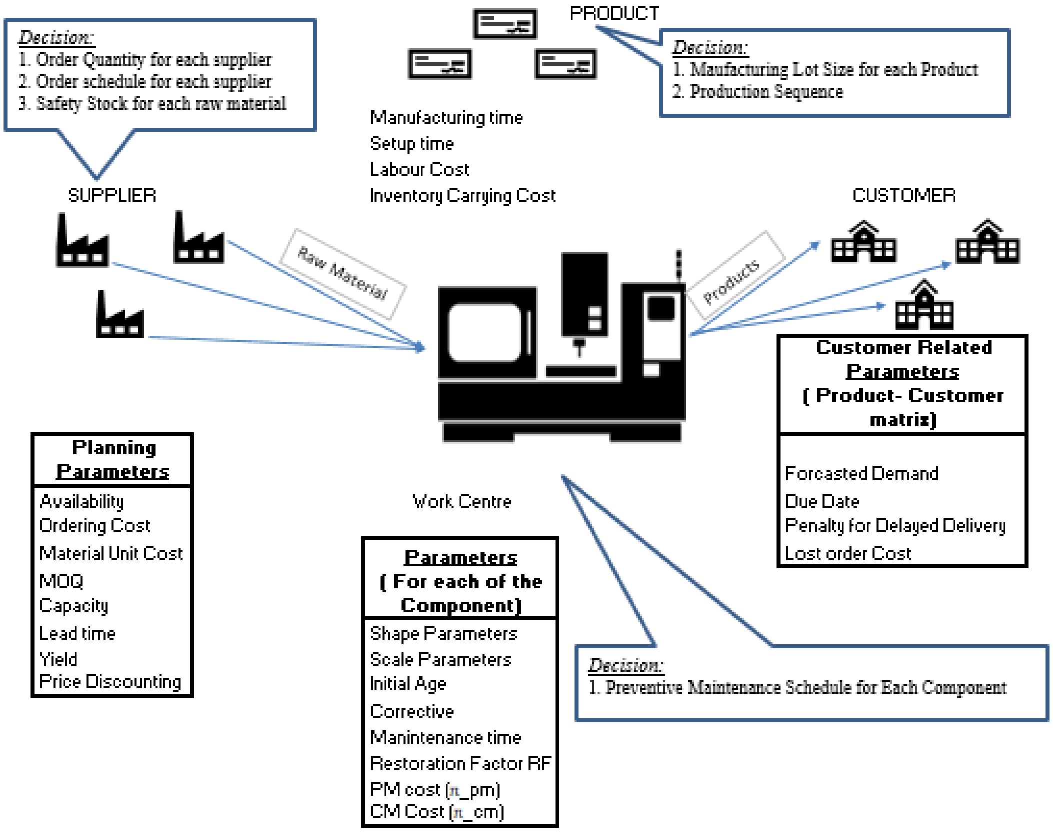


Figure 5.1 Reresentaion of the industrial evironment

5.3 **Model development and data set**

5.3.1 Model Development: Objective function, decision variables and constraints

The organization's prime objective is to minimize the "Total Cost of Operation" (TCO)

i.e.:$Objective : Minimize\ (TCO)$

Total cost of operation consists of multiple cost elements such as maintenance cost, material cost, backorder cost etc. and is impacted by various parameters and decisions. However, as a prelude for integration of Supply Planning, Maintenance

Planning and Production Planning, the key decision variables which are primarily looked upon are as mentioned in table 5.1.

Table 5.1 Functions and key decisions

Function	**Supply Planning**	**Maintenance Planning**	**Production Planning**
Key Decision	Order Quantity for individual Suppliers Safety Stock	Preventive Maintenance plan for Individual Component	Production Sequence Production Batch Size

These decision variables can be illustrated as:

i. Decision of Sequencing i^{th} product in s^{th} production run : [λ_{is}]
ii. Decision of manufacturing batch size of Z^{th} product in x^{th} month :[$q_z x$]
iii. Decision of Preventive Maintenance of w^{th} component before z^{th} production run in x^{th} month: [PMF_{xwz}]
iv. Decision of Safety Stock for z^{th} product in x^{th} month :[SS_{zx}]
v. Decision of Order Quantity: [Q_{xyz}]

As mentioned in section 5.2, each of these decisions have significant impact on each other and thus an improvisation upon total cost requires trade-off between decisions related to various functions. This interaction and trade-off between various function is inhibited in objective function in the form of various cost elements by which it is constituted. However, due to combinatorial nature, this relationship is not explicitly evident from the equation of objective function and thus individual costs are separately elaborated below:

5.3.1.1 Total Supply Cost (TSC)

In current work it is assumed that each product is manufactured using single raw material i.e. product 1 is manufactured from raw material 1, product 2 is manufactured using raw material 2 and so on. However, these raw materials can be supplied by multiple suppliers. Total Supply Cost (TSC) for these raw materials includes Cost of Ordering (C_o) and Cost of Raw Material (C_m) i.e.

$$TSC = C_o + C_{rm} \tag{5.1}$$

Cost of ordering includes expenses involved in placing an order, such as administrative cost, preliminary labor cost etc. These costs generally do not vary with types of raw materials and therefore, it is assumed that ordering cost also does not depends on the type of raw material. However, such costs may slightly vary with each supplier as each supplier may have different procedure for processing the order. In addition, an order can have only one type of raw material. Thus, to order multiple raw materials from a single supplier, different orders needs to be placed. Further, if the order is split amongst multiple suppliers then ordering cost for each of the supplier for the particular raw material will be added.

Thus, cost of ordering for each product from respective supplier / suppliers is mathematically represented as:

$$C_o = \sum_{x=1}^{x=m} \sum_{y=1}^{y=s} \sum_{z=1}^{z=p} (CO_y \times SSF_{xyz}) \tag{5.2}$$

Where CO_y is the cost per order for y^{th} supplier and SSF_{xyz} is supplier selection factor for z^{th} product for y^{th} supplier in x^{th} month, such that

$$SSF_{xyz} = \begin{cases} 1, & \text{if } y^{th} \text{ supplier is selected for delivering raw material of } z^{th} \text{ product in } x^{th} \text{ month} \\ 0, & \text{if } y^{th} \text{ supplier is NOT selected for delivering raw material of } z^{th} \text{ product in } x^{th} \text{ month} \end{cases} \tag{5.3}$$

Similarly, cost of raw material is the multiplication of Unit Price (UP) of product, Discount Factor(DF), Quantity ordered(Q) and Supplier Selection Factor(SF). Discount factor refers to the concession provided by supplier for procuring higher quantities. This is generally provided to attract customers to buy more. TRMC can be mathematically written as:

$$C_{rm} = \sum_{x=1}^{x=m} \sum_{y=1}^{y=s} \sum_{z=1}^{z=p} Q_{xyz} \times UP_{yz} \times DF_{zy} \times SF_{xyz} \quad (5.4)$$

Where Q_{xyz} is quantity ordered in x^{th} month of z^{th} product from y^{th} supplier and UP_{yz} and DF_{zy} refers to unit price and discount factor for raw material of z^{th} product from y^{th} supplier.

5.3.1.2 Total Production Cost (TPC)

It is sum of cost of setup (C_s) and cost of machining (C_m) i.e.

$$TPC = C_s + C_m. \quad (5.5)$$

Machining requirements for each product is different and thus need different machine setup in terms of tooling, clamping, lubrication etc. The changeover time of setup for each product thus depends on the previous setup and therefore current work considers sequence dependent set up time for each product. Cost of setup (C_s) is evaluated as:

$$C_s = \sum_{x=1}^{x=m} \sum_{z=1}^{z=p} [(\tau_{zx}) \times LC_p \times \lambda_{is}] \quad (5.6)$$

where τ_z is set up time for z^{th} product in x^{th} month for a given sequence of production and LC_p is Labor Cost for production.

Likewise, cost of machining (C_m) is calculated as:

$$C_m = \sum_{x=1}^{x=m} \sum_{z=1}^{z=p} (Q_{zx} \times MT_z \times MLC) \quad (5.7)$$

where Q_{zx} is the manufacturing lot size of z^{th} product in x^{th} month and MT_z is the time for machining of z^{th} product.

5.3.1.3 Total Maintenance Cost (TMC)

Total Maintenance Cost is sum of Cost of Preventive Maintenance (COPM) and Cost of Corrective Maintenance (COCM) i.e

$$TMC = COPM + COCM \quad (5.8)$$

Each maintenance activity requires various consumables, spares etc., the need of which depends upon the condition of the component. Consumables like oil grease etc. are required during every maintenance activity and thus incur a fixed cost. In addition, based upon the pattern and extent of usage, there may be some extra spare parts/consumables required during maintenance, the necessity of which is only decided after inspecting the condition of the component. Due to such uncertainties involved, the cost of maintenance is uncertain. Uniform distribution being the simplest way to represent two-sided bound, the same is considered to represent handle such uncertainties.

Considering this, total cost of preventive maintenance (COPM) is evaluated as:

$$COPM = \sum_{x=1}^{x=m} \sum_{w=1}^{w=c} \sum_{z=1}^{z=p} [\{(T_{PM_w} \times MLC) + COCM_w\} \times PMF_{xwz}] \quad (5.9)$$

where T_{PM_w} is the time to execute preventive maintenance on wth component, $COPM_w$ is preventive maintenance cost of wth component, LC_m is the maintenance labor cost per hour and PMF_{xwz} is preventive maintenance factor for wth component before zth production run in xth month such that,

$$PMF_{xwz} = \begin{cases} 1 & if\ \mathrm{w}^{th}\ component\ goes\ for\ PM \text{ before } \mathrm{z}^{th} \text{ production run in } \mathrm{x}^{\mathrm{th}} \text{ month} \\ 0 & if\ \mathrm{w}^{th}\ component\ doesnot\ go\ for\ PM \text{ before } \mathrm{z}^{th} \text{ production run in } \mathrm{x}^{\mathrm{th}} \text{ month} \end{cases} \quad (5.10)$$

Further, in case of random breakdowns, the nature of fault and particulars of corrective actions required are not precisely known in advance. This makes it difficult to predict duration of corrective maintenance. To accommodate this, time for corrective maintenance is assumed to be normally distributed whose mean and standard deviation can be captured from past maintenance records.

Thus, cost of corrective Maintenance ($COCM$)is calculated as:

$$\mathrm{C}_{cm} = \sum_{x=1}^{x=m} \sum_{w=1}^{w=c} \sum_{z=1}^{z=k} \left(NF_{xwz} \times [\{T_{CM_w} \times MLC\} + COPM_w]\right) \quad (5.11)$$

where T_{CM_w} is time to perform corrective maintenance of wth component and $COPM_w$ is the corrective maintenance cost for wth component. NF_{xwz} is number of failures of wth component during zth production run in xth month.

Considering minimal repair for corrective maintenance, number of failures, NF_{xwz}, during this production run can be calculated as:

$$NF_{xwz} = \left[\frac{((MT_z \times q_{zx}) + Ia_{xwz})^{\beta_w}}{\eta_w}\right] - \left[\frac{(Ia_{xwz})}{\eta_w}\right]^{\beta_w} \quad (5.12)$$

where, β_w and η_w are shape and scale and shape of w^{th} component respectively and Ia_{xwz} is the initial age of wth component before zth production run in xth month.

5.3.1.4 Total Inventory Cost (TIC)

In the current work it is assumed that if the products are manufactured before committed due date, they are immediately shipped to customer and therefore not considered for finished goods inventory calculation. However, if the produced quantity is more than the quantity required by the customer, the excess quantity of finished goods is considered for inventory calculation along with raw material inventory. Thus, based on average monthly inventory, total inventory carrying cost (TIC) can be evaluated as:

$$TIC = \sum_{x=1}^{x=m} \sum_{z=1}^{z=p} ([I_{avg}] + SS_{zx} \times IC_Z) \quad (5.13)$$

where, I_{avg} is the average inventory of zth product for xth month and IC_Z is the inventory carrying cost for the zth product.

5.3.1.5 Total Penalty Cost (T$\bar{\bar{P}}$C)

Current work considers Total Penalty Cost (T$\bar{\bar{P}}$C) as sum of Cost of Delayed Deliveries (C_D) and Cost of Back Orders (BO) i.e.

$$T\bar{\bar{P}}C = C_D + C_B. \quad (5.14)$$

Cost of delayed deliveries is imposed by customer to manufacturer in case the delivery of products is made after the committed due date and thus only depends on the tardiness. Each customer may impose different cost for different product and thus C_d calculated as:

$$C_D = \sum_{x=1}^{x=m} \sum_{z=1}^{z=p} \sum_{t=1}^{t=h} DC_{zxt} \qquad (5.15)$$

Where is DC_{zxt} the delay cost for t^th^ customer for the z^th^ product in x^th^ month such that,

$$DC_{zxt} = \begin{cases} 0 & , ADD_{zxt} \leq CDD_{zxt} \\ \sum_{t=1}^{t=h} (ADD_{zxt} - CDD_{zxt}) \times P_{zt} & , ADD_{zxt} \geq CDD_{zxt} \end{cases} \qquad (5.16)$$

where ADD_{zxt} and $CDD_{zxt}$the actual and committed delivery date for the $\mathrm{z^{th}}$ product in x^{th} month from t^{th} customer and P_{zt} is the per day penalty cost for delay of the $\mathrm{z^{th}}$ product for t^{th} customer.

Likewise, if the quantity delivered to customer is less than the quantity ordered, then backorders are charged to manufacturer, proportional to the difference between the quantity ordered by customer and actual quantity delivered to him. Backorder may arise due to several factors such as higher internal rejections, inadequate supply of raw material etc. Each customer may charge different backorder cost and thus total backorder cost is evaluated as:

$$C_b = \sum_{x=1}^{x=m} \sum_{t=1}^{t=h} \sum_{z=1}^{z=p} (BO_{tz} \times \epsilon_{xtz}) \qquad (5.17)$$

where, BO_{tz} is the cost per unit of backorder for t^{th} customer for z^{th} product and ϵ_{xtz} is the number of backorders in x^{th} month for t^{th} customer for z^{th} product.

The above mentioned decisions are subjected to the following constraints:

- Dispatch Schedule Constraint:

Organization follows policy of periodical dispatches, which are generally scheduled on timely basis. This sets up a time constraint which can be written as:

$$\pi_t \leq S_t \tag{5.18}$$

- Demand Constraint:

Besides the constraint of timely shipment, there is another constraint for the quantity to be shipped in a particular time period. This translates in to constraint for minimum quantity to be produced, in order to fulfill the complete demand. The same can be written as:

$$\{Min.(Q_i)\} \geq D \tag{5.19}$$

5.3.2 Data set

In order to illustrate the application of the proposed approach, following example is presented.

The dataset used in the example is aligned with the industrial observations made during similar assignments by the authors in a machine tool industry where the authors have performed similar studies for process improvement.

Consider a multicomponent machine constituted by "c" components where c = 5. The maintenance characteristics of these components are as mentioned in table 5.2.

