Production Control of Unreliable Systems in the Context of Green Manufacturing and Reverse Logistics

by

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MANUSCRIPT-BASED THESIS PRESENTED TO ÉCOLE DE TECHNOLOGIE SUPÉRIEURE IN PARTIAL FULFILLMENT FOR THE DEGREE OF DOCTOR OF PHILOSOPHY
Ph. D.

MONTREAL, SEPTEMBRE, 23, 2022

ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
UNIVERSITÉ DU QUÉBEC

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ACKNOWLEDGMENT

First, I wish to acknowledge my parents for their love and support throughout my life. Thank you both for giving me the strength and support me to chase my dreams.

Then, I would like to thank my supervisors, Prof. Gharbi, and Prof. Ouhimmou for their guidance, comments, questions, and all their supports financially and emotionally throughout this study. This journey would not have been possible to accomplish without their guidance, encouragement, and supports.

Finally, to all my friends, thanks for your help, encouragement, and support during this journey. I cannot list them here, but you are always on my mind, and I wish you the best of luck.

Contrôle de la production de systèmes non fiables dans le contexte de la fabrication verte et de la logistique inverse

Arezou ENTEZAMINIA

RÉSUMÉ

Tout au long du siècle dernier, le public a pris de plus en plus conscience des problèmes environnementaux et des effets graves des émissions de gaz à effet de serre (GES), tels que le réchauffement de la planète et le changement climatique. Au niveau gouvernemental, le protocole de Kyoto (1997), qui a été signé par 37 pays industrialisés, les a exhortés à réduire leurs émissions de GES. Les changements dans la conscience environnementale ont également un impact sur les secteurs industriels. En ce qui concerne les préoccupations environnementales et les réglementations qui ont été promulguées, il est essentiel que les industries fournissent des efforts pour atténuer les émissions.

Par conséquent, les décideurs doivent établir les meilleures stratégies de gestion environnementale tout en gardant à l'esprit l'aspect économique. À cet égard, nous nous sommes concentrés sur le thème de l'intégration des préoccupations environnementales dans la gestion des systèmes de fabrication en utilisant une approche de commande optimale stochastique. En pratique, le secteur manufacturier a un comportement particulièrement dynamique en raison des multiples événements aléatoires tels que les pannes, les activités de réparation. Dans cette thèse, nous abordons le problème de planification de la production des systèmes de fabrication non fiables intégrés aux aspects environnementaux. Dans la première partie, nous nous concentrons sur le problème de planification de la production des systèmes de fabrication constitués de machines à hautes émissions (HEM), qui sont prêts à investir progressivement dans des machines à faibles émissions (LEM). De nouvelles politiques de commande rentables et respectueuses de l'environnement ont été développées pour ces entreprises afin d'aider le décideur à synchroniser HEM et LEM. En conséquence, nous avons développé deux nouvelles politiques en vertu desquelles HEM et LEM peuvent fonctionner en même temps pour augmenter la disponibilité du système tout en réduisant simultanément les stocks, le retard et les émissions générées. La modélisation par simulation, l'approche expérimentale et la méthodologie de surface de réponse ont été utilisées pour obtenir les paramètres optimaux de ces politiques de commande. Enfin, diverses expériences qui ont été menées pour un large éventail de paramètres de coût et de système, ont révélé que nos politiques de commande ont entraîné des économies de coûts et une réduction des émissions de GES considérables.

Dans la deuxième partie, nous avons abordé le problème de la planification des échanges et de la production pour les systèmes de fabrication sujets aux défaillances réglementés par un système de plafonnement et d'échange. Dans le cas du prix du carbone, qui change aléatoirement sur le marché, il est difficile et compliqué pour les entreprises de déterminer leur taux de production et leur volume d'échange afin de tirer profit du marché du carbone. Nous avons développé une nouvelle politique conjointe de contrôle de la production et des échanges

pour aider les gestionnaires à déterminer quand acheter/vendre des quotas ou augmenter/diminuer le taux de production afin de minimiser le coût total et de réduire les émissions de GES. Enfin, une analyse de sensibilité et une étude comparative sont menées pour démontrer comment notre politique conjointe proposée conduit à des économies de coûts significatives et à une diminution des émissions par rapport aux politiques existantes adaptées à partir de la littérature.

Dans la troisième partie, nous avons intégré les considérations environnementales dans des systèmes de fabrication/refabrication sujets aux défaillances prenant en compte de différentes qualités de retours. Des conditions de qualité spécifiques (haute ou basse qualité) ont été attribuées aux produits retournés. L'impact de la qualité des retours sur les émissions de GES et les taux de production a également été pris en compte. Nous avons développé deux politiques de contrôle de la production pour synchroniser la fabrication et la remise à neuf en tenant compte à la fois des retours de haute et de basse qualité afin d'atteindre les objectifs environnementaux et économiques. La valeur optimale des paramètres est calculée en utilisant la simulation, la conception de l'expérience et la méthodologie de surface de réponse. Sur la base des résultats, nos politiques proposées ont surpassé les politiques existantes adaptées de la littérature en termes à la fois de coûts totaux optimaux et de réduction des émissions.

Dans la quatrième partie, nous nous concentrons sur les systèmes de fabrication peu fiables qui consomment des carburants à fortes émissions (par exemple, le charbon) et ont tendance à réduire les émissions en passant à des carburants plus propres (par exemple, le gaz naturel (GN)). En effet, la production utilisant un type de carburant plus propre réduit les émissions de GES mais entraîne des coûts de carburant plus élevés. Nous tenons également compte de la fluctuation aléatoire des prix du GN. Nous avons développé des politiques de contrôle de la production pour les systèmes de fabrication sujets aux pannes avec la possibilité de changer de carburant pour minimiser les coûts totaux tout en réduisant les émissions de GES. Dans cette veine, deux politiques de commande de la production sont développées pour atteindre des objectifs à la fois économiques et environnementaux. Selon les politiques que nous proposons, les décisions de changement de carburant sont prises en fonction de la fluctuation aléatoire du prix du GN et des éléments clés du système, notamment son état, son inventaire et son niveau d'émissions. Nos politiques proposées pourraient réduire les émissions tout en minimisant les coûts totaux, y compris les coûts d'inventaire, d'arriérés, de carburant et d'émissions. La valeur optimale des facteurs de contrôle est déterminée à l'aide d'une simulation, d'un plan d'expérience et d'une méthodologie de surface de réponse. Nos politiques de commande proposées surpassent les politiques dérivées de la littérature en termes de coûts totaux optimaux et de réduction des émissions.

En conclusion, cette thèse contribue au domaine de la planification de la production des systèmes de fabrication peu fiables de plusieurs manières. En effet, nous avons examiné les aspects environnementaux de tels systèmes sous plusieurs angles (technologies à faibles émissions, échange de carbone, logistique inverse). Des structures efficaces de politiques de commande de la production sont développées, contribuant à une meilleure compréhension du comportement dynamique et stochastique de tels systèmes. Une étude comparative et une

analyse de sensibilité approfondie sont réalisées pour valider la structure des politiques de commande développées.

Mots-clés : politique de commande de la production environnementale, système de fabrication non fiable, émissions de gaz à effet de serre, taxe carbone, plafonnement et échange, remise à neuf, changement de carburant, optimisation de la simulation.

Production Control of Unreliable Systems in the Context of Green Manufacturing and Reverse Logistics

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ABSTRACT

Throughout the last century, there has been a growing public awareness about environmental issues and serious effects of greenhouse gas (GHG) emissions, such as global warming and climate change. At the governmental level, the Kyoto Protocol (1997), which was signed by 37 industrialised countries, has urged them to decrease their GHG emissions. Changes in environmental consciousness have also an impact on the industrial sectors. Regarding the environmental concerns and regulations that have been enacted, it is critical for industries to put effort into emission mitigation.

As a result, decision-makers must establish the best environmental management strategies while keeping the economic aspect in mind. In this regard, we focus on the topic of integrating environmental concerns in the management of manufacturing systems using a stochastic optimal control approach. In practice, the manufacturing sector has a particularly dynamic behaviour due to the multiple variables and random events such as random failure and repair times. In this thesis, we address the production planning problem of unreliable manufacturing systems integrated with environmental aspects.

In the first part, we focus on the production planning problem of manufacturing systems consisting of high-emitting machines (HEMs), which are willing to gradually invest in low-emitting machines (LEMs). New cost-effective and environmentally friendly control policies are developed for such companies to help the decision-maker in synchronising HEM and LEM. Accordingly, we develop two new policies under which both HEM and LEM can run at the same time to boost system availability while simultaneously reducing inventory, backlog, and generated emissions. The simulation modeling, experimental approach, and response surface methodology are used to obtain the optimal parameters of these control policies. Finally, various experiments conducted for a wide range of cost and system parameters, revealed that our control policies result in considerable cost saving and GHG emissions reduction.

In the second part, we address the problem of trading and production planning for failure-prone manufacturing systems regulated by cap-and-trade scheme. In the case of the carbon price, which randomly changes in the market, it is difficult and complicated for businesses to determine their production rate and trading volume in order to make a profit from the carbon market. We develop a new joint production and trading control policy to help managers in determining when to buy/sell allowances or increase/decrease the production rate in order to minimize the total cost and reduce GHG emissions. Finally, sensitivity analysis and a comparative study are conducted to demonstrate how our proposed joint policy leads to significant cost savings and emissions decrease when compared to existing policies adapted from the literature.

In the third part, we integrate the environmental considerations into failure-prone manufacturing/remanufacturing systems taking variate quality returns into account. Specific quality conditions (high- or low-quality) are assigned to returned products. The impact of the returns' quality on GHG emissions and production rates is also taken into consideration. We develop two production control policies to synchronise manufacturing and remanufacturing considering both high- and low-quality returns in order to achieve environmental and economic goals. The optimal value of parameters is calculated using simulation, design of experiment, and response surface methodology. Based on the results, our proposed policies outperform the existing policies adapted from the literature in terms of both optimal total costs and emissions reduction.

In the fourth part, we focus on unreliable manufacturing systems which consume high-emitting fuels (e.g., coal) and tend to reduce emissions by switching to cleaner fuels (e.g., natural gas (NG)). Indeed, production using a cleaner fuel type reduces GHG emissions but results in higher fuel cost. We also take the random fluctuation of NG price into account. We developed production control policies for failure-prone manufacturing systems with the possibility of fuel switching to minimize total costs while reducing GHG emissions. In this vein, two production control policies are developed to achieve both economic and environmental goals. According to our proposed policies, decisions on fuel switching are made based on the random fluctuation of NG price, and the key elements of the system including its state, inventory, and emissions level. Our proposed policies could reduce emissions while minimizing total costs including inventory, backlog, fuel, and emission costs. The optimal value of control factors is determined using simulation, design of experiment, and response surface methodology. Our proposed control policies surpass the policies derived from the literature in terms of both optimal total costs and emissions reduction.

In conclusion, this thesis contributes to the field of production planning and control of unreliable manufacturing systems in several ways. Indeed, we look at the environmental aspects of such systems from multiple perspectives (low-emitting technologies, carbon trading, reverse logistics, fuel switching). Efficient structures of production control policies are developed, contributing to a better understanding of the dynamic and stochastic behavior of such systems. Comparative study and in-depth sensitivity analysis are performed to validate the structure of developed control policies.

Keywords: Environmental production control policy, unreliable manufacturing system, greenhouse gas emissions, carbon tax, cap-and-trade, remanufacturing, fuel switching, simulation optimization.

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LIST OF ABREVIATIONS

ANOVA	Analysis of variance
CE	Circular economy
CLSC	Closed-loop supply chain
DOE	Design of experiment
EU ETS	European union's emissions trading system
EOQ	Economic order quantity
EPQ	Economic production quantity
EOL	End of life
HPP	Hedging point policy
EHPP	Environmental hedging point policy
MHPP	Multiple hedging point policy
GHG	Greenhouse gas
HEM	High-emitting machine
LEM	Low-emitting machine
MTTR	Mean time to repair
MTTF	Mean time to failure
RL	Reverse logistics
RSM	Response surface methodology
SD	Standard deviation
WEEE	Waste electrical and electronic equipment
WIP	Work-in-process
NG	Natural gas

INTRODUCTION

Currently, all entrepreneurs seek to maximize their profit by satisfying demands in the competitive market. In this context, companies must manage their resources and adapt their capacities to face various challenges. In practice, several internal and external events can affect the economic efficiency of the production system. Indeed, the random aspects of machine failures, repairs, or fluctuation in demand make it difficult to control the production capacity. Faced with this complexity, the interest of manufacturers is benefit from all their resources and capacities.