Table 5.2 Component maintenance characteristics

Component no.	Corrective		PM Fixed Time T_{PM}	Initial Age (Ia) in hours	Scale factor (η)	Shape factor (β)	Restoration factor (RF)	Maintenance cost	
	Mean	Std. Dev.						PM cost π_{pm}	CM Cost π_{cm}
1	8.2	5.11	4	2000	1658	2.24	0.7	400-	1300-
2	6.1	4.61	4	2000	1311	2.51	0.7	350-	1200-
3	10.1	6.39	4	2000	1752	3.09	0.7	450-	1600-
4	6.2	4.18	4	2000	1811	1.51	0.7	350-	1200-
5	4.4	3.52	4	2000	2109	1.86	0.7	300-	800-1400

The machine mainly produces four products, whose characteristics are as mentioned in table 5.3 and table 5.4. The changeover time of setup for each product thus depends on the previous setup and therefore current work considers sequence dependent set up time for each product, the details of which are as in table 5.6.

Table 5.3 Product Cost Characteristics

Product	P1	P2	P3	P4
Manufacturing time in hours (MT)	0.51	0.42	0.37	0.28
Labor Cost per hour (L_c)	100	100	100	100
Inventory carrying cost per unit per month (Φ_{RM})	12	10	11	8

Table 5.4 Due dates and penalty costs

		P1	P2	P3	P4
Committed Due Date (CDD)	Customer 1	15	15		
	Customer 2			21	21
	Customer 3	17	17	17	
	Customer 4		21	21	21
Delayed Delivery Cost /per day (Ω)	Customer 1	7	7		
	Customer 2			8	8
	Customer 3	5	5	5	
	Customer 4		9	6	6
Back Order Cost Per Unit (ω)	Customer 1	250	210		
	Customer 2			190	150
	Customer 3	270	200	175	
	Customer 4		215	180	160

Table 5.5 Monthly demand (January)

		Product			
		P1	P2	P3	P4
Demand Forecast	C1	90	90		
	C2			85	95
	C3	85	95	85	
	C4		95	95	100
Uniformly Distributed Actual	C1	81-99	81-99		
	C2			76-94	85-
	C3	76-94	85-105	76-94	
	C4		85-105	85-105	90-

Table 5.6 Sequence dependent set up time (τ) in hours

		Preceding Job			
		P1	P2	P3	P4
Current Job	P1	0	2.2	1.5	1.8
	P2	2.1	0	1.9	1.7
	P3	1.8	2.2	0	2.0
	P4	1.4	1.8	1.65	0

Table 5.7 Discount Factor (DF) window

	Order Quantity	RM 1	RM	RM	RM4
		Percentage Discount for per			
Supplier 1	0 to175	0	0		
	176 to235	9	10		
	above235	12	13		
Supplier 2	0 to 180		0		0
	181 to240		10		9
	Above240		11		13
Supplier 3	0 to160	0	0	0	
	161 to210	7	7	7	
	above210	12	12	12	
Supplier 4	0 to170			0	0
	171 to225			6	6
	above 225			11	12

Table 5.8 Supplier characteristics

		RM1	RM2	RM3	RM4
1= Providing 0=Not Providing	Supplier 1	1	1	0	0
	Supplier 2	0	1	0	1
	Supplier 3	1	1	1	0
	Supplier 4	0	0	1	1
Cost Per order	Supplier 1	150	150		
	Supplier 2		200		200
	Supplier 3	180	180	180	
	Supplier 4			160	160
RM Unit price (UP)	Supplier 1	150	120		
	Supplier 2		110		90
	Supplier 3	160	115	110	
	Supplier 4			115	85
Minimum Order Quantity	Supplier 1	50	50		
	Supplier 2		70		70
	Supplier 3	50	50	50	
	Supplier 4			70	70
Maximum Order Quantity	Supplier 1	300	300		
	Supplier 2		280		280
	Supplier 3	265	265	265	
	Supplier 4			285	285
Lead time in days (Uniformly Distributed)	Supplier 1	8-12	5-7		
	Supplier 2		6-8		6-8
	Supplier 3	7-10	7-9	7-10	
	Supplier 4			5-9	5-9
Quality Rating	Supplier 1	0.96	0.96		
	Supplier 2		0.97		0.95
	Supplier 3	0.94	0.94	0.93	
	Supplier 4			0.97	0.99

The supply planning for raw material is aligned with the demand from the customers. But considering the lead time related to transportation, manufacturing etc., the procurement is done much in advance. This procurement quantity is based on the forecast of the demand. The forecast may not be accurate and generally deviates from the actual demand which is uncertain but uniformly distributed. In specific, the demand for the month of January is as shown in table 5.6. The demand for the consecutive months follows approximately similar pattern.

The raw material for these products are supplied by various suppliers whose characteristics are as shown in table 5.8. These suppliers, in order to attract bulk procurement, provides discounted pricing depending upon the quantity ordered. The discounted rates are as shown in table 5.7.

5.4 Result: Integrated supply, production and maintenance plan

With data set mentioned in section 3, the model was simulated for over one lakh trials, each having 100 iterations, to arrive at an improved value for decision variables.

The objective function was used as the fitness function for GA and crossover rate and the remaining GA parameters are as mentioned below:

GA Parameters

- Population Size 200
- Number of Generations 100
- Crossover Rate 0.1
- Mutation Rate 0.5
- Selection Scheme Roulette wheel with elitist

However, various combinations of mutation rate and crossover rate were also considered, and results were found insensitive for crossover rate range between 0.5 and 0.8 and mutation rate ranging between 0.01 and 0.1.

Table 5.9 shows a part of log of total time elapsed vis-à-vis progressive improvement in objective function (Goal Results). The complete log is represented in figure 5.2 which demonstrates that the marginal improvement is diminishing as the time progresses. To trade-off between the quality of result and time elapsed, a termination condition is being imposed to end the optimization. It will stop when best individual value doesn't improve over 20000 generations.

Such termination may not provide the global optimum and the solution can be improved further. However, the optimization results obtained here are within the confidence bound of 95 percent which provides an outlook for the quality of the learned local optimum against the global optimum.

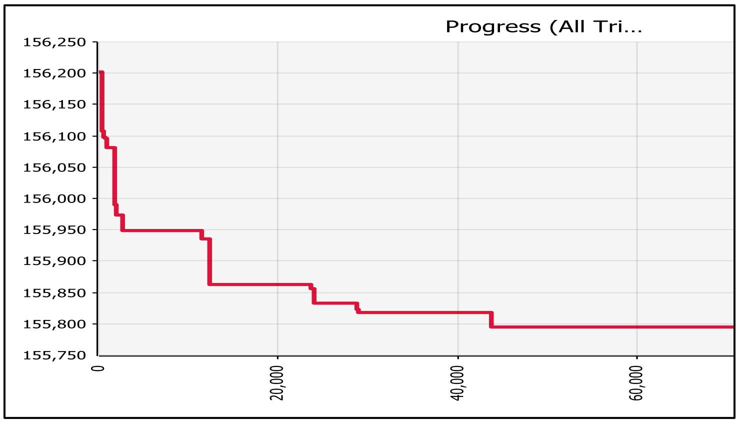


Figure 5.2 Optimization progress log

Table 5.9 Representative log of progress trial

Trial no.	Iterations	Goal Result (Mean)	Elapsed Time (Minute)
1483	100	156211	24.63
1694	100	156092	62.58
18052	100	155861	101.56
23568	100	155837	162.2
43586	100	155798	169.45

The final result is collated in the form of “Integrated Operations Schedule”, a representative part of which is displayed in table 5.10.

A close look at the table shows that it integrates multiple decisions in the form of a unified operations plan. For example, for the month of January, production sequence should be in the order of product 1, product 3, product 4 and finally product 2. The corresponding manufacturing quantities should be 191, 272, 202 and 287 respectively.

It also demonstrates the splitting of raw material order amongst the supplier and the date on which the order should be placed so as to have it available when the production is due. For example, for raw material 1, it proposes to get it split amongst supplier 1 and supplier 3 with respective order quantity as 180 and 50. Also the raw material order to supplier1 should be placed ten days before the start of the month, and four days before the start of the month for supplier 3 and likewise for other suppliers. In addition, the optimal quantity of safety stock is also mentioned to accommodate the variability related to transportation lead time, process rejections etc.

Another, critical information that the plan provides, is related to maintenance of individual component of the machine. Under the "component maintenance decision" number "1" signifies that PM should be executed for that particular component before the start of particular production run. For example, before production run1, PM should only be performed on component C1, C2 and C3. For production run 2, component C4 should have PM. Likewise, optimal incidences for PM activities is illustrated for the entire planning duration.

5.5 Validation

For validating the proposed approach, the model was simulated for number of intuitive scenarios. These scenarios were generated by altering the process and equipment related parameters. The results obtained were in line with the expected outcomes. For example, when the simulation was performed considering higher age of machine, the results indicated increased frequency of PM. Likewise, when model was simulated for perfect maintenance procedure, less incidences of machine breakdown was observed. Likewise, various other scenarios were also tested and all the observations were found to be aligned with expected outcomes. This validates the correctness of the proposed model.

Table 5.10 Integrated operations plan

INTEGRATED OPERATIONS PLANNING SCHEDULES

JANUARY

Monthly supplier decisions					Optimized Initial Safety Stock		Production 1				Production 2				Production 3				Production 4			
S	Quantity ordered						Maitenance		Prod. Schedule decision	Lot Size Decision	Maitenance		Prod. Schedule decision	Lot Size Decision	Maitenance		Prod. Schedule decision	Lot Size Decision	Maitenance		Prod. Schedule decision	Lot Size Decision
	P1	P2	P3	P4			compo	PM (1=yes, 0=no)			compo	PM (1=yes, 0=no)			compo	PM (1=yes, 0=no)			compo	PM (1=yes, 0=no)		
							C1	1			C1	1			C1	1			C1	1		
S1	180	0			P1	0	C2	1			C2	1			C2	1			C2	1		
S2		250		183	P2	190	C3	1			C3	1			C3	1			C3	1		
S3	50	70	170		P3	86	C4	1			C4	1			C4	1			C4	1		
S4			160	70	P4	57	C5	1	1	191	C5	1	3	232	C5	1	4	202	C5	1	2	287

FEBRUARY

Monthly supplier decisions					Optimized Initial Safety Stock		Production 1				Production 2				Production 3				Production 4			
S	Quantity ordered						Maitenance		Prod. Schedule decision	Production Lot Size Decision	Maitenance		Prod. Schedule decision	Production Lot Size Decision	Maitenance		Prod. Schedule decision	Production Lot Size Decision	Maitenance		Prod. Schedule decision	Production Lot Size Decision
	P1	P2	P3	P4			compo	PM (1=yes, 0=no)			compo	PM (1=yes, 0=no)			compo	PM (1=yes, 0=no)			compo	PM (1=yes, 0=no)		
							C1	1			C1	1			C1	1			C1	1		
S1	212				P1	96	C2	1			C2	1			C2	1			C2	1		
S2		224		227	P2	228	C3	1			C3	1			C3	1			C3	1		
S3	108		237		P3	0	C4	1			C4	1			C4	1			C4	1		
S4					P4	114	C5	1	3	198	C5	1	1	283	C5	1	2	293	C5	1	4	192

MARCH

Monthly supplier decisions					Optimized Initial Safety Stock		Production 1				Production 2				Production 3				Production 4			
S	Quantity ordered						Maitenance		Prod. Schedule decision	Production Lot Size Decision	Maitenance		Prod. Schedule decision	Production Lot Size Decision	Maitenance		Prod. Schedule decision	Production Lot Size Decision	Maitenance		Prod. Schedule decision	Production Lot Size Decision
	P1	P2	P3	P4			compo	PM (1=yes, 0=no)			compo	PM (1=yes, 0=no)			compo	PM (1=yes, 0=no)			compo	PM (1=yes, 0=no)		
							C1	1			C1	1			C1	1			C1	1		
S1	300				P1	128	C2	1			C2	1			C2	1			C2	1		
S2		196		302	P2	152	C3	1			C3	1			C3	1			C3	1		
S3			201		P3	43	C4	1			C4	1			C4	1			C4	1		
S4					P4	114	C5	1	1	187	C5	1	2	277	C5	1	3	273	C5	1	4	174

5.6 Comparative evaluation

The proposed approach is evaluated for multiple scenarios which covers a wide range of industrial systems in practice. These scenarios are generated by varying parameters related to demand, lead time, preventive maintenance and safety stock.

Firstly, environments are generated by considering the extent of variability related to lead time and customer's demand. For both these parameters, three levels of variability were considered namely high, medium and low.

In context of lead time, high variability refers to an environment where maximum deviation of lead time from its mean can be as high as fifty percent, whereas this deviation is considered as thirty percent and ten percent respectively for "medium" and "low" variability scenarios. Similarly, in context of demand, high variability refers to an environment where maximum deviation of actual demand from forecasted demand can be as high as 70 per cent. For medium and low variability demand this deviation is considered as 40 and 10 per cent respectively.

This resulted into nine possible environments as shown in figure 5.3. For instance, environment 1 refers to a scenario where there is high variability (H) in lead time and low variability (L) in demand.

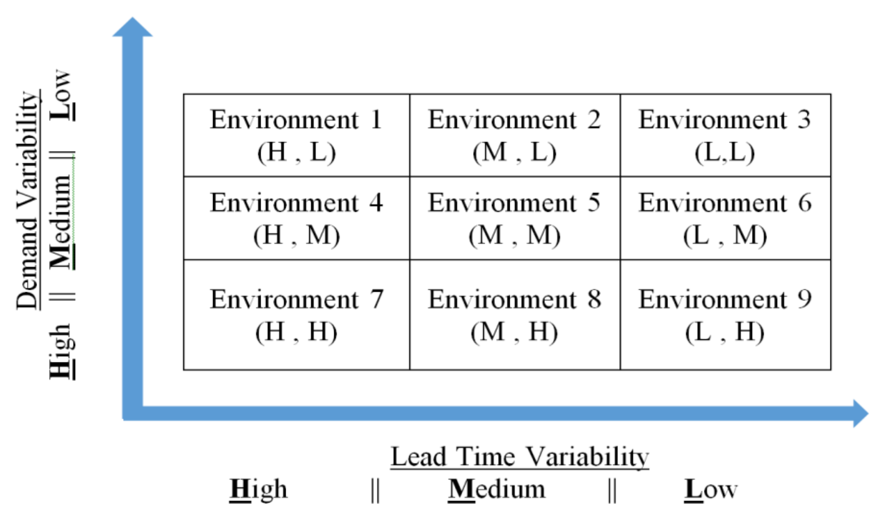


Figure 5.3 Manufacturing environment

Secondly, for each of these nine environments, six different decision alternative related to preventive maintenance frequency and safety stock were also considered.

Specific to preventive maintenance frequency, three alternatives were considered as described below:

1. In first alternative, no preventive maintenance was performed at all. Only corrective maintenance was performed i.e. components are only repaired on their failure
2. In second alternative, in addition to corrective maintenance, preventive maintenance is performed at the start of each month
3. In third alternative, in addition to corrective maintenance, preventive maintenance is performed at the start of each production run.

Similarly, two alternatives were considered related to safety stock viz. “No safety stock” and “Safety stock to accommodate maximum lead time variability”.