In recent years, environmental regulations and above all social pressures have forced companies to integrate the environmental considerations into their strategies. Several industrial sectors such as the chemical, petroleum and mining industries need to pay close attention to the environmental consequences of their manufacturing processes. Operationally, the industrial sector is experiencing a lack of development of manufacturing strategies to meet standards and requirements in terms of emissions, waste, or toxic discharges. This lack is accentuated by the difficulty of doing research on dynamic and stochastic context of failure-prone manufacturing systems. Over the years, researchers considered simplifying conditions and assumptions to comply with the complexity of manufacturing environment.

In this vein, our main objective is to study the production planning of unreliable manufacturing systems considering environmental aspects in green as well as closed-loop supply chains. The originality of this project is that we propose production control policies for polluting unreliable production systems under environmental regulations to attain both economic and environmental goals. To solve these problems, we use an experimental resolution approach by integrating simulation technique, a design of experiment and a response surface methodology.

This thesis is organized into 5 chapters: at the beginning, Chapter 1 presents a detailed review of the literature. In the same chapter, we define the general framework of this thesis including the system under study, research problem, objectives, as well as the resolution approach and methodology. The Chapter 2 includes our first scientific article published in “Journal of Cleaner Production”, entitled “Environmental hedging point policies for collaborative unreliable manufacturing systems with variant emitting level technologies”. Our second article published in “Journal of Cleaner Production”, entitled “A joint production and carbon trading policy for unreliable manufacturing systems under cap-and-trade regulation” is presented in Chapter 3. The Chapter 4 also presents our third scientific article, entitled “Environmental production planning of unreliable manufacturing/remanufacturing systems considering quality impact of returns under carbon tax regulation” which has been submitted to “Computers & Industrial Engineering”. The Chapter 5 also presents our fourth scientific article, entitled “Production planning of failure-prone manufacturing systems in the context of emissions reduction by fuel switching” which recently has been submitted in “The International Journal of Production Economics”. Conclusion and future work are presented at the end of the thesis.

CHAPTER 1

LITERATURE REVIEW

1.1 Introduction

In this chapter, a critical review of the existing literature will be presented. First, we will provide a general definition of flexible manufacturing systems, unreliable manufacturing systems and the production control policies for such systems. Second, the environmental aspects of manufacturing systems will be addressed by focusing on environmental regulations, green manufacturing, and integration of environmental considerations into manufacturing systems. Third, we will provide a general definition of reverse logistics and closed-loop supply chain. Afterward, we will concentrate on integration of manufacturing and remanufacturing, integrating quality of returns into remanufacturing, environmental aspects of remanufacturing, as well as integrating environmental consideration into manufacturing/remanufacturing systems. Finally, the research problem, objectives, contributions, methodology and resolution approach as well as thesis' structure will be presented.

1.2 Flexible manufacturing systems

Variation in product demand occurs in the market because of fluctuating customers' requirements. In today's market, customer demand and product specifications change at a rapid speed, making it critical for a manufacturing system to deal with to these changes as efficiently as possible to remain competitive. A flexible manufacturing system (FMS) provides various levels of flexibility in order to respond appropriately in the event of a change (El-Tamimi et al., 2012). The four different flexibility tests used to assess whether a manufacturing system is flexible, are part variety (capacity to produce different part types), schedule change (capacity to perform adequately in the event of a schedule change), error recovery (ability to elegantly handle any breakdown), and new part test (ease of bringing new part) (Yadav et al., 2018).

1.2.1 Unreliable manufacturing systems

Unreliable manufacturing systems are a subset of flexible manufacturing systems in which stochastic failure and repair of machines are considered. In such systems, the objective is to find the production rate so that inventory and backlog costs are minimized for a long-time horizon. Many research studies have been devoted to optimal production planning and control problems of unreliable manufacturing systems. Several approaches have been conducted to deal with these systems (Amelian et al., 2019).

1.2.2 Management of unreliable manufacturing systems

Feedback control policies have been implemented by several authors to address the dynamic and stochastic context of the failure-prone manufacturing systems. As one of the pioneers in studying the unreliable manufacturing systems, Kimemia and Gershwin (1983) introduced a critical threshold control policy called Hedging Point Policy (HPP). According to this policy, the manufacturing system maintains a safety stock of the finished product inventory at an optimal level to decrease the effect of uncertain machine failure and repair on demand satisfaction. Hence, it is important to find the optimal level of safety stock (threshold level) that minimizes the inventory and backlog costs. Following their work, Akella and Kumar (1986) obtained an analytical solution to the Hamilton-Jacobi-Bellman equations in the case of a single machine that produces only one sort of product subject to random failure and repair times. They found the optimal threshold level, also known as the hedging point, which minimizes total costs. The following is the formulation of this control policy:

$$u(t) = \begin{cases} u^{max} & if\ x(t) < Z \\ d & if\ x(t) = Z \\ 0 & if\ x(t) > Z \end{cases} \tag{1.1}$$

Where $u(t)$ is the production rate which depends on the inventory level. Accordingly, if the inventory level is below the threshold level z, the production rate is maximum. If the level of inventory is maintained at the threshold level, the production rate is equal to the rate of the demand. If the inventory level is above the threshold level, the production stops to avoid additional inventory costs.

HPP has been extended by several authors to consider practical aspects. Sharifnia (1988) studied a manufacturing system producing one type of product with multiple machine failures. The average cost to obtain the optimum inventory threshold level is minimized in his model. Perkins (2004) presented a hedging point policy for a single-product and single-machine unreliable manufacturing system. In his study, the times between failures follow exponential distribution and the times between repairs are fixed. Mok and Porter (2006) proposed an evolutionary stochastic optimisation procedure to estimate the optimal hedging points for failure-prone manufacturing systems producing multiple products with different priorities. Chan et al., (2008) studied the multi-product unreliable manufacturing systems where additional production capacity can be obtained from other machines in addition to the initial production system. An optimal production policy is defined with two threshold levels for each product type to satisfy uncertain demands. Mourani et al., (2008) considered a continuous-flow manufacturing system consists of one failure-prone machine for producing one product type with transportation delay and they used the hedging point policy to control the production of the machine. Gharbi et al., (2011) demonstrated that the nonexponential failure and repair time distributions can be used in HPP to determine the optimal production policy. Sajadi et al., (2011) concentrated on a single-product failure-prone manufacturing system with constant demand. The discrete event simulation and response surface methodology (RSM) are used to minimize total costs, including inventory and backlog costs. Rivera-Gómez et al., (2013) used a mix of simulation and RSM to handle a single-machine and single-product failure-prone manufacturing system, considering the rate of defective items. Bouslah et al., (2013a) addressed the production planning of failure-prone manufacturing systems considering the process and product quality. For an unreliable batch manufacturing system, Bouslah et al., (2014) focused on a combined production control policy and a cost-effective single sampling plan design. A modified hedging point policy is used to control production, which entails maintaining a safety stock of finished goods to prevent shortages during corrective maintenance. Assid et al., (2014) studied a multi-product unreliable system and developed a setup time hedging corridor policy. Khoury (2016) studied a single-product and single-machine unreliable manufacturing system where times between failures follow exponential distribution, and the repair time follows general distribution. They obtained the optimal production rate to minimize total cost of inventory and backlog. Rivera-Gómez et al., (2018) developed a multiple hedging point policy to address production, subcontracting, and maintenance policies all at the same time.