Thus, in total 54 (9 times 6) possible scenarios were evaluated initially. Each of these conventional scenarios considered “Earliest Delivery Date” as priority rule for production scheduling. Total Cost of Operation (TCO) for all such scenarios was evaluated and compared against the TCO value obtained using integrated approach. The evaluation for a specific environment, where the demand variability is high, is represented in table 5.11.

Table 5.11 Comparative evaluation

Demand variability: **HIGH**					
LEAD TIME VARIABILITY	Environment 7		No	With Safety Stock	Integrated
		No PM	240902	227107	167269
		PM at the start of each	206477	188343	
		PM at the start of each	211928	197928	
LEAD TIME VARIABILITY	Environment 8		No	With Safety Stock	Integrated
		No PM	217362	214070	169304
		PM at the start of each	202247	182893	
		PM at the start of each	188642	199280	
LEAD TIME VARIABILITY	Environment 9		No	With Safety Stock	Integrated
		No PM	209804	201907	163853
		PM at the start of each	191027	179680	
		PM at the start of each	184001	194298	

Close look at table value indicates that in environment 7, variability related to both demand and lead time is high. Thus, decision to have a safety stock provided lesser TCO as compared to decision of having no safety stock, as the risk of losing an order is reduced in earlier decision. However, this calls for extra material cost, which can be compared against same demand variability in environment 9, when lead time variability has gone down. Compared to all the environment mentioned in table, it can be seen that integrated approach provides better solution against all other traditional approaches. These results from table 5.11 are summarized in the form of a bar graph as shown in figure 5.4.

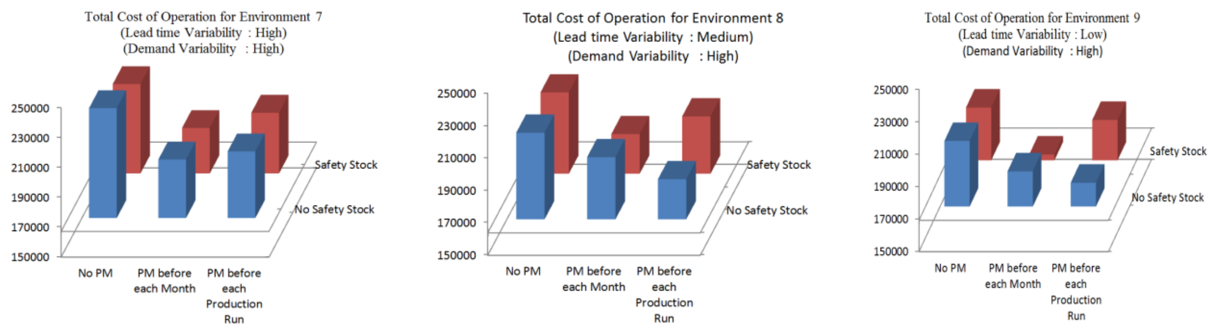


Figure 5.4 TCO for different environments

The cutting surface in the figures represents the total cost of operations using integrated approach. It is clearly visible that in all the environments, proposed approach provides minimal cost.

Further, the minimum of "total cost of operation" for three different environments (Environment 7, 8and 9; lead time variability: high/ medium / low), were individually compared with "TCO" for integrated approach and the percentage improvement are as shown in figure 5.5. It can be observed that though the proposed approach improvises the result; the improvements are more significant in the scenarios where the variability of lead time is high.

The evaluation was extended for the environment where the variations related to demand was also considered and similar results were obtained. It can thus be arrived that integrated approach becomes increasingly beneficial when variability in the system increases.

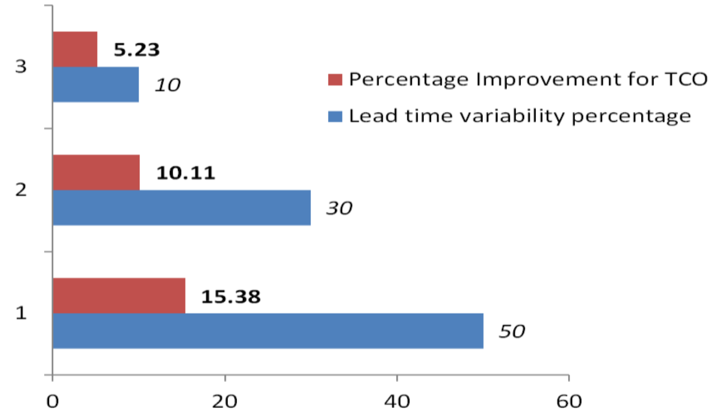


Figure 5.5 Percentage improvement in TCO using integrated approach

5.7 Summary

Current chapter is most likely the first attempt to integrate supply planning with maintenance and production planning. It demonstrates the impact which maintenance schedule can have on the material supply plan. Such a correlation was rarely explored in past but it acts as an additional input for conventional supply planning. Using an integrated approach, current work also leverages all other interdependencies and develops an integrated operations plan. It suggests a deviation from a traditional policy of fixed safety stock and proposes a dynamic value which depends on factors like machine yield, maintenance effectiveness, job schedule etc. Further, instead of considering a small planning horizon, current work develops an approach for a time which extends over three months and can be extended further. Such a flexibility of time frame for study, though complex to model, provides wider visibility and better control over industrial management and also assists practicing managers for efficient decision makin

CHAPTER 6*

PANORAMIC INTEGRATION OF THE MANUFACTURING VALUE CHAIN

Key Highlights

Purpose: Current chapter aims to leverage the integrated approach for the planning of an entire value chain. It utilizes the integrated model developed in earlier chapters viz production and maintenance (chapter 3), maintenance and quality (chapter 4), and production, maintenance and quality (chapter 5), to extend the concept of parametric integration at the value chain level. This holistic integration is then evaluated for its value under a broad range of manufacturing environment. Considering the large size of solution space, the application of agent based distribute planning approach as a solution approach is also demonstrated in this chapter.

Objective fulfilled: The current chapter simultaneously addresses all the four sub objectives mentioned in chapter 1. (SO1, SO2, SO3 and SO4)

Findings: It is observed that in a generic environment, an improvement of around 15% in the total operating cost can be realized using the integrated approach for the entire value chain planning. Further, in the environment characterized by high parametric variability, as the extent of the integration is increased from two function integration to four function integration, the improvisation in the objective function grew from around 2% to 18 %. It is also observed that under certain environment, integration of two function is better than integration of three function. This amelioration is significantly impacted by the choice of the functions considered for integration in a particular environment.

Originality and Contribution: In past, the application of integrated approach is confined to the integration of two to three function. Further, the approach is not demonstrated from the perspective of the enterprise level planning. Current work fills this gap by encompassing all the key functions of an organization and demonstrates the application of the integrated planning at a value chain level. Such a comprehensive extension of the integrated approach and the evaluation of its value was missing in literature and thus form

A part of the work presented in this chapter is accepted for publication under the title "Integrated Decision Support System for Manufacturing Value Chain". Purohit, B.S., Manjrekar, V., Singh V., and Lad,B.K. in the International Journal of Value Chain Management (IJVCM).

the contribution of the current chapter. Further, to contemplate the parametric integration, a joint performance indicator called "Overall Operations Rating" is also explicated in this work.

Practical Implication: Through the application of the integrated for the value chain planning, operations managers can get a panoramic perspective of the plan for each function. This at one end gives a wider visibility of the performance of individual function and at the other hand ensure that improvement in performance is not confined to specific function but is realized at the system level.

6.1 Introduction

The review of the literature presented in chapter 5 brings forth the fact that majority of the reported work related to integrated planning is confined to the integration of two functions only. The combination of function mainly considered for integration is either production and maintenance, or maintenance and quality or production and quality. In addition, the integration of supply planning with the function like maintenance is also absent. With such a confinement on the extent of integration, its applicability to optimize the planning at an enterprise level is curtailed. Also, as highlighted earlier, consideration of more functions for integration increases the decision variables and increases the solution space by manifolds. This further prolongs the time to arrive at the optimal solution and limits the adaptation of the integrated planning approach on the shop floor

Current chapter aims to bridge this gap by leveraging the detailed models developed in earlier chapters and utilize them to optimize the key decisions of an entire value chain. This holistic integration is evaluated in terms of the improvement in the system's performance. To gain an insight on the practices related to performance measurement of the value chain, the relevant literature was reviewed. The same is represented underneath.

Gunasekaran et al. (2004) in their work highlights that though performance measurement has an important role to play in setting objectives, the same pertaining to value chain planning have not received adequate attention from researchers or practitioners. In the similar context, Craig and Günter (2010) highlighted a range of limitations of existing performance index for manufacturing, including: short termism, lack of strategic focus and more importantly it encourages local optimization by forcing algorithms to lean towards specific parameter. It also states that the performance index should remain aligned with dynamic environments and changing strategies. Beamon (1999) in his work also stated that since the value chain as a whole is large and complex system, selecting appropriate performance measures is particularly critical. It further concludes that current value chain performance measurement systems are inadequate because they rely heavily on the use of cost as a primary measure, they are not inclusive. The same observation is aligned with the literature cited in earlier chapter as in majority of those literature the objective function was operating cost. However, when the value chain perspective is impinged, factors extending beyond the shop floor operating cost becomes significant, as the optimal performance of the individual functions also needs to be indexed. Thus, despite of the cost incurred, performance of all the functions needs to closely and carefully managed for the efficient management of the individual functions, and thus, a joint index is required which not only optimizes the overall value chain performance, but also provide an outlook of the performance of the individual functions to ensure the optimal tradeoff.

Also, other than cost, the majorly used indicators used to evaluate the performance of different interrelated functions are specific and relevant to function. For example, in the context of production scheduling, total tardiness and average number of late job becomes an indicator for measuring the performance. These indicators, when used as an objective function, tends to optimize the integrated schedule from the perspective of production only. (Cassady ad Kutanoglu, 2003).

It is thus required that the integration performed at the parametric level should be complemented by the similar integration of the performance indicators of different interrelated functions as well. In the absence of an “Integrated” or joint indicator, the optimization algorithm tends to optimize indicators specific to a particular function thereby losing the effectiveness of parametric integration performed at value chain level (Löfsten, H. 2000). Beamon (1999) also determined few characteristics which should be a part of an effective performance measurement systems. These characteristics must have: a) Inclusiveness (measurement of all pertinent aspects), b) Universality (allow for comparison under various operating conditions), c) Measurability (data required are measurable), and d) consistency (measures consistent with organization goals).

In addition to gaps related to integrated planning which are highlighted earlier, (Simplistic environment, consideration of specific environment, generalization, practical application, comprehensive evaluation etc.) current work also aims to address gap of a composite index as it is arguably better comprehendible by the practicing managers. For the same, the explication of a composite performance index called "Overall Operations Rating (OOR)" is reported in this work.

Subsequently, the agent based approach introduced in chapter 4 for solving the integrated maintenance and quality problem, is extended and applied for the integration of an entire value chain.

6.2 Description of representative manufacturing environment

To exhibit the value chain integration, this chapter considers the same manufacturing environment which is considered in chapter 2. The environment is of a real shop-floor and exhibits all the characteristics complexities of a shop floor. While chapter two focused mainly on the production function, current chapter encompasses other functions such maintenance, quality and material supply planning. The description regarding the current execution policy of various other functions is as under.

In context of maintenance, the firm performs the preventive maintenance activity at fixed intervals, which is after every thirtieth production run. Also, machine's operating parameters and failure and repair characteristics are overlooked while finalizing this frequency. The parts processed on machine are inspected at fixed interval for all of their multiple characteristics which are Critical to Quality (CTQ). The sample size for all these inspections is one. Based on the inspection result, further actions are taken by line supervisor's discretion. Though the firm has been following this fixed interval inspection policy, it has resulted into escape of defective product owing to the stochastic characteristic associated with sampling inspection. To overcome such incidences, 100 % inspection is one of the options but since each inspection consumes cost and is considered as non value-added activity, a carefully selected inspection plan is required which optimizes the inspection frequency of individual CTQs.

Further, the material supply schedule also needs to be aligned likewise. In order to mitigate risk related to continuity of material supply, firm follows multi-sourcing policy. As per this policy, it is preferred to have more than one supplier for raw materials. The split of quantity of raw material amongst individual suppliers is influenced by factors like cost, availability, lead time etc. This split significantly impacts the cost and thus optimizing this distribution is also critical. In addition, the time when the order should be placed is also very critical. It will be economical if the material is made available only when required and in the required quantity. Scenarios in which material is waiting either because the machine is undergoing maintenance or the machine is processing another material; will lead to the rise in overall cost. On the other hand, late ordering may lead to unavailability of material at the time of production. In the current state, material planning is unorganized and the material is ordered in ad hoc manner.

Deliberating the similarity in terms of operations planning, process management etc., one of the several machines is considered for the detailed analysis. This machine is referred as "WS- SAMP". It processes five components which is the maximum number of components processed by any machines on the shop floor. This makes "WS- SAMP" as the busiest machine on the floor and also the one whose management significantly impacts the delivery of the end product. As per these process flow charts, the predecessor processes of these five individual components can be performed on multiple machines, which eventually act as a "Supplier" to WS-SAMP. Each of these supplier machines has its own cycle time, setup-time and operating cost. It thus becomes the role of production planner to decide that from which machine how much quantity of material will be fed to WS –SAMP. Likewise, the parts coming out of WS-SAMP needs to be forwarded to yet another set of machines for successive operations. These set of machines thus becomes "Customer" to WS-SAMP. In addition, the machine under consideration has its own maintenance and product inspection schedule.

The above-mentioned environment is contemporaneous to a small value chain with "Supplier Machines" at one end, "Customer Machines" at another end and the producer in between for which the production, maintenance and quality plan is to be optimized. The same has been illustrated in figure 6.1 below. From the supplier end to customer end, this figure depicts multiple junctions along with multiple decision variables. Optimizing the entire value chains thus becomes critical to ensure the performance at the system level is enhanced.