Hedging point policy for unreliable manufacturing systems have been also integrated with environmental aspects as well as remanufacturing. The relevant literature review will be respectively provided in Subsections 1.3.3 and 1.4.4.

1.3 Environmental aspects of manufacturing systems

The current environmental crisis is one of the most pressing challenges in the globe today. One of the primary causes of this predicament is pollution. Global warming due to the greenhouse effect, rising waste, and the depletion of resources have made it imperative for governments to improve the effectiveness of environmental regulations in recent years. Although the transportation and energy sectors are the first to be impacted by these issues, the manufacturing industry is also a sector that must contribute. For a long time, manufacturers have been focused on lowering costs to increase profits while ignoring environmental considerations. Authorities have begun to put pressure on businesses to limit the environmental impacts and encourage the incorporation of sustainable development into their operations in recent years.

According to Elkington (1998), the definition of sustainability is based on three main aspects: 1) the environment, 2) the economy, and 3) society. We recommend that the reader examine the work of Carter and Rogers (2008) and Seuring and Muller (2009) to understand the concept of sustainability. In this study, we will focus on the first two aspects of sustainability, the environment and the economy.

Only a few authors have looked at the topic of sustainable development and how it interacts with production planning in the literature. However, due to economic and social pressures, the literature on this subject begins to grow.

1.3.1 Environmental regulations

In general, studies that has focused on the environmental impact of manufacturing have considered different approaches to environmental control and regulations: regulatory, market-based, and voluntary approaches.

1.3.1.1 Regulatory approaches

Regulatory approaches known as command and control, consist of dictating a particular technology, setting a standard for environmental performance, or considering emission limits without using economic incentives beyond announced limits.

Command and control scheme has specified an across-the-board timeline for emission mitigation or defined specific technologies for pollution control. The enforcement of this regulatory approaches is made through the sanctions (Schmalensee and Stavins, 2013).
Although, this approach is not as flexible as other ones, it is effective for carbon reduction. For example, a command-and-control was used by China to deal with climate challenges.

1.3.1.2 Market-based approaches (tax-based and cap-and-trade)

In contrast to the regulatory approaches, market-based approaches are more responsive to changes in knowledge and technology and provide economic incentives in order to reduce emissions. These cost-effective approaches are more flexible to easily integrate costs and benefits of emissions mitigation. They could result in at least 15 percent to around 90 percent of cost savings compared to regulatory approaches. Two of the most widely used regulations are tax-based regulation and cap-and-trade (Hoen et al., 2014).

Carbon tax was introduced in 1991 for the first time in Norway as a national policy for mitigating CO_2 emissions, and similar policies have been developed in other countries (Gottinger, 1995). Carbon tax is a penalty or levy on each fossil fuel, proportional to the amount of carbon emitted when the fuel is burned, that is specified and controlled by the government. Different kinds of emission taxes are defined in the tax-based approaches like 'CO_2 tax' and 'energy tax'. A carbon tax is defined for per ton of emitted CO_2. As a ton of carbon corresponds to 3.67 tons of CO_2, it is easy to translate it to carbon tax. An energy tax is defined based on the amount of energy consumed. Therefore, an energy tax can also cover renewable and nuclear energy (Baranzini et al., 2000).

Under this approach, companies are charged for their emissions at a constant level of tax rate. There is no cap for generated emission. The quantity of emissions to mitigate is decided by companies based on the carbon prices. Australia, Sweden, Norway, South Africa, Mexico, and the Canadian province of British Columbia are examples of some countries that have applied this approach (Varsei et al., 2014). In addition, a carbon tax could be combined with emission caps as an international hybrid "cap-and-tax" approach (Avi-Yonah and Uhlmann, 2009).

Many international organizations considered carbon tax as a more cost-effective policy than other regulatory approaches for mitigating CO_2 emissions (Baranzini et al., 2000). Because the tax or levy can encourage companies to switch from fuel use to clean energy resources or drive innovative means to achieve carbon reduction (Varma, 2003). On the other hand, carbon taxes are revenue for the governments, which allow the governments to reduce other kind of taxes, such as income, sales, and profit.

Moreover, about 50 years ago, the idea of trading in pollution rights was offered by economists to meet environmental objectives. The first and biggest international scheme established for permits trade is European Union's Emissions Trading System (EU ETS). EU ETS could cover 11,000 power stations and industrial factories in 30 countries up to 2010. Regional programs include cap-and-trade program in the US Northeast went into effect in 2008. National programs include cap-and-trade system in Australia and New Zealand. International trading in GHG emissions is allowed under the Kyoto Protocol in order to reduce greenhouse gas emissions (Goulder, 2013).

A cap-and-trade program went into effect in California in 2013. In Canada, Quebec cap-and-trade system has involved in activities to fight against climate change since January 1, 2013. Ontario's cap and trade program signed a cap and trade linking agreement with Quebec and California on September 22, 2017. It came into effect on January 1, 2018. Based on this program, electricity importers, facility or natural gas distributors that emit 25,000 tons or more of greenhouse gas emissions per year are subject to cap-and-trade regulation (Purdon et al., 2014).

According to the cap-and-trade regulation, a limited amount of tradable emissions allowances (cap) is considered for distribution among emitters. Companies which generate emissions more than the allocated allowances are penalized by significant fines or purchase allowances from companies which generate emission fewer than the allowed level. Pressures (fines for over-emitting) and incentives (financial reward for selling surplus emission allowances) are created to motivate firms to purchase allowances or invest in technology and practices to mitigate greenhouse gas emissions (Sarkis et al., 2010).

Cap-and-trade regulation is also defined as a principal form of trading the pollution rights. In contrast with a regulatory approach, a cap-and-trade regulation aims to find ways to decrease GHG emissions at the lowest cost. In this regulation, the government sets a target on the emission mitigation. However, if the limitations are not respected, there are multiple options (Huisingh et al., 2015).

To achieve the environmental targets, companies are allowed to decide whether to make modification to their processes to curb the generated emissions or to buy exceeding carbon credits in carbon market. Moreover, companies are able to sell carbon credits on condition that they have an emission surplus. The decision depends on the cost of mitigating one metric ton of GHG emissions in comparison with carbon prices (Goulder, 2013).

In comparison with regulatory approaches, cap-and-trade can not only lead to a static cost effectiveness but also lead to cost reduction over time based on the evidence. Because cap-and-trade provides motivation for innovation and technology which are generally stronger than those provided by traditional regulatory approaches. For instance, companies learned how to take allowance prices into consideration in their operating decisions, how to use combinations of various types of coal, and how to provide cost-effective devices for flue gas desulfurization which is called "scrubbers" (Frey, 2013).

In sum, actual costs of cap-and-trade approach, even if the companies exceeded the cost-effective ideal for cap-and-trade, were much lower than the incurred cost of a comparable regulatory approach (Schmalensee and Stavins, 2013). Cap-and-trade is not the only kind of pollution trading, but it is the most widely used one that has drawn most attention. This trading approach has been developed for bringing greater participation by developing countries in efforts to mitigate GHGs (Kerr and Millard-Ball, 2012).

1.3.1.3 Voluntary approaches

Based on the voluntary approach, an internal self-regulated restriction is imposed by decision support system in order to avoid going further than standard considered limitations. In recent years there has been an increase interest in implementing of voluntary approaches such as labelling, environmental management systems as well as different voluntary programs to improve the scope and effectiveness of current regulations or reduce emissions in sectors in which formal environmental rules is lacking (Lee and Yik, 2004).

According to the literature several possible explanations have been offered for voluntarily participation in programs provided to decrease the quantity of emissions beyond levels needed by regulations. Voluntary approaches may lead to reduction in costs or enhance environmental reputation of firms. There are environmental arguments for strategically limiting emission using voluntary programs to show the environmental responsibility in order to reduce the possibility of being forced by regulators to implement future regulations. It is worth noting that voluntary approaches are the center of attention providing that they achieve environmental goals “in a more innovative manner” or “more quickly and at lower costs” than regulatory approach (Brouhle et al., 2009).

1.3.2 Green Manufacturing

Manufacturing is material-intensive, energy-intensive and usually water consumer. Environmental impacts of the manufacturing systems can be elaborated from the perspective of toxic chemicals, waste generation, energy consumption, and carbon emissions (Dornfeld, 2012). Over recent years, considerable attention has been on the concept of green manufacturing due to the increasing environmental concerns involved. In this regard, many countries, enterprises, and organizations focus on green issues and spend time and money to protect the environment.

Researchers from their own point of view can define green manufacturing, but one of the most widely used and effective definitions is the definition presented by Melnyk and Smith (1996): “a system that integrates product and process design issues with issues of manufacturing planning and control in such a manner as to identify, quantify, assess, and manage the flow of environmental waste with the goal of reducing and ultimately minimizing environmental impact while also trying to maximize resource efficiency.”

According to the flow of green supply chain management in Figure 1.1 considered by Barange and Agarwal (2016), the green manufacturing system consists of green suppliers, green material and green technology. It is important to remove environmental pollution from production process using technologies with low emissions or waste and replacing poisonous material and harmful fuels for the environment (Barange and Agarwal, 2016).

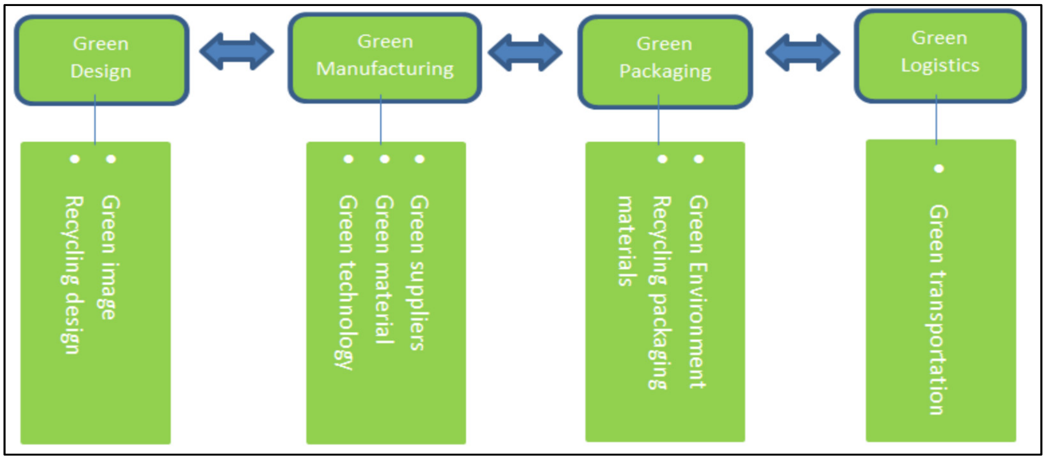

Figure 1.1 Flow of green supply chain management
Taken from Barange and Agarwal (2016, p.49)

Mostly manufacturing industries rely on particular materials, processes, or technologies to produce their products that may result in adverse environmental effects. The manufacturing system in most industries, including as electronics, pulp and paper, and plastics, is composed of machinery and facilities that produce a lot of carbon emissions (Huisingh et al., 2015). Some studies in the field of environmental technologies dealt with finding appropriate strategies for the technology investment. Li et al., (2010) presented a methodology for choosing a portfolio for green technology from the environmental strategy viewpoint. The aim was to help firms in effectively implementation of green manufacturing with limited environmental investment. Saberi et al., (2018) presented a multi-period supply chain in which minimizes the net present value of all manufacturers, retailers, and carriers considering ecologically friendly technology. They considered the trade-off between the initial investment in technology and its following ecological impact during the planning period. Hilson (2000) addressed the barriers to implement cleaner technologies and production in the mining industry and mineral processing activities. Moors et al., (2005) identified the barriers to implement clean technologies in the base metals production and aimed to design appropriate strategies towards cleaner production technologies in this industry. The most significant barriers for technology innovations seem to be the investment cost, the high risk of capital investment in technology, and the intertwinement of current system.