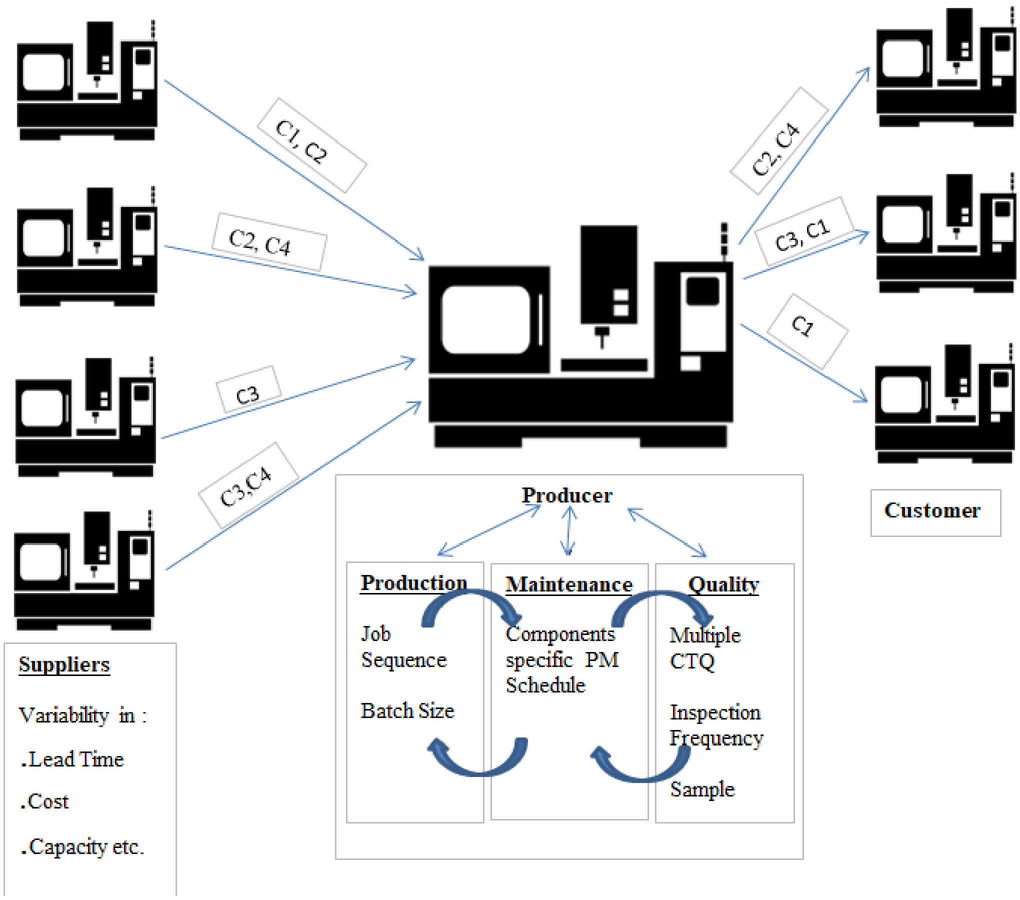


Figure 6.1 Illustration of value chain Setup

6.3 Problem description

Based on the preceding discussion the problem targeted in the current work is stated as follows:

"To investigate the value of joint decision making for a manufacturing industry and develop a decision support system for the same."

The focus is on operational level decisions along the entire value chain. In specific, following decisions are considered:

- Production Planning: Sequencing of Jobs, Batch Sizes
- Supply Planning: When to order the raw material, from which supplier to order, how much to order
- Maintenance Planning: Time for PM for a machine's individual component
- Quality Planning: Sample Size, Sampling Frequency

All these decisions directly impact the operating cost. It is thus required that the decisions related to each of these functions need to be optimally arrived at, considering the interdependencies among them.

Further, to complement the integration done at the parametric level by the similar integration of the performance indicators of the functions, a composite index called "Overall Operations Rating" (OOR) is developed. Later, the composite index is evaluated and respective improvisation of individual functions is analyzed to demonstrate the balanced performance of the all the functions of the value chain.

6.4 Model development

Further, based on the problem description, the decision variables can be summarized as below:

I. $Decision\ of\ Sequencing : \lambda_{pn}$,such that $\lambda_{pn} =$

$$\begin{cases} 1, & when\ p^{th}\ part\ is\ scheduled\ during\ n^{th}\ production\ run \\ 0, & otherwise \end{cases} \quad (6.1)$$

II. $Decision\ of\ Batch\ Sizing : \alpha_p$, such that

$$\alpha_p = The\ Batch\ size\ for\ p^{th}\ part \quad (6.2)$$

III. $Decision\ of\ Inspection: IF_{ncj}$, such that

$I_{Fncj} =$

$$\begin{cases} 0, & if\ j^{th}\ job\ is\ not\ inspected\ for\ \mathrm{c^{th}}\ characteristics\ during\ n^{th} production\ run \\ 1, & if\ j^{th}\ job\ is\ inspected for\ \mathrm{c^{th}}\ characteristics\ during\ n^{th} production\ run \end{cases}$$

(6.3)

IV. $Decision\ for\ preventive\ maintenance$: PMF_n , such that

$$PMF_n = \begin{cases} 0, & when\ maintenance\ \ is\ not\ performed\ \ after\ n^{th} production\ run \\ 1, & when\ maintenance\ is\ performed\ after\ n^{th} production\ run \end{cases}$$

(6.4)

V. $Decision\ for\ Quantity\ of\ ordering$: Q_{ps} , such that

Q_{ps} = Quantity ordered for pth product from sth supplier (6.5)

VI. $Decision\ for\ Schedule\ of\ ordering$: T_{ps} , such that

T_{ps} = Time when order for pth product is made to sth supplier

(6.6)

And objective is to minimize the Total Operating Cost (TCO) which can be mathematically written as:

Minimize: TCO

Total Operating Cost (TCO) in the current problem is the sum of following interdependent cost elements.

a) Maintenance Cost (Preventive and Corrective Maintenance)
b) Overtime Cost
c) Material Cost
d) Rejection Cost (Detected and Undetected)

These individual costs elements are interrelated and have significant impact on each other. Therefore, an improvisation upon total cost requires trade-off between cost impacting decisions of various functions. For example, higher the frequency of preventive maintenance, lower is the chances of quality rejection and hence the cost of rejection. Frequent preventive maintenance also reduces the likelihood of sudden breakdown thereby reducing the corrective maintenance cost. On the other hand, higher the time incurred in maintenance, higher may be the overtime cost owing to the compensation of production halt during preventive maintenance of machine. Further, to ensure the availability of the material for production, the order for the same is placed considering the lead time, variability in lead time, unit cost etc. However, if the machine is undergoing maintenance or is processing another component, the ordered material will have to wait irrespective of the fact that it might be ordered at a higher cost to get delivered early and being paid a higher price. However, if the material ordering schedule is adjusted to accommodate the machine downtime, such waiting of the material can be minimized and ordering cost can be economized. This establishes the dependencies between the schedule of maintenance, inspection and production.

These dynamics of trade-off between various function is inhibited in objective function. However, due to combinatorial nature, this relationship is not explicitly evident from the equation of objective function and thus individual cost models are separately elaborated below. Further few of the cost models for presented here are the same which are developed in earlier. However, they are reproduced here to maintain the continuity of the calculations.

6.4.1 Maintenance cost

Maintenance upkeeps the machine and improves their availability for production. Maintenance activities require various consumables, spares etc., the need of which depends upon the condition of the component. Consumables like oil grease etc. are required during every maintenance activity and thus incur a fixed cost. Further, in case of random breakdowns, the nature of fault and particulars of corrective actions required are not precisely known in advance. This makes it difficult to predict duration of corrective maintenance. To accommodate this, time for corrective maintenance is assumed to be normally distributed whose mean and standard deviation are captured from past maintenance record. Uniform distribution being the simplest way to represent two-sided bound, the same is considered to represent handle such uncertainties.

Considering this, cost of preventive maintenance (COPM) is evaluated as:

$$COPM = \sum_{n=1}^{n=n} [\{(T_{PM} \times MCL) + FC_{PM}\} \times PMF_n] \quad (6.7)$$

where T_{PM_w} is the time to execute preventive maintenance, FC_{pm} is fixed cost for preventive maintenance cost, MLC_m is the labor cost per hour and PMF_n is preventive maintenance factor for nth production run, such that

$$PMF_n = \begin{cases} 1 \quad if\ PM\ is\ executed \text{ before n}^{th} \text{ production run} \\ 0 \quad f\ PM\ is\ executed \text{ before n}^{th} \text{ production run} \end{cases} \tag{6.8}$$

Likewise, Corrective maintenance cost, C_{cm} is calculated as:

$$COCM = \sum_{n=1}^{n=n}(NF_n \times [\{T_{CM} \times MCL\} + FC_{CM}]) \tag{6.9}$$

where T_{CM} is time to perform corrective maintenance and FC_{CM} is fixed cost for corrective maintenance. NF_n is number of failures during n^{th} production run.

For minimal corrective repair, the number of failures during a time "t" can be calculated as cited by Lad and Kulkarni (2012), where F is failure rate.

$$Nf(t) = \int_0^t F(t)dt \tag{6.10}$$

Since Weibull failure distribution can be used to model increasing, decreasing as well as constant failure rate, the same is used to characterize failure characteristics of Machines under consideration.

Further, if η and β be the scale and shape parameters, the conditional number of failures during n^{th} production run can be calculated as:

$$Nf_n = \left[\frac{\{(\mathrm{CT}\times\alpha_{\mathrm{n}}) + t_n)\}^{\beta}}{\eta}\right] - \left[\frac{t_n}{\eta}\right]^{\beta} \tag{6.11}$$

Where CT is the cycle time, α is the batch size and t_n is the age of component before n^{th} production run such that:

$$t_n = [t_{(n-1)}] + [\{C\,T_n \times \alpha_{(n-1)}\} \times \{1 - (r \times \Phi_{(n-1)})\}] \tag{6.12}$$

where t_n is the machine's age before nth production run, CT_n is the cycle during n^{th} production run time and r is the restoration factor. Restoration factor (r) is used to model the degree of repair of any such PM action. It is a fraction which signifies how much life of the component can be restored after performing a maintenance activity.

6.4.2 Overtime cost

Overtime is work performed by a worker in excess of a basic workday. Such situation arises when the organization decides to extend their working hours in order to meet the business targets under dynamic environment. This incurs total overtime cost which is to be paid to workers and is calculated as:

$$TOTC = \begin{cases} 0 \quad , & (TTO - BWT) \leq 0 \\ (TTO - MRT) \times OT, & (TTO - BWT) > 0 \end{cases} \tag{6.13}$$

where OT is overtime cost per hour, BWT is the basic work time and MRT is the actual machine run time. Total time of operation, TTO, is summation of total time for CM time, total time for PM time, total manufacturing time and total set-up time

6.4.3 Material cost

Material cost is the cost of raw material required for production. In general, there are multiple suppliers which provide the raw material. Because of variation in production economy of individual suppliers, the unit price at which the raw material is supplied may vary from supplier to supplier. The total material cost thus depends on the fact that which suppliers are selected and how much quantity is ordered from selected supplier. It can thus be calculated as:

$$M = \sum_{s=1}^{s=s} c_{rm_s} \times SSF_s \times Q_s \tag{6.14}$$

Where, “s” is number of suppliers, c_{rm_s} is Unit Price of raw material from s^{th} supplier and Q_s and SSF_s are Quantity ordered and Supplier Selection Factor for S^{th} supplier.

6.4.4 Rejection cost

The model considers both detected as well as undetected rejection for cost calculation. The detected rejections are those parts which do not meet the quality requirement and are detected during the inspection process. However, due stochastic nature of inspection sampling, it is possible that sometimes the poor quality parts remains undetected and are delivered to customers. Such undetected rejections cost is identified by the customers and negatively impacts the producer's performance rating. These costs are calculated as:

$$Detected\ Rejection\ Cost = \left(\sum_{n=1}^{n=n} \sum_{j=1}^{j=j} (D_{np} \times CDR\right) , \quad (6.15)$$

whereD_{np} are the detected rejections for n^th^ part in p^th^ production run and CDR is unit "Detected Rejection" Cost.

Likewise,

$$Undetected\ Rejection\ Cost = \left(\sum_{n=1}^{n=n} \sum_{j=1}^{j=j} (U_{np} \times CUDR\right) , \quad (6.16)$$

Where U_{nj} is the undetected rejection for n^th^ part in p^th^ production run and $CUDR$ is unit "Un Detected Rejection" Cost.

$$U_{nj} = \begin{cases} 1 \ , & if\ SM_{pj} = 1\ and\ I_{nj} = 0 \\ 0 \ , & Otherwise \end{cases} \quad (6.17)$$

$$D_{nj} = \begin{cases} 1 \ , & if\ SM_{pj} = 1\ and\ I_{nj} = 1 \\ 0 \ , & Otherwise \end{cases} \quad (6.18)$$

and

$$SM_{nj} = \begin{cases} 0, & USL \geq V_{jn} \geq LSL \\ 1, & USL < V_{pn}\ or\ V_{pn} < LSL \end{cases} \qquad \text{for all n } \epsilon \text{ N} \quad (6.19)$$

SM_{jn} is the check for specification met and USL and LSL are upper specification limit and lower specification limit of c^th^ characteristics of n^th^ part and V_{jn}, is measured value of n^th^ part in j^th^.run

The defective parts received by the customers are actually rejections which remained undetected in-house during sampling inspection.

6.5 Results

Below mentioned data is extracted from the shop floor for further analysis of the operating environment.

Table 6.1 represents a part of failure history of WS SAMP.

Table 6.1 Failure details of WS SAMP

Work	Asset	Description	Scheduled	Durat
AMI14	P005022	selector switch not working / new	5/6/2014	2
AMI15	P005022	cutter not rotating	5/22/2014	3.5
AMI15	P005022	m/c abnormal noise	5/27/2014	0.5
AMI19	P005022	Spindle direction not changing	7/30/2014	23.5

The machine being the central and pivotal element of this representative value chain, precise estimation of its parameters is critical for realistic modeling. For this, detailed analysis of above mentioned failure history was performed. The analysis brings out that failure characteristics of the machine best follows two parameter Weibull distribution and the time to repair for this machine best fits a Gamma distribution. These characteristics are summarized in table 6.2. Further, table 6.3 shows the list of components which gets processed through WS SAMP. It also highlights the suppliers and their corresponding characteristics like lead time, cost etc.

Table 6.2 Failure and repair characteristics of WS SAMP

Shape parameter β	Scale parameter η	TTR for corrective			TTR for preventive maintenance (Hours)	Maintenance labor cost (Per hour)
		Mu	Sigma	Lambda		
1.04	17.5	-.117	+.808	-1.98	0.5	200

Table 6.3 List of components and supplier machines

Component Processed on WS SAMP	Supplier Machines	Lead Time including		Operating Cost per Unit	Average Yield
		Mean	Standard Deviation		
CGS (C1)	Gleason New	380	131.6	1700	0.998
TGS (C2)	Cooper (M2)	605	275.19	680	0.984
	Gleason 777 (M3)	620	237.39	1250	0.991
	Gleason RG (M4)	430	180.1	900	0.989
G3M (C3)	Gleason 125 (M5)	930	413.973	1250	0.988
	Gleason RG (M4)	860	372.903	900	0.989
	Cooper (M2)	720	318.73	680	0.984
G5M (C4)	Gleason 777 (M3)	1470	731.913	1250	0.991
	Cooper (M2)	1340	665.616	680	0.984
	Pfauter (M6)	830	753.51	560	0.978

Simulation based optimization was applied to above mentioned data set to arrive at near optimal decisions in the form of an Integrated Operations Plan. To trade-off between the quality of result and simulation time elapsed, a termination condition is being imposed to end the optimization. It will stop when either of the below mentioned conditions is fulfilled:

3. Best individual value does not improve over 200 generations
4. Total improvement of the last 10 best solutions is less than 0.1 percent

Such termination may not provide the global optimum, and the solution can be improved further. However, the optimization results obtained here are within the confidence bound of 95 percent which provides an outlook for the quality of the learned local optimum against the global optimum.

The corresponding decision variables related to production, maintenance, quality and supply planning are collated in the form of "Integrated Operations Schedule" as displayed in table 6.4.

A close look communicates that for the first production run, G3M should be produced and its production quantity should be 3008. The raw material for G3M should be supplied by Cooper and the order quantity should be 3011. Further, the order should be placed before 1197 hours of the start of production. Since the start of production is considered as "0" hour, negative sign before the trigger date implies that the order should be placed 1197 hours before the production is started so as to make it available for production, considering the lead time and its variations. In addition, in first production setup, maintenance activity should be performed before the start of the production and for first produced job, only CTQ 1 needs to be inspected.

Considering the data control policy of the organization, only percentage improvement in the objective function and associated cost is captivated in the figure 6.2 below. The figure further captures the percentage contribution of individual cost element in the objective function in existing as well as proposed approach.

Table 6.4 Operations schedule

Supplier	CGS		TGS		G3M		G5M		GLM	
	Order	**Trigger**	Order	Trigger	Order	Trigger	Order	Trigger	Order	Trigger
Gleason	3008	1810	NA	NA	NA	NA	NA	NA	NA	NA
Cooper			0	----	3011	(-)1197	0	---	1	1
Gleason			NA	NA	0	--	NA	NA	0	---
Pfauter			NA	NA	NA	NA	0	---	1	---

1st Production Setup					2nd Production Set up				
Job no.	**Part**	G3M	**Batch**	3008	Job no.	Part	GLM	Batch	3011
	Maintenance (1= Yes ,	**Inspection**				CLRI (1= Yes	Inspection		
		CTQ 1	CTQ 2	CTQ 3			CTQ 4	CTQ 5	CTQ 6
1	1	1	0	0	1	0	1	1	
2	0	0	1	0	2	0	0	0	0
3	0	0	0	0	3	0	0	0	0
4	0	0	0	0	4	0	0	0	0
5	0	0	0	0	5	0	0	0	0

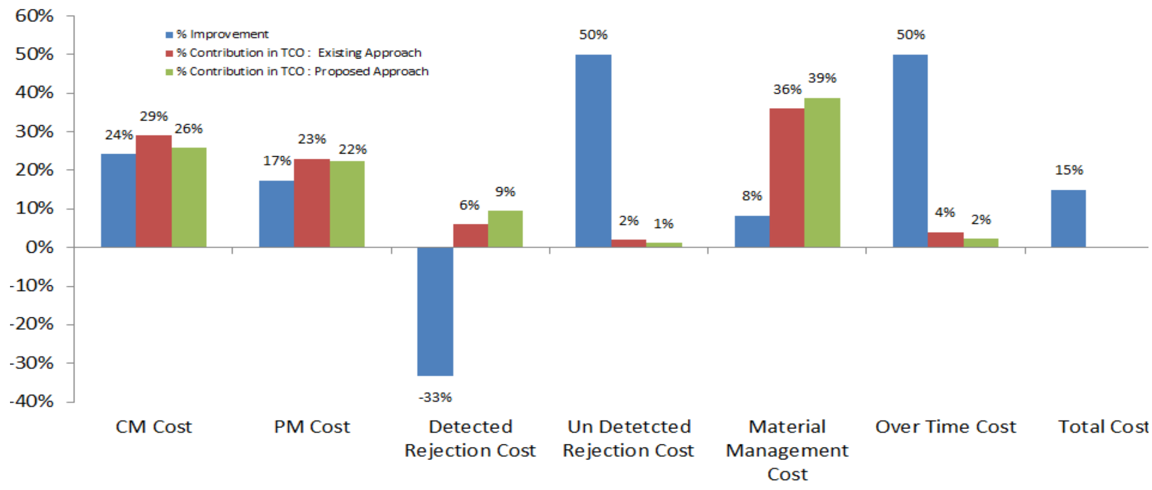


Figure 6.2 Percentage improvement using integrated approach

It can be observed that there is around fifteen percentage improvement in objective function (TCO) using proposed approach against the existing approach. It is also observed that amongst all the cost elements, only detected rejection cost has increased in the proposed approach. This is attributed to the more appropriate opportunities identified for the inspection engendering a significant reduction in the undetected rejections.

6.6 Development of "Overall Operations Rating"

Inferring figure 6.2, it is observed that though the overall cost has reduced using the proposed approach, individual cost element such as detected rejection cost has increase significantly. From the business continuity and development perspective it is required for individual cost elements also to perform at minimum predefined levels. Further, few of the operational aspects are tangible and cannot be directly translated into cost. For instance, if the orders are not processed on time and miss the committed delivery schedule, there is no direct cost which can be factored into TCO. However, it may impact in terms of losing the future orders and loss in organizations goodwill.

It is thus required to align the objective function to encompass the key metrics of the organization viz. quality, cost and delivery While there can be multiple parameters which can be leveraged to assess the performance of an operating system., in the context of the current dissertation, the empahsis is given on three widely used parameters viz. Quality, Cost and Delivery.

As a prelude, these factors are adequeate to provide an overview of the system performance. However, more insights can be gained when parameters like safety rating, financical ratios etc are also incorprated. However, in the light of maintenance, production, supply planning and quality, only QCD parameters are scoped.

From the management perspective, all the three metrics are equally important and needs to be weighted equally. Considering the same, an objective function called "Overall Operations Rating: R_o " is defined as which is product of quality rating, cost rating and delivery rating. The individual ratings are defined as in equations below.

And objective of maximizing operations rating can be mathematically written as:

Maximize: Overall Operations Rating- "OOR",

Such that,

$$OOR\ (R_o) = R_Q \times R_C \times R_D \tag{6.20}$$

6.6.1 R_Q: Quality rating

Quality rating takes into the quality loss i.e. the parts which donot meet quality requirements. It is the ratio of good parts produced versus the total number of part produced. Number of good parts can be calculated by reducing the detected and undetected rejections from the total quantity produced.

The same can be mathematically written as:

$$R_Q = \left[1 - \frac{\left(\sum_{n=1}^{n=n} \sum_{j=1}^{j=j} (D_{nj})\right) + \sum_{n=1}^{n=n} \sum_{j=1}^{j=j} (U_{nj})}{\left(\sum_{p=1}^{p=p} \alpha_p\right)}\right] x\ 100\ , \tag{6.21}$$

6.6.2 R_C: Cost rating

From financial perspective, any organization is evaluated on the basis of current ratio, debt asset ratio etc. But from a view point of production economy, cost performance is measured in terms of variance from last year's total cost of operation. It can be noted that if the significant cost cutting measure are taken, cost rating can be higher than one and is recorded as:

$$R_C = \frac{TCO\ \ per\ unit\ for\ previous\ year}{TCO\ per\ unit\ for\ current\ year} \tag{6.22}$$

6.6.3 $\boldsymbol{R_D}$: Delivery rating

"Delivery" performance is measured in terms of "On Time in Full-OTIF". OTIF is a performance measurement which indicates how many deliveries are supplied on time without any article missing. It is calculated as:

$$\boldsymbol{R_D} = \left[\frac{Number\ of\ Customer\ Orders\ Delivered\ On\ Time\ and\ in\ Full}{The\ Total\ Number\ of\ Customer\ Orders}\right] x\ 100\ \% \tag{6.23}$$

Or mathematically,

If Õ be the total number of orders, and for O^th^ order, CD_O be committed delivery date, AD_O is the actual delivery date, CQ_O be the committed order quantity and AQ_O be the actual order quantity in O^{th} then ,

$$\boldsymbol{R_D} = \frac{\sum_{o=1}^{o=\tilde{O}} \mathrm{OTIF}_{\tilde{O}}}{\tilde{O}} \tag{6.24}$$

Such that,

$$\mathrm{OTIF}_{\tilde{O}} = \begin{cases} 1 & , \quad \mathrm{CD_o} \leq \mathrm{AD_o}\ and\ \mathrm{CQ_o} \geq \mathrm{AQ_o} \\ 0 & , \quad otherwise \end{cases} \tag{6.25}$$

The improvement in individual rating using the proposed was also evaluated and the results are as shown on figure 6.3 below. It can be noted that there is improvement in all the ratings using the proposed approach. Further, figure 6.3 provides holistic view and is aligned with the organizational key performance indicators. It can be observed that while there is an overall improvement in total cost, there is a simultaneous improvement in all the key metrices of the organization viz. delivery, cost and quality. This demonstrates that the parametric integration has not benefited a specific metric or function but simultaneously improved the performance across the value chain.

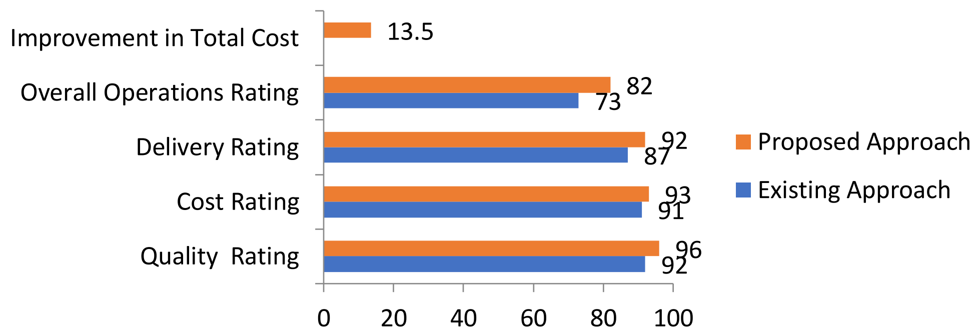


Figure 6.3 Improvisation in individual ratings

6.7 Comprehensive evaluation and generalization

The application of proposed approach in a specific environment has resulted into significant improvement in system's performance which has been demonstrated in section 6.6. However, despite of the comprehended gain from the integrated planning, there are no evidences either in literature and or in industries which exhibits comprehensive adaptation of this approach. Absence of such adaptation can be imputed to complicated modeling, complex algorithm and time lapse to arrive at optimal solution. To address this, the outcome of the proposed approach needs to be generalized so as to serve as references for practicing managers.

Subsequently, to analyze the significance of individual functions for integration, an evaluation was performed by varying the combination and extent of integration. The extent of integration refers to the number of function considered for integration. Initially, integration of two functions was considered and all the possible sets for integrating two functions were evaluated. The same are listed below:

- Production and Maintenance (P & M)
- Maintenance and Quality (M & Q)
- Production and Supply (P & S)
- Maintenance and Supply (M & S)
- Production and Quality (P & Q)
- Quality and Supply (Q & S)

While integrating any two functions, decision related to other functions were kept constant and were aligned with the conventional approaches, few of which are as mentioned in table 6.5.

Table 6.5 Conventional approaches for management of various functions

Function	**Production**	**Maintenance**	**Quality**	**Supply (Material Planning)**
Conventional Policies / Rules	• Shortest Processing Time (SPT) • Longest Processing Time (LPT) • Smallest Critical Ratio (SCR)	• Age based (Fixed Interval)	• Periodic Inspection (Fixed Interval)	• Single Source ○ One Time Order ○ Staggered Order • Multi-Source ○ One Time Order ○ Staggered Order

For all the sets of two functions, the proposed approach was evaluated against multiple scenarios. These scenarios were generated by varying the combination of conventional policies related to the involved functions. The improvisation realized in R_Q, R_C, R_D and R_O for these sets were mapped and are mentioned as in figure 6.4 (a to f).

To illustrates, consider the first case (P & M), in which it can be observed that the proposed approach significantly improves value of all the performance indicators for all the scenarios. However, the improvement in R_O is maximum when the approach was applied for an environment which uses Longest Processing Time (LPT) as the sequencing rule and where consecutive maintenance activities are distantly executed i.e. at an interval of 120 production runs.

An additional two-level analysis was also performed where at the first level, an analysis was performed by increasing the extent of integration and varying the functions involved in integration. Considering the stochastic nature of the manufacturing environment, at the second level, the approach was also evaluated for multiple scenarios which differ in the extent of variability in parameters like lead time, repair time and the machine age. Since the firm's focus is more towards overall operations rating, only percentage improvement in"Ro" is reported. Table 6.6 summarizes such observations and the same is illustrated using figure 6.5.