1.3.3 Integrating environmental considerations into manufacturing systems

Recently, researchers have shown an increased interest in production planning of manufacturing systems considering environmental aspects. They aim to manage the GHG emissions generated from the manufacturing process under carbon tax or cap and trade regulations. In this context, Letmathe and Balakrishnan (2005) proposed a mathematical model for determining optimal production quantities for manufacturing systems with a single operation method for each product under carbon tax and cap-and-trade regulations. They performed a number of scenarios to see what would happen if the emission tax and cap were changed. Hua et al., (2011) looked into the challenge of inventory management for companies using the carbon allowance trading mechanism. The optimal order quantity is calculated, and the impact of carbon trading, carbon price, and carbon caps on ordering decisions is investigated. The multi-item production planning problem with a carbon cap and trade mechanism is studied by Zhang and Xu (2013). To characterise the optimization problem, a profit-maximization model is developed. The best production strategy and carbon trading decisions are investigated, and an efficient solution approach with linear computational complexity is proposed for finding the best solution. To reduce total costs, Gong and Zhou (2013) suggested optimal production and carbon emissions trading strategies for a single product manufacturing system. The best allowance trading policy is a target interval policy with two thresholds that decrease as inventory increases. Under a carbon tax regulation, Fahimnia et al., (2015) proposed a tactical supply chain planning model that considers both economic and carbon emission objectives. The aim was to find tactical planning decisions, including production and distribution allocation strategies, in order to minimise overall supply chain cost and carbon emissions. He et al., (2015) addressed the problem of lot-sizing in manufacturing based on the economic order quantity (EOQ) for a corporation subject to carbon tax and cap-and-trade regulations. Zhou et al., (2016) formed a multi dynamic optimization model to find the best solutions for operational decisions in cap-and-trade manufacturing systems, such as purchasing carbon credits and carrying over surplus emissions. Xu et al., (2016) looked at how carbon taxes and cap-and-trade affect multi-product manufacturing enterprises' production and price. Du et al., (2016a) investigated the multi-product pricing and production problem under the assumption that environmentally conscious consumers place a higher value on low-carbon items than on regular products. Du et al., (2016b) looked at the impact of carbon emissions and low-carbon preferences on demand, market supply, and production decisions, and came up with an optimization model for cap-and-trade enterprises' production decisions. Wang et al., (2017) looked at the problem of manufacturing/remanufacturing planning in the context of cap-and-trade and used a downward substitution technique to find the best production quantity. Song et al., (2017) developed a two-stage stochastic model to find the optimal capacity expansion and production decisions for manufacturing firms under cap-and-trade and carbon tax regulations. The challenge of pricing and production for an upstream company producing two goods under cap-and-trade was the focus of Xu et al., (2017a). Xu et al., (2017b) looked at how a manufacturer and retailer in a supply chain should use cap-and-trade to make production and emissions reduction decisions. Yang et al., (2018) developed a cap-and-trade mathematical model to assist companies in deciding on green technology investment and emission permit trading. Wang et al., (2018) suggested a mathematical model to account for the impact of cap-and-trade on company production planning. They utilised cost-benefit analysis to determine the best plan for reducing emissions, choosing between buying carbon credits and implementing low-carbon technologies. Ghosh et al., (2018) concentrated on a two-echelon integrated supply chain with stochastic demand, which allows for both backorders and lost sales. To discover the optimal production rate, order amount, number of shipments, and reorder point while reducing overall costs, an unconstrained mixed integer non-linear programming problem is formulated and solved. Zhang et al., (2019) created evolutionary game models between manufacturers and governments in the context of dynamic carbon trading prices.

According to the literature, majority of researchers focused on environmental aspects of manufacturing systems without taking machine failures into account. Indeed, there has been relatively little research into considering environmental issues in dynamic stochastic context of the unreliable systems. In this vein, Ben-Salem et al., (2015a) presented the Environmental Hedging Point Policy (EHPP) as a novel expanded structure of HPP for unreliable systems under carbon tax regulation. In addition to inventory level feedback, extra emissions level feedback is used to determine production amounts. To manage overall emissions, the manufacturer must have an emissions limit above which he decides to stop the production process. Ben-Salem et al., (2015b) suggested an EHPP for controlling system maintenance, production, and emission rates while taking into account degradation phenomena. Ben-Salem et al., (2016) created a production and subcontracting control policy for unstable manufacturing systems producing under the carbon price. To control total generated emissions, the system can partially supply demand with an unreliable green subcontractor. Afshar-Bakeshloo et al., (2018) designed an EHPP for an unreliable manufacturing system that incorporates low-emitting technologies, after reaching a particular emission limit. By putting their proposed policy into action, they looked into carbon tax regulation as well as cap-and-trade. Under cap-and-trade regulation, Turki et al., (2018a) examined an optimal manufacturing/remanufacturing and inventory planning under random demand, random machine failures, and carbon constraint. In the case of a fixed carbon allowance pricing, if the carbon emitted is less than the cap, the additional allowances are sold by the manufacturer. Otherwise, he will be forced to purchase carbon allowances. According to the findings, a high allowance trading price or/and a lower cap will induce the system to recover returned products, remanufacture them, and thereby cut emissions.

Some researchers have explored analytical modelling of stochastic and dynamic production control problems. In this context, Hajej et al., (2017a) established an optimal maintenance and production control policy governed by a carbon tax, taking into account the impact of system deterioration in order to minimize total costs of production, emissions, inventories, and maintenance. Hajej et al., (2017b) proposed an ecological production, subcontracting, and maintenance policy for a failure-prone production system that is sensitive to deterioration and is regulated by a carbon price. Hajej et al., (2019) proposed an optimal maintenance and production policy for unreliable manufacturing/remanufacturing systems with subcontracting enforced by carbon tax. The subcontractor is regarded to assist either the manufacturing system or the remanufacturing system during the manufacturing process in order to reduce total emissions. Minimizing overall costs is used to create an economic plan for manufacturing, remanufacturing, subcontracting, and preventive maintenance.