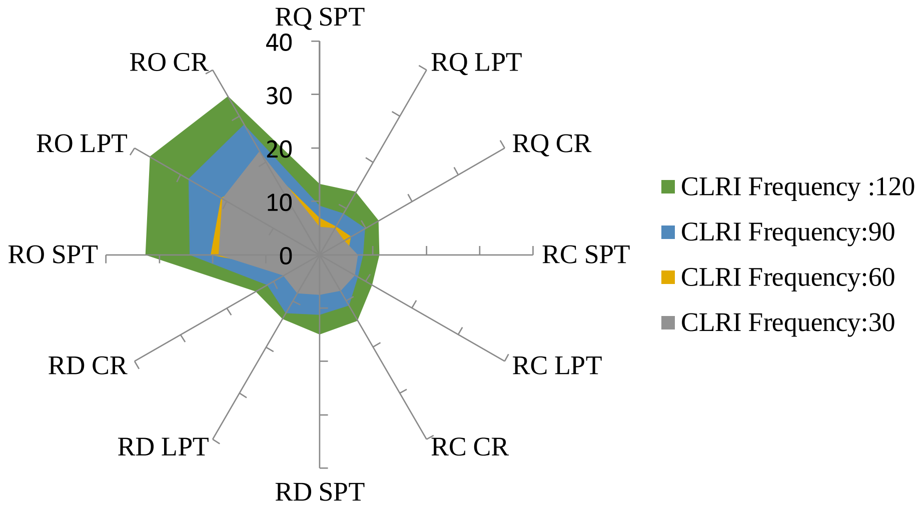


Figure 6.4 (a) Improvement in performance indicators by integrating P & M

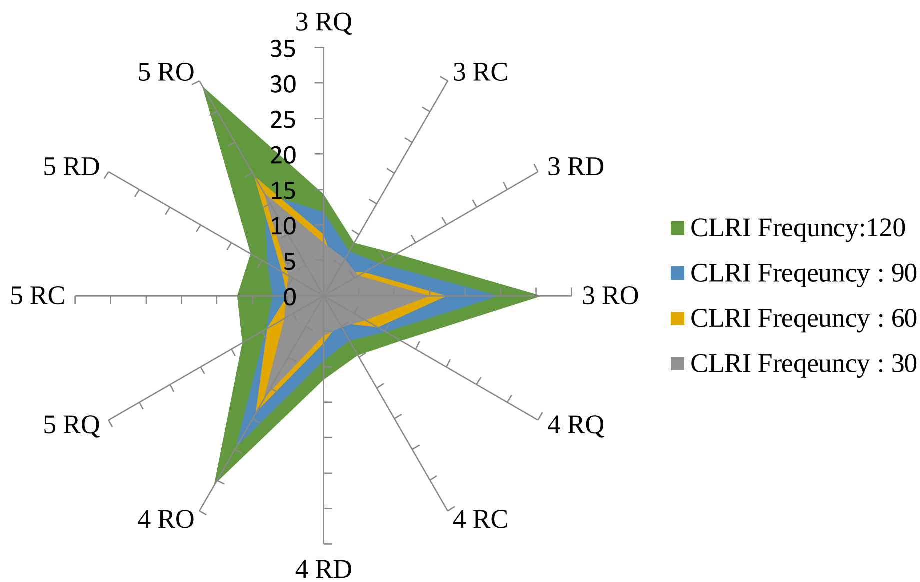


Figure 6.4 (b) Improvement in performance indicators by integrating M & Q

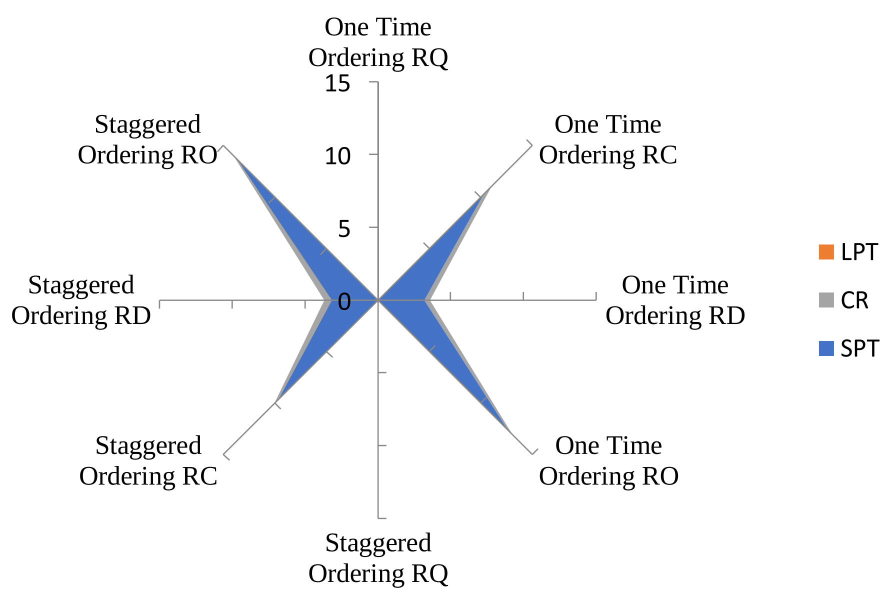


Figure 6.4 (c) Improvement in performance indicators by integrating P & S

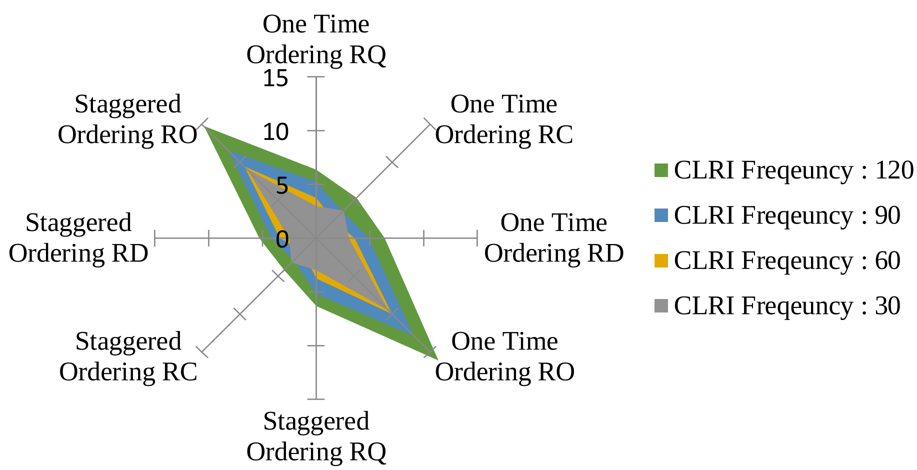


Figure 6.4 (d) Improvement in performance indicators by integrating M & S

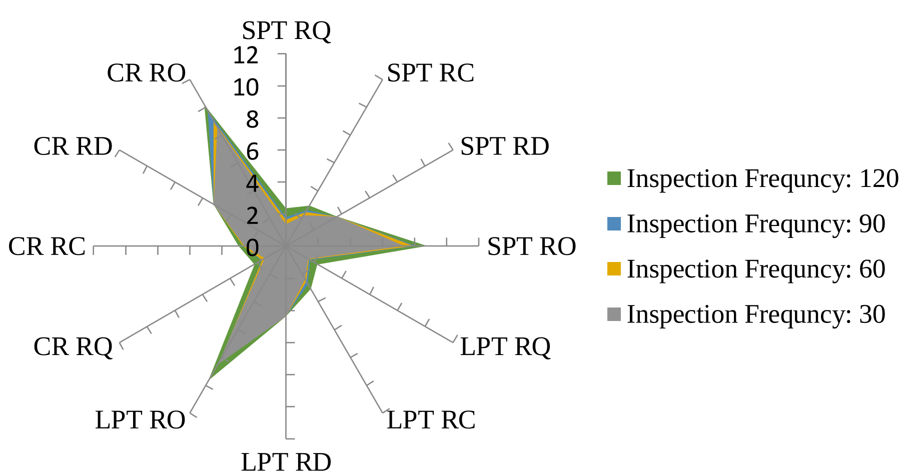


Figure 6.4 (e) Improvement in performance indicators by integrating P & Q

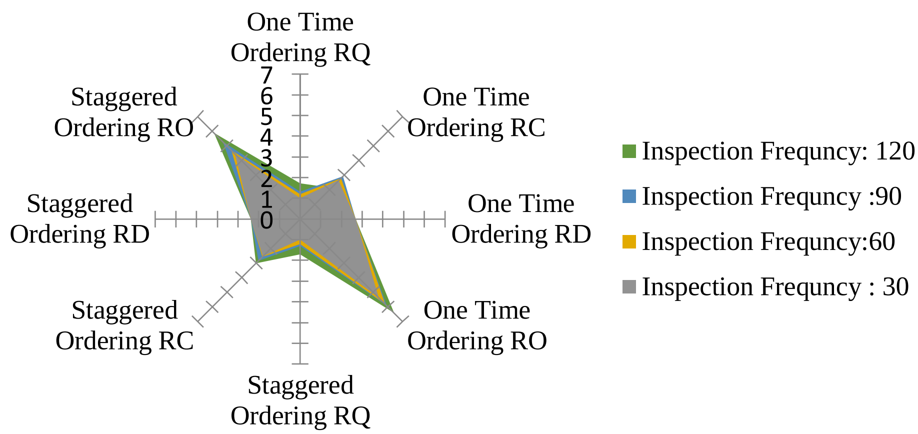


Figure 6.4 (f) Improvement in performance indicators Q & S

Table 6.6 Percentage improvement in Ro in various scenarios

Parameter	Variability	Integrating 2 Functions						Integrating 3 Functions				Integrati
		P+Q	P+M	P+S	M+	M+S	Q+S	P+M+	P+M+	M+Q+	P+S	P+M+Q
Lead Time	No	2.26	4.28	6.58	3.16	8.64	6.18	9.26	16.56	12.47	14.5	18.65
	+ / - 10	6.58	8.51	11.6	5.62	14.2	10.5	12.59	21.64	16.56	18.6	24.54
	+ / - 20	12.5	14.5	18.8	8.23	24.8	15.6	19.64	29.35	24.9	26.0	31.61
	+ / - 30	19.6	21.6	24.0	11.5	29.3	19.1	20.85	34.91	31.5	32.6	38.61
Machine Age	New	3.19	5.68	2.19	4.59	3.59	1.59	5.68	8.16	4.26	2.24	16.59
	Moderat	5.68	14.6	7.6	8.56	6.84	3.18	16.59	21.65	11.59	3.25	27.15
	Erstwhil	12.6	21.5	7.34	15.0	9.54	5.36	23.08	28.10	17.43	5.27	36.58
Time To Repair for Corrective Maintenance	No	2.01	6.04	1.59	3.59	6.15	0.59	9.39	12.56	7.58	2.19	14.58
	+ / - 10	4.79	9.14	3.25	6.31	11.3	2.52	13.18	15.61	9.26	4.01	19.35
	+ / - 20	9.54	15.6	4.51	7.16	19.1	3.14	22.89	26.56	14.68	4.59	31.81
	+ / - 30	13.6	18.9	6.15	7.98	23.6	4.29	27.5	31.56	19.58	5.34	36.18

A close look at figure 6.5(a) demonstrates that for an environment where the variability in repair time is high, integration of production and maintenance provided better results as compared to the integration of production, quality and supply planning. This highlights that the two functions integration can provide better results than three function integration depending on the combination of the functions considered for integration and the environment for which integration is performed. However, maximum improvement is realized when all the four functions are integrated. Similar observations can be derived from figure 6.5 (b) and 6.5 (c) which highlights that that for a given extent of integration, the selection of the functions to be integrated plays a significant role. Further, considering the increase in complexity and solution time with the increase in extent of integration, practicing manager may prefer to limit the integration up to two or three functions only. It is therefore required to identify the relative importance of individual function in a particular environment which is characterized by variability in a specific parameter.

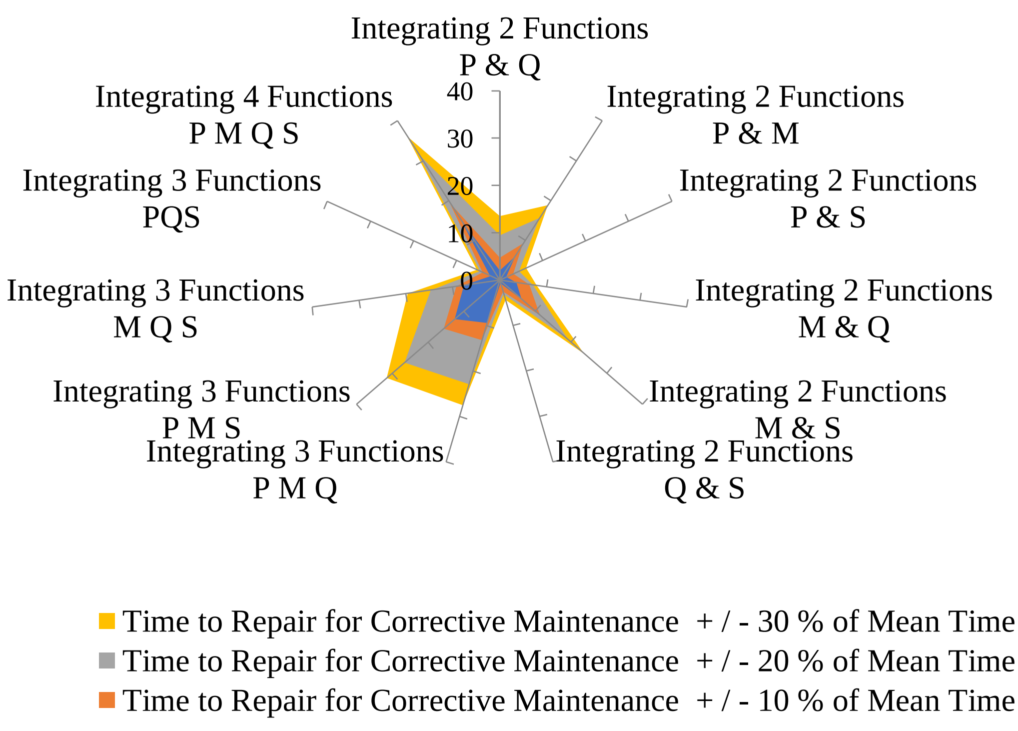


Figure 6.5 (a) Percentage improvement in Ro for an environment with variation in repair time

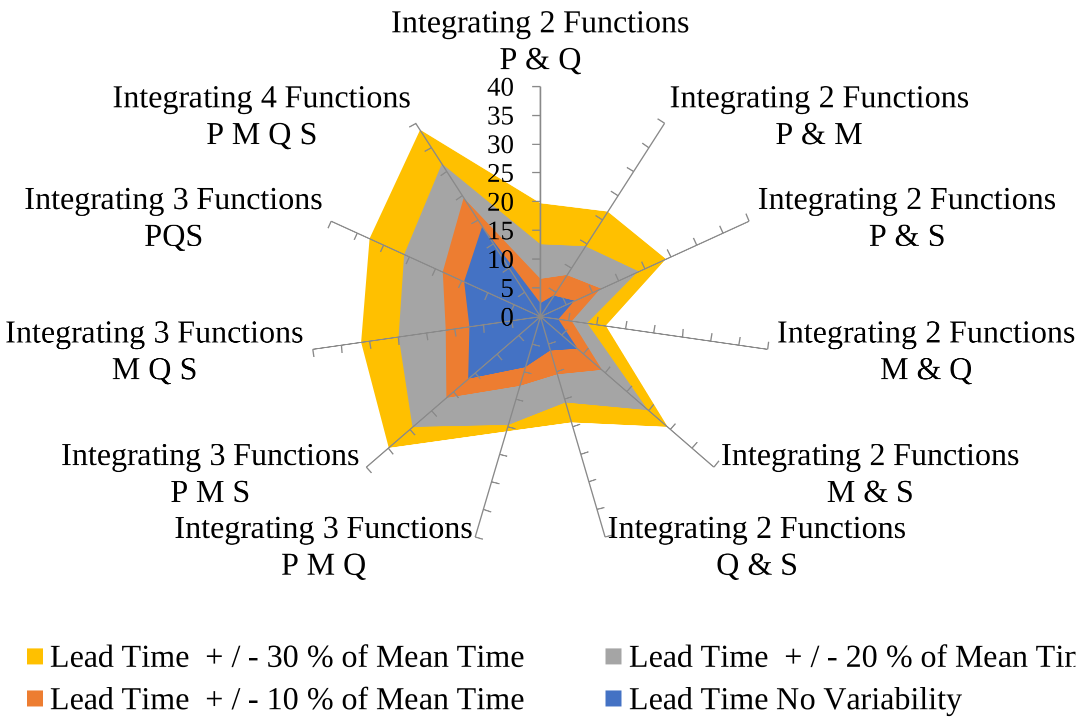


Figure 6.5 (b) Percentage improvement in *Ro* for an environment with variation in lead time

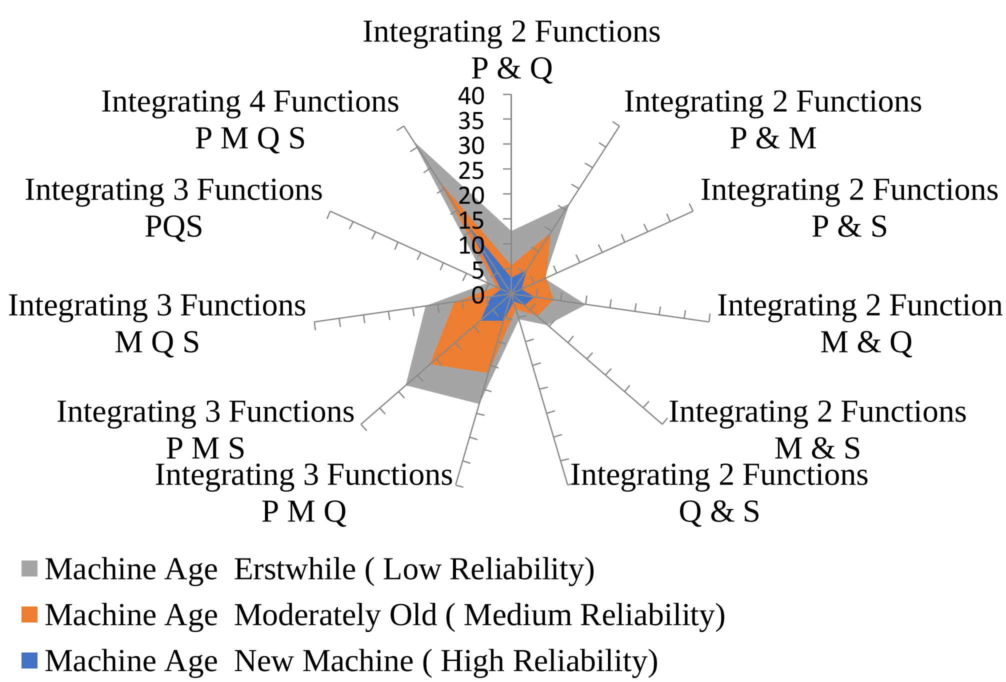


Figure 6.5 (c) Percentage improvement in *Ro* for an environment with variation in machine age