1.4 Reverse logistics and closed-loop supply chain

Since sustainability has been defined, many enterprises have implemented strategies to reduce their environmental impacts, minimize their costs and improve workforce welfare to gain more competitive advantage in terms of sustainability performance (Neri et al., 2021). Faced with increasing sustainable concerns, many companies decided to practice reverse logistics starting from end users and collect used products and then attempt to manage end-of-life products through different decisions including recycling, remanufacturing, repairing and finally, disposing of some used products.

The definition of reverse logistics (RL) has been evolving over time. Rogers and Tibben-Lembke (1999) established the most widely used definition of RL as “the process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal”. In this way, the end-of-life products are collected from customers to be performed under appropriate recovery process (Soleimani and Kannan, 2015).

Iintegration of forward and reverse supply chain into a unique system has also introduced the concept of closed-loop supply chain (CLSC). A closed-loop supply chain management is defined by Guide and Van Wassenhove (2009) as the design, control, and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time. Forward activities may consist of product design, procurement, production, and sales, while reverse activities may include reverse logistics, sorting, recycling, remanufacturing, recovery, and re-selling (De Giovanni and Zaccour 2014). In recent years, managing closed-loop supply chains with remanufacturing has been an active area of research which will be addressed in the following sections.

1.4.1 Integration of manufacturing and remanufacturing

Indeed, there is no responsibility for returned products in the forward supply chain. The reverse supply chain, on the other hand, is aiming to think about returned products in the most environmentally responsible possible way. The enhancement of supply chains leads to a coordinated new methodology that simultaneously studies forward and reverse supply chains (Govindan and Soleimani 2017).

An increasing number of manufacturing companies are incorporating remanufacturing activities into their manufacturing systems as a result of market changes and newly enacted environmental legislation (Atasu et al., 2008). Van der Laan and Salomon (1997) addressed a stochastic inventory system including production, remanufacturing, and disposal processes. They extend the well-known push and pull strategy to regulate a system in which all returned products are remanufactured and no planned disposals are made. Tang and Teunter (2006) investigated the multi-product economic lot scheduling problem for a hybrid manufacturing and remanufacturing system, motivated by a case study of vehicle parts company. Teunter et al., (2008) looked at the topic of economic lot scheduling with two production sources: manufacturing and remanufacturing, both of which have their own dedicated lines. They found that devoting production lines to manufacturing and remanufacturing can result in significant cost savings and scheduling flexibility. In a similar vein, Francas and Minner (2009) investigated a multiproduct network design problem and concluded that configuring a flexible production site is more advantageous if all products are headed to the same market. They focused on capacity planning and the benefits of various network configurations for remanufacturing. Using a queueing theory-based method, Flapper, (2014) investigated the optimal scheduling for a hybrid single-product manufacturing/remanufacturing system with negligible setup time and costs. They proposed a manufacturing schedule that would reduce the average discounted long-term costs including manufacturing, remanufacturing, holding, and backorder costs. The model of recycled products that are considered with the minimum quality level in the manufacturing/remanufacturing system is examined by Guo and Ya (2015). A constant demand is met in this approach by manufacturing raw materials and remanufacturing recycled items that meet quality standards. Fang et al., (2017) focused on a hybrid manufacturing/remanufacturing system in which the optimal operation plan is determined by taking into account the costs, the uncertainty regarding recycling, demand substitution, capacity constraints, and component durability. With remanufacturing under service level limitations, Kilic et al., (2018) tackled the stochastic economic lot sizing challenge considering stochastic period demands and returns. They presented two heuristic methods to control manufacturing and remanufacturing operations using simple decision rules. Moreover, there are few studies shown interest in integrating remanufacturing with consideration of quality of returns. The following paragraphs will go over these works in further depth.

1.4.2 Integrating the quality of returns into remanufacturing

Variability in the quality of returns is a major issue for production planning and inventory management since the remanufacturing cost and processing time are directly dependent on quality condition of returns (Korugan et al., 2013). Recently, researchers have shown an increased interest in considering the quality of the returned product in the remanufacturing process. In this context, Souza et al., (2002) focused on production planning of remanufacturing activities considering three different quality categories for returned products, each requiring different remanufacturing methods. Similarly, Aras et al., (2004) explained that classifying returns according to their level of quality before the remanufacturing process could significantly reduce operating costs. The authors used the classification of returns to determine those requiring less remanufacturing effort and those of low quality in order to minimize the total cost. The work of Behret and Korugan (2009) went in the same direction by analyzing remanufacturing activities according to the level of quality of the returns. By considering three different categories of returns (good, average and bad which requires more remanufacturing efforts), the authors showed that the classification leads to significant savings, especially in the case of high rates of returns. Korugan et al., (2013) analyzed the impact of variation in quality returns on the remanufacturing process when the facility may be shut down either due to operational failure or production of low-quality units. Garg et al., (2015) merged the idea of a vehicle routing problem with the concept of a closed-loop supply chain. Repair, decomposition, and disposal are among the potential techniques for recovery. The rate of return for remanufacturing activities should be determined ahead of time in their task. It considered that incentive pricing should be changeable because the returns have different values depending on their quality. Guo and Ya (2015) investigated the optimal production strategy for a hybrid manufacturing/remanufacturing system where the return rate, buyback cost, and remanufacturing cost are all affected by the quality level. Jeihoonian et al., (2017) evaluated a closed-loop supply chain with reusing, remanufacturing, and recycling as recovery alternatives. They considered the unpredictability of returned product quality and modelled it using binary scenarios for each component and module. Maiti and Giri (2017) looked at recovery options using game theory. They set a minimum quality in their system based on remanufacturing costs; if the quality of returned products exceeded the minimum, they were sent to remanufacturing; otherwise, they were sold on the secondary market.

1.4.3 Environmental aspects of remanufacturing systems

The usage of natural resources and materials, particularly minerals and fossil fuels, has increased dramatically over the last century, resulting in resource scarcity (Kirsch 2020). There is no doubting that the industrial sector is a major contributor to environmental challenges such as greenhouse gas emissions, waste generation, and resource depletion (Yi et al., 2021).