Based on the outcome of the comprehensive evaluation following corollaries are developed for primitive prioritization of functions for integration:

a) For a manufacturing environment where machines are special purpose or are erstwhile, variability in machine repair time is high as time consumed in fault diagnosis and repair time is uncertain. In such environment, for two function integration maintenance and supply planning should be considered. If the extent of integration is to be increased, production should be prioritized over quality function.

b) For industries using multi modal transportation for supply or who manufactures "Design to Order" engineering products, variability in supply lead time is high. In such environment, for two function integration supply planning and production should be considered. If the extent of integration is to be increased, maintenance function should be prioritized over quality function.

c) For an environment where variability in demand is high, for two function integration of production and supply planning should be considered. If the extent of integration is to be increased, maintenance should be prioritized over quality function. Such environment exists during the introduction phase of the new product or in food industry and apparel industries. (Rabbi et al. 2013)

6.8 Distributed approach as an alternative solution method

As mentioned in chapter 2, a simulation-based GA approach is first used to solve this problem. A termination condition is being imposed to end the optimization. It will stop when either of the below mentioned conditions is fulfilled:

1. Best individual value does not improve over 200 generations
2. Total improvement of the last 10 best solutions is less than 0.1 percent

The log of the simulation time elapsed is mentioned in the table 6.7 below. It could be seen that to arrive at the solution from where the best value did not improve significantly over time, it took close to 7 hours. This time is further expected to increase if the integration has to incorporate more functions and associated decision variables. However, with increasing level of automation and paradigm shift towards agile manufacturing environment, it is required to arrive at the solution as early as possible. Considering the same, an agent based distributed approach was proposed in section 4.6 of chapter 4. The development process and the algorithm for negotiation remains same as explained earlier. However, the supply planning agent and the production are added to apply distributed method to the entire value chain. Further for the distributed approach also, the number of solution considered for the negotiations are varied. It considers top 3, 5 and 10 solutions from each agent which undergoes the negotiations as per steps as per the steps demonstrated in the flow chart (Figure 4.6 of chapter 4). The results so obtained are compared with the other planning approaches and the solution methods.

Table 6.7 Log of successive trials

Trial No.	**Elapsed**	**Iterations**	**Result**
8735	53	100	560
11096	67	100	512
16520	90	100	473
32216	212	100	423
60053	380	100	385
71235	400	100	344

Table 6.8 Comparison of the various planning approaches and solution methods

<table>
<tr><th colspan="2">Planning Approach</th><th>Time</th><th>Objective</th><th>Percentage</th><th>Percentage</th></tr>
<tr><td colspan="2">Experience based Planning</td><td>900</td><td>704.231</td><td>NA</td><td>NA</td></tr>
<tr><td colspan="2">Integrated planning</td><td>400</td><td>344.64</td><td>51.062</td><td>55.611</td></tr>
<tr><td colspan="2">Independent planning</td><td>95</td><td>446.026</td><td>36.665</td><td>89.444</td></tr>
<tr><td rowspan="3">Integrated planning (Distributed)</td><td>Top 3</td><td>37</td><td>438.889</td><td>37.678</td><td>95.889</td></tr>
<tr><td>Top 5</td><td>232</td><td>381.724</td><td>45.796</td><td>74.278</td></tr>
<tr><td>Top 10</td><td>246</td><td>353.323</td><td>49.829</td><td>72.722</td></tr>
</table>

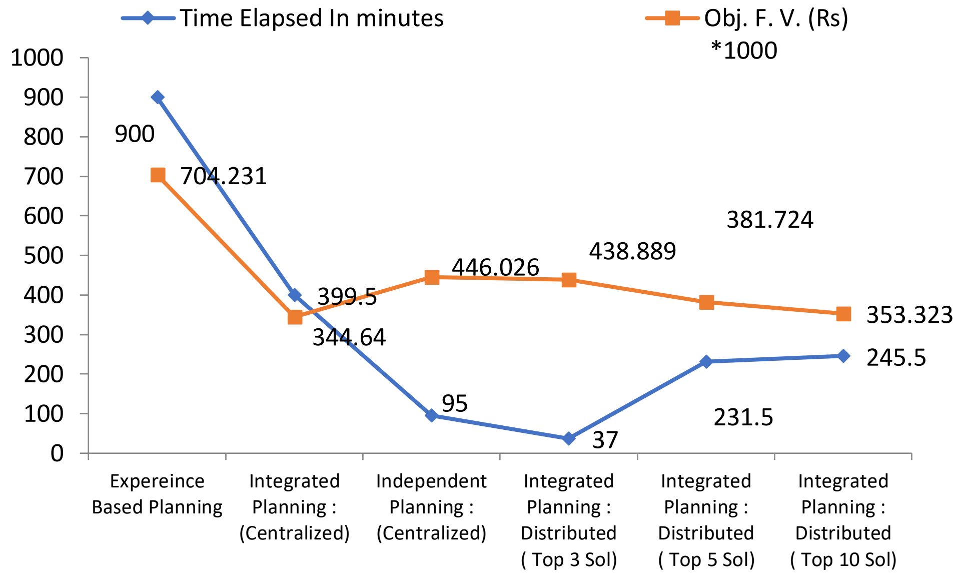


Figure 6.6 Time elapsed and value of objective function using various approaches

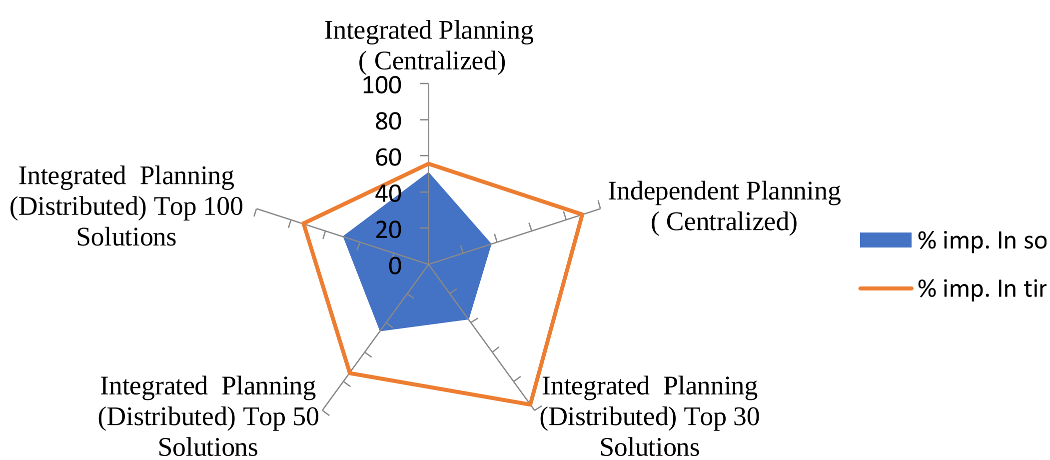


Figure 6.7 Percentage Improvement in objective function and time

It can be observed that the best value for objective function is observed when the in integrated approach is applied using centralized approach. However, the time taken to arrive at the optimized solution is way too high. Due to the dynamic business environment and the prolonged time consummated in optimization, the final optimized value may no longer be valid for implementation. On the other hand, the distribute approach provided the solution in least time as compared to all the other approaches, but the quality of solution is inferior to that of the centralized approach. It can be also observed that as the number of solution considered for negotiation in the distributed approach increases from 3 to 10, the solution quality approaches that of the centralized integrated approach. This demonstrates that the distributed approach converges toward the centralized approach as the number of top solution considered for negotiation increases. Based on the balance between the quality of the solution and the time arrive at the solution the number of top solution can be fixed.

6.9 Summary

Current chapter develops the framework for the parametric level integration for an entire value chain. The framework is demonstrated through the real industrial data. It successfully leverages the strong interdependencies amongst disjoint functions and improves overall performance rating of the firm under consideration. Also, an distributed approach is presented to balance the timeliness and quality of the solution and enhance the applicability of the integrated approach on the shopfloor.

Further, on the extent of integration following conclusions are drawn:

- For a given extent of integration i.e. 2/3/ or 4 function integration, the improvement in overall performance is significantly impacted by the choice of functions considered for integration. For the same set of functions, the improvement in performance also varies with the surrounding environment.
- Firm's overall performance rating follows a positive but non-linear correlation with individual function's improvement. This relation is dissimilar for different functions. Further, even if the performance improvements of individual functions are same, the overall improvement will vary with the selection of the function considered for integration.
- Integrating all the functions together always leads to improvement in system performance irrespective of the degree of uncertainties in the environment.

However, the improvements are diminishing for the stable and predictable environment.

- Irrespective of environment, parameters, and constraints, the proposed approach outperforms all the existing approaches.

CHAPTER 7
CONCLUSION

Current chapter summarizes the contribution of this dissertation. It highlights the novelty of the research work and its practical implications. Towards, the end it mentions the limitation of this work and the scope for further extension.

7.1 Summary

The outcomes of the research in this work advance the existing body of knowledge by comprehensively investigating the value of integrated operations planning approaches for various manufacturing scenarios and proposing an agent-based approach as a solution method. These approaches help in the systematic expansion of operations planning in diverse real-world manufacturing environments. In general, this research work can be assessed as follows:

7.1.1 Research contributions

The present research resulted in a number of contributions which can be summarized as follows:

a) First time in the literature, the problem of integrated operations planning for more than three operations functions is presented.

b) First time in the literature, integrated planning approach is exemplified through the planning of an entire value chain and provides a panoramic perspective of the operations at an enterprise level.

c) For the first time, integration is evaluated across the hierarchy and compared against the various policies existing at long term, short term as well as immediate.

d) For the first time, the multi-component aspect of the machine is considered in depth for integration and all the dependencies (structural, economic and stochastic) which exists between the constituent components of the machine are simultaneously addressed to optimize machine maintenance and product inspection plan.

e) For the first time, multiple failure mode of each component and their impact on individual quality characteristics is considered in the context of integrated planning.

f) Integration of the supply planning function with maintenance is comprehensively demonstrated for the first time. Parameters such as those related to machine's failure and repair characteristics, effectiveness of the preventive maintenance etc. were never correlated with the material supply planning earlier but are essential to synchronize the machine availability with the material availability. This has resulted into minimization of wait time, both for machine and material and thus improves the production economy.

g) To contemplate the integration performed at the parametric level a similar integration of the performance indicators of different interrelated functions was required. Considering the same, a composite index called "Overall Operations Rating" (OOR) is developed in this work. The composite index is evaluated and respective improvisation of individual functions is analyzed to demonstrate the balanced performance of all the functions of the value chain.

h) As the complexity of the problem rises due multiple parameters and decision variables, a distributed approach is developed as a solution method. The approach balances the timelines and quality of solution and facilitates the adaption of the integrated approach on the shop floor.

i) The work simultaneously defies all the simplistic assumptions made earlier through the consideration of a real manufacturing environment. Complexities related to machine architecture, multiple products with multiple CTQs, various failure modes, imperfect mainenance processes, stochastic nature of the business processes etc. are simultaneously considred in this work thereby making the approach directly applicable to shopfloor without significant amendments.

j) All the approaches are comprehensively evaluated for various manufacturing scenarios generated by varying parameters related to each functions. This helps in generalizing the results and help the operations managers in selecting a suitable case for the immediate adaption of the presented integrated approaches. The outcomes of extensive value investigations are as follows:

    - It is observed that integration of production and maintenance plan, the total cost of operations can be reduced in the range of 3 to 14 % depending on the operating environment. Additionally, for a specific environment, there was a significant reduction in the number of failures machine and the availability was increased to a level of 93%.

- Integration of maintenance and quality planning leads to an improvement an improvement in the range of 2.3% to 14.55 % was realized for different manufacturing environment. Additionally, using a distributed approach an improvement in the solution time of around 12 percent was realized against around 9% increase in objective function value i.e. operating cost.
- As a result of integrating material planning with production and maintenance planning, an improvement in the total cost of operation in the range of 5.23 to 15.28 percent was observed.
- It is observed that in a generic environment, an improvement of around 15% in the total operating cost can be realized using the integrated approach for the entire value chain planning. Further, in the environment characterized by high parametric variability, as the extent of the integration is increased from two function integration to four function integration, the improvisation in the objective function grew from around 2% to 18 %. It is also observed that under certain environment, integration of two function is better than integration of three function. This amelioration is significantly impacted by the choice of the functions considered for integration in a particular environment
- In general, it is concluded that integrated operations planning approaches give improved system performance for manufacturing industies having older machines, low maintenance effectiveness, higher cost of rejection, and in environment characterised by high uncertainty of peripheral parameters such as lead time, demand etc. In other words, the integrated operatiosn planning approaches deliver better system performance with the inctrese unceratinitiy of the manufacturing system.

In essence, the outcomes of the research in this thesis advances the existing body of knowledge by comprehensively investigating the value of integrated operations planning approaches for various manufacturing scenarios and developing a distributed approach as a solution method. This work forms the framework for parametric level integration of various disjoint functions viz. production planning, maintenance planning, quality planning, and material supply planning under dynamic manufacturing environments. The research attempts to enrich the existing body of research and contributes from the multiple perspectives. From the corroborative perspective, it accommodates stochastic nature and associated uncertainties related to peripheral activities such as time to repair, type of failure etc. by identifying appropriate distributions. This brings the model much closer to the realistic environment. From the research perspective, it provides exhaustive analysis of impact of functions involved and extent of integration on goal results. From the applicability and relevance perspective it provides wider visibility and better control over industrial management and also assists practicing managers for efficient decision making.

7.1.2 Utility and industrial implications of the research work

The outcomes of the present research will help manufacturing industries in the following manner:

1. The successful implementation of the present approaches will help in integrating various operations planning aspects at the initial stage of decision-making, thereby reducing human intervention in coordinating and implementing various operations plans.
2. Sub-optimal performance of existing operations planning approaches coupled with the prolonged time to arrive at solution often results industry professionals to lean toward the experience-based planning in industries. The distributed approach as an alternative solution method will resolve this concern of practitioners and will enhance the adaptability of integrated planning thereby reducing the subjectivity involved in the conventional decision-making process.
3. Integrated operations planning may not result into same performance improvement for all the manufacturing industries. The results of comprehensive evaluation obtained by varying parameters related to maintenance, process, and quality control help the operations managers in evolving thumb rules for easy adaption of integrated approaches for their respective manufacturing environment.
4. The results of this research are presented in form of an integrated operations plan. The plan provides functions specific directives in the simplest form which are easy to interpret across the hierarchy. While it takes away the dubiety related to the series of

actions to be executed, at the same time it provides a panoramic view of the operation of various functions in a single look.

5. The work also develops corollaries which assist in primitive prioritization of functions for integration. Using these corollaries, firms can decide on building the roadmap for implementing end to end integration of the functions.
6. Lastly, the research equips the manufacturing industries with autonomous decision-support system that allows high level responsiveness to the dynamic conditions for various real-world manufacturing environments.

7.2 Limitation and future scope of the research work

The comprehensive approaches for the integrated operation developed in this research have a good potential for application in the manufacturing industry. Any such research study aimed at meeting the academic requirements in a somewhat limited duration is bound to suffer from certain limitations. This research is also not an exception. Moreover, the limitations of the present research offer an excellent scope for future research. While deliberating various issues related to the study reported in this thesis, a few points were noticed which could be identified as the limitations of the present work, some of which are as follows.

As a prelude, the primary objective of the research work is to develop a framework for multi-function integration and evaluate it value for a broad range of manufacturing setup. Considering the increasingly large solution space which increases by manifolds with the inclusion of additional function, current work limits the integration to four critical functions only. With the progressive development of optimization algorithm for such complex problems, function like logistics, manpower planning and more can be added to develop an all-inclusive enterprise level integrated operation planning platform. Additionally, the work focuses on a single machine. The next logical expansion can be the demonstration of the value of integrated planning for an extended environment which comprises of a multi-machine layout.

Also, in the context of maintenance scheduling factors such as the skill of the maintenance personnel, quality of spares etc. are not considered in the present work.

Further, the operations rating mentioned in chapter 6 focuses mainly on quality, cost and delivery performance. While these factors are generally practiced factors across the industry, there is wide scope for further development of this rating. An immediate succession in this raring could be consideration of financial ratios of the organization which provided an economic health of the organization.

Further, the integration can be extended to include sub-tiers at the downstream and customers at the upstream. Such an extended integration will lead to an establishment of a manufacturing ecosystem which is holistically integrated. Additionally, in the present work, integrated problems have been solved primarily for a single objective function i.e. total operating cost and for the overall operations rating in chapter 6. Such an overall operation rating can be deployed for each of the integration scoped out for extension

REFERENCES

Ahmadi, R. (2019). An integrated approach to maintenance scheduling of multi-state production systems subject to deterioration. *IMA Journal of Management Mathematics*, 30(2), 235-264.

Alfares, H. K., Khursheed, S. N., & Noman, S. M. (2005). Integrating quality and maintenance decisions in a production-inventory model for deteriorating items. *International Journal of Production Research*, *43*(5), 899-911.

Anosike, A.I., Zhang, D.Z. (2009), An agent-based approach for integrating manufacturing operations, *International Journal of Production Economics*, 121(2), 333-352.

Aytug, H., Khouja, M., & Vergara, F. E. (2003). Use of genetic algorithms to solve production and operations management problems: a review. *International Journal of Production Research*, *41*(17), 3955-4009.

Beamon, B. M. (1999). Measuring supply chain performance. *International journal of operations & production management*, *19*(3), 275-292.

Bilge, Ü., Kıraç, F., Kurtulan, M., & Pekgün, P. (2004). A tabu search algorithm for parallel machine total tardiness problem. *Computers & Operations Research*, *31*(3), 397-414.

Cassady, C. R., & Kutanoglu, E. (2003). Minimizing job tardiness using integrated preventive maintenance planning and production scheduling. *IIE transactions*, *35*(6), 503-513.

Chansombat, S., Pongcharoen, P. and Hicks, C (2020). Grey Wolf production scheduling for the capital goods industry. *Applied Soft Computing*, 106480.

Cho, D. I., & Parlar, M. (1991). A survey of maintenance models for multi-unit systems. *European journal of operational research*, *51*(1), 1-23.

Chung, T. P., Xue, Z., Wu, T., & Shih, S. C. (2019). Minimising total completion time on single-machine scheduling with new integrated maintenance activities. *International Journal of Production Research*, 57(3), 918-930.

Cieniawski, S. E., Eheart, J. W., & Ranjithan, S. (1995). Using genetic algorithms to solve a multiobjective groundwater monitoring problem. *Water Resources Research*, *31*(2), 399-409.

Cui, W. (2020). Approximate Approach to Deal with the Uncertainty in Integrated Production Scheduling and Maintenance Planning. *Journal of Shanghai* Jiaotong University (Science), 25(1), 106-117.

Delporte, C. M., & Thomas, L. J. (1977). Lot sizing and sequencing for N products on one facility. *Management Science*, *23*(10), 1070-1079.

Duan, L., Doğru, M.K., Özen, U., Beck, J.C. (2012), A negotiation framework for linked combinatorial optimization problems, *Autonomous Agents and Multi-Agent Systems*, 25(1), 158-182

Dudek, R. A., Panwalkar, S. S., & Smith, M. L. (1992). The lessons of flowshop scheduling research. *Operations Research*, *40*(1), 7-13.

Erol, R., Sahin, C., Baykasoglu, A., Kaplanoglu, V. (2012), A multi-agent based approach to dynamic scheduling of machines and automated guided vehicles in manufacturing systems, *Applied soft computing*, 12(6), 1720-1732.

Fikar, C., Hirsch, P., & Nolz, P. C. (2018). Agent-based simulation optimization for dynamic disaster relief distribution. *Central European Journal of Operations Research*, *26*(2), 423-442.

Frohlich, M. T., & Westbrook, R. (2001). Arcs of integration: an international study of supply chain strategies. *Journal of operations management*, *19*(2), 185-200.

Gaafar, L. (2006). Applying genetic algorithms to dynamic lot sizing with batch ordering. *Computers & Industrial Engineering*, *51*(3), 433-444.

Ghaleb, M., Taghipour, S., Sharifi, M., & Zolfagharinia, H. (2020). Integrated production and maintenance scheduling in a single degrading machine with deterioration-based failures. *Computers & Industrial Engineering*, 106432.

Goyal, S. K., & Deshmukh, S. G. (1997). Integrated procurement-production system in a just-in-time environment-modelling and analysis. *Production Planning & Control*, *8*(1), 31-36.

Gunasekaran, A., Patel, C., & McGaughey, R. E. (2004). A framework for supply chain performance measurement. *International journal of production economics*, *87*(3), 333-347.

Haraguchi, N., Cheng, C. F. C., & Smeets, E. (2017). The Importance of manufacturing in Economic Development: Has this changed?. *World Development*, *93*, 293-315.

Hazır, Ö., & Kedad-Sidhoum, S. (2014). Batch sizing and just-in-time scheduling with common due date. *Annals of Operations Research*, *213*(1), 187-202.

Henchiri, A., Ennigrou, M. (2013), Particle swarm optimization combined with tabu search in a multi-agent model for flexible job shop problem. *Proceedings of International Conference in Swarm Intelligence*, 385-394

Hsu, W. L. (1983). On the general feasibility test of scheduling lot sizes for several products on one machine. *Management science*, *29*(1), 93-105.

Hyun, C. J., Kim, Y., & Kim, Y. K. (1998). A genetic algorithm for multiple objective sequencing problems in mixed model assembly lines. *Computers & Operations Research*, *25*(7-8), 675-690.

Jans, R., & Degraeve, Z. (2007). Meta-heuristics for dynamic lot sizing: A review and comparison of solution approaches. *European journal of operational research*, *177*(3), 1855-1875.

Kaehkonen, A. K., & Lintukangas, K. (2013). Supply management as a value creating element in a firm. *International Journal of Value Chain Management*, *6*(4), 358-374.

Kanyalkar, A. P., & Adil, G. K. (2007). Aggregate and detailed production planning integrating procurement and distribution plans in a multi-site environment. *International Journal of Production Research*, *45*(22), 5329-5353.

Khelifati, S.L., Benbouzid-Sitayeb, F., (2011), A multi-agent scheduling approach for the joint scheduling of jobs and maintenance operations in the flow shop sequencing problem, *Proceedings of International Conference on Computational Collective Intelligence*, 60-69.

Kijima, M. (1989). Some results for repairable systems with general repair. *Journal of Applied probability*, *26*(1), 89-102.

Kouedeu, A. F., Kenne, J. P., Dejax, P., Songmene, V., & Polotski, V. (2015). Production and maintenance planning for a failure-prone deteriorating manufacturing system: a hierarchical control approach. *The International Journal of Advanced Manufacturing Technology*, *76*(9-12), 1607-1619.

Kumar, S., & Lad, B. K. (2017). Integrated production and maintenance planning for parallel machine system considering cost of rejection. *Journal of the Operational Research Society*, *68*(7), 834-846.

Lad, B. K., & Kulkarni, M. S. (2012). Optimal maintenance schedule decisions for machine tools considering the user's cost structure. *International Journal of Production Research, 50*(20), 5859-5871.

Laggoune, R., Chateauneuf, A., & Aissani, D. (2010). Impact of few failure data on the opportunistic replacement policy for multi-component systems. *Reliability Engineering & System Safety*, *95*(2), 108-119.

Lam, J. Y. J., & Banjevic, D. (2015). A myopic policy for optimal inspection scheduling for condition based maintenance. *Reliability Engineering & System Safety*, *144*, 1-11.

Liu, Q., Dong, M., & Chen, F. F. (2018). Single-machine-based joint optimization of predictive maintenance planning and production scheduling. *Robotics and Computer-Integrated Manufacturing*, 51, 238-247.

Lou, P., Liu, Q., Zhou, Z., Wang, H., Sun, S.X. (2012), Multi-agent-based proactive–reactive scheduling for a job shop, *The International Journal of Advanced Manufacturing Technology*, 59(1-4), 311-324

Löfsten, H. (2000). Measuring maintenance performance–in search for a maintenance productivity index. *International Journal of Production Economics*, *63*(1), 47-58.

Mortezaei, N., & Zulkifli, N. (2013). Integration of lot sizing and flow shop scheduling with lot streaming. *Journal of Applied Mathematics*.

Nakagawa, T., & Murthy, D. N. P. (1993). Optimal replacement policies for a two-unit system with failure interactions. *RAIRO-Operations Research*, *27*(4), 427-438.

Njike, A. N., Pellerin, R., & Kenne, J. P. (2012). Simultaneous control of maintenance and production rates of a manufacturing system with defective products. *Journal of Intelligent Manufacturing*, *23*(2), 323-332.

Nourelfath, M., & Châtelet, E. (2012). Integrating production, inventory and maintenance planning for a parallel system with dependent components. *Reliability Engineering & System Safety*, *101*, 59-66.

Nowakowski, T., & Werbińka, S. (2009). On problems of multicomponent system maintenance modelling. *International Journal of Automation and Computing*, *6*(4), 364.

Pal, A., Chan, F. T. S., Mahanty, B., & Tiwari, M. K. (2011). Aggregate procurement, production, and shipment planning decision problem for a three-echelon supply chain using swarm-based heuristics. *International Journal of Production Research*, *49*(10), 2873-2905.

Pandey, D., Kulkarni, M. S., & Vrat, P. (2011). A methodology for joint optimization for maintenance planning, process quality and production scheduling. *Computers & Industrial Engineering*, *61*(4), 1098-1106.

Paprocka, I. (2019). The model of maintenance planning and production scheduling for maximising robustness. *International Journal of Production Research*, 57(14), 4480-4501.

Peterson, R., & Silver, E. A. (1979). Decision systems for inventory management and production planning John Wiley and Sons. *Inc., NY*.

Pinedo, M., & Hadavi, K. (1992). Scheduling: theory, algorithms and systems development. In *Operations Research Proceedings 1991* (pp. 35-42). Springer, Berlin, Heidelberg.

Polyakovskiy, S., M'Hallah, R. (2014), A multi-agent system for the weighted earliness tardiness parallel machine problem, *Computers & Operations Research*, 44, 115-136.

Rabbi, F., Ahmed, T., Saha, A., & Sutradhar, P. (2013). Identification of causes of demand variation and its impact on sales volume-an exploratory study in processed food industry in bangladesh. *European Scientific Journal*, *9*(22).

Shepherd, C., & Günter, H. (2010). Measuring supply chain performance: current research and future directions. In *Behavioral Operations in Planning and Scheduling* (pp. 105-121). Springer, Berlin, Heidelberg.

Seif, J., Dehghanimohammadabadi, M., & Yu, A. J. (2019). Integrated preventive maintenance and flow shop scheduling under uncertainty. *Flexible Services and Manufacturing Journal*, 1-36.

Simatupang, T. M., Piboonrungroj, P., & Williams, S. J. (2017). The emergence of value chain thinking. *International Journal of value chain management*, *8*(1), 40-57.

Tambe, P. P., & Kulkarni, M. S. (2015). A superimposition based approach for maintenance and quality plan optimization with production schedule, availability, repair time and detection time constraints for a single machine. *Journal of Manufacturing Systems*, *37*, 17-32.

Tambe, P. P., Mohite, S., & Kulkarni, M. S. (2013). Optimisation of opportunistic maintenance of a multi-component system considering the effect of failures on quality and production schedule: A case study. *The International Journal of Advanced Manufacturing Technology*, *69*(5-8), 1743-1756.

Torabi 1, S. A., & Hassini, E. (2009). Multi-site production planning integrating procurement and distribution plans in multi-echelon supply chains: an interactive fuzzy goal programming approach. *International Journal of Production Research*, *47*(19), 5475-5499.

Ventura, J. A., & Kim, D. (2003). Parallel machine scheduling with earliness–tardiness penalties and additional resource constraints. *Computers & Operations Research*, *30*(13), 1945-1958.

Von Hoyningen-Huene, W., & Kiesmüller, G. P. (2015). *Maintenance and production scheduling on a single machine with stochastic failures*. Arbeitspapiere des Instituts für Betriebswirtschaftslehre, Universität Kiel.

Wankhade, N., & Kundu, G. K. (2018). Supply chain performance management: a structured literature review. *International Journal of Value Chain Management*, *9*(3), 209-240.

Wolter, A., & Helber, S. (2016). Simultaneous production and maintenance planning for a single capacitated resource facing both a dynamic demand and intensive wear and tear. *Central European Journal of Operations Research*, *24*(3), 489-513.

Xiang, Y., Cassady, C. R., Jin, T., & Zhang, C. W. (2014). Joint production and maintenance planning with machine deterioration and random yield. *International Journal of Production Research*, *52*(6), 1644-1657.

Xing, L. (2007). Reliability evaluation of phased-mission systems with imperfect fault coverage and common-cause failures. *IEEE Transactions on Reliability*, *56*(1), 58-68.

Yildirim, M. B., & Nezami, F. G. (2014). Integrated maintenance and production planning with energy consumption and minimal repair. *The International Journal of Advanced Manufacturing Technology*, *74*(9-12), 1419-1430.

Zhu, X., & Wilhelm, W. E. (2006). Scheduling and lot sizing with sequence-dependent setup: A literature review. *IIE transactions*, *38*(11), 987-1007.

Zhou, X., Lu, Z., & Xi, L. (2012). Preventive maintenance optimization for a multi-component system under changing job shop schedule. *Reliability Engineering & System Safety*, *101*, 14-20

Zied, H., Sofiene, D., & Nidhal, R. (2011). Optimal integrated maintenance/production policy for randomly failing systems with variable failure rate. *International Journal of Production Research*, *49*(19), 5695-5712.

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