Many countries around the world are struggling with the major problem of generating large quantities of waste which do not fit into natural cycles. In 2014, the total waste production of European Union (EU) was 2500 million tons, of which around 53% was not recovered, reused, or recycled. So, every year the EU economy loses great amounts of resources which can be secondary raw materials (Tomić et al., 2020). Over the last decades, waste-related regulations have been implemented by authorities and governments to force industries to take care of their End of Life (EOL) products. For instance, in 2003, EU passed the Waste Electrical and Electronic Equipment (WEEE) directives which required manufacturers to actively collect, recycle, and recover electrical goods (Romero-Hernández et al., 2018). Canada, Japan, China, and many states in the US also introduced WEEE-like legislations (Govindan et al., 2015). Furthermore, the EU and several national governments promoted the concept of circular economy (CE) to get valuable materials back into the economy. CE aims to maintain the value of the materials at each point in their product's life and minimize the generation of waste by closing the loop of materials through reusing, recycling, or remanufacturing (Pires and Martinho 2019).

In today's business environment, every year, a large number of products are returned as they are defective, damaged, or exchanged. Remanufacturing is an effective method to minimize the consumption of resources and generation of waste by extending product's useful life (Shekarian et al., 2021). Remanufacturing is a rather large business in the United States and Europe, due to its profitable business and environmental legislative pressure such as WEEE of the European Union (Östlin et al., 2008). Remanufactured products have a number of advantages than new products including up to 70% less raw materials required to produce and up to 50% less total production costs, and lower prices for consumers. Recently, the consumers′ purchase behavior towards remanufactured products has also been changed. Considering how reuse of products can add value to the society, the customers' willingness to pay for remanufactured products has increased (Wang and Hazen 2016). All in all, Remanufacturing offers a golden opportunity to deliver a sustainable future.

1.4.4 Integrating environmental considerations into manufacturing/ remanufacturing systems

there are few studies which dealt with the GHG emissions and serious environmental impacts of production process in manufacturing/remanufacturing systems regulated by carbon tax or cap and trade. In this context, Chang et al., (2015) investigated a monopolistic system under cap-and-trade legislation, in which new products are manufactured in the first period and new and remanufactured products are manufactured simultaneously in the second. In both independent and substitutable demand markets, the optimal production quantity is calculated for a two-period planning horizon. Shu et al., (2017) extended an economic order quantity (EOQ) model under cap-and-trade regulation considering GHG emissions from manufacturing, remanufacturing as well as transportation activities. The optimal batch sizes for manufacturing and remanufacturing are obtained with and without carbon constraint. Bazan et al., (2017) addressed a two-level closed-loop supply chain model involving a manufacturer and a retailer for remanufacturing of used/returned products under the carbon tax legislation. They reduced the total costs by taking into account GHG emissions from manufacturing and transportation, as well as the extension of a product's life cycle through recurrent recovery. Dou et al., (2019) addressed the production planning for a two-periods manufacturing/remanufacturing system under carbon tax regulation where tax price varies over the two periods. Selectively increasing the tax price by the regulator considering production decisions of manufacturer could effectively control total emissions. Singhal et al., (2019) studied how remanufacturing can assist electronics firms in achieving sustainable e-waste management goals by extending the life cycle of electronics devices. Chen et al., (2020) looked at a monopolistic remanufacturing system that was subjected to both take-back and emissions capacity regulations. The most profitable decisions for the remanufacturer are determined, and the environmental and economic consequences of legislation are explored. Shekarian et al., (2021) looked at the effects of remanufacturing and GHG emissions on a dual-channel closed-loop supply chain, both forward and reverse logistics, in the context of a collection competition. The effects of various dual-collection arrangements are investigated, considering the competitiveness between collector parties in three different scenarios: manufacturer-retailer, manufacturer-third party, and retailer-third party.

According to the literature, there are only few studies on production planning of failure-prone manufacturing/remanufacturing systems considering environmental aspects. Accordingly, a mathematical model for a failure-prone manufacturing and remanufacturing production problem under environmental constraints was presented by Salim et al., (2017). They obtained manufacturing and remanufacturing machine production plans, as well as the amount of emissions emitted throughout each production period. Turki et al., (2018a) addressed manufacturing/remanufacturing system production planning, considering the differences between new and remanufactured items, random customer demand, random machine breakdowns, and carbon emission limits. Turki et al., (2018b) proposed a model for manufacturing/remanufacturing systems that distinguishes between remanufactured and new items in order to achieve optimal production rates and storage capacities while optimising total profit. Under carbon tax legislation, Hajej et al., (2019) proposed a production and maintenance policy for failure-prone manufacturing/remanufacturing systems. During the manufacturing or remanufacturing process, a subcontractor is engaged to assist in the control of total emissions. Under environmental restrictions, Ndhaief et al., (2020) provided an economic and environmental production and maintenance plan for unreliable manufacturing/ remanufacturing systems.

1.5 Critical literature review and research motivation

The studies provided in the literature review has achieved very interesting results in terms of integrating the environmental considerations into the manufacturing systems. However, in response to the growing awareness of environmental issues, it is necessary to continue research around production planning for manufacturing systems considering environmental impacts. In this section, we present some limitations of the previous work.

To the best of our knowledge, majority of studies have used mathematical methods and analytical approaches to address such problems (e.g., Ma et al., 2010; He et al., 2015; Xu et al., 2016; Wang et al., 2017). Although these analytical approaches have yielded remarkable results, their considered models and hypotheses do not take the stochastic and dynamic characteristics of the manufacturing systems (failures, repair times, delivery time, etc.) into account. In the literature, the consideration of environmental aspects at an operational level of decision-making is relatively new. As a result, it is needed to broaden our understanding of the various phenomena that can influence decision-making.

Regarding unreliable manufacturing systems, the literature has shown that the critical threshold control policy has given better control of production systems, integrated with setup policy (e.g., Assid et al., 2014), quality control (e.g., Bouslah et al., 2013a), degradation phenomenon (e.g., Rivera-Gómez et al., 2013). According to the literature, a few critical threshold control policies have been proposed integrating with environmental aspects (e.g., Ben-Salem et al., 2015a; Ben-Salem et al., 2015b; Ben-Salem et al., 2016; Afshar-Bakeshloo et al., 2018). So, when it comes to environmental issues, a gap exists in the field of unreliable manufacturing systems, and our thesis takes that into account to provide more realistic and applicable solutions. In most industries, including electronics, pulp and paper and plastics, the manufacturing system consists of machines with a certain production capacity generating high levels of greenhouse gas emissions (Huisingh et al., 2015). Regarding the rules and regulations imposed by governments for each industry, many companies may need to apply green criteria to control the level of GHG generated. Companies such as Simons and Dell are willing to invest in green and low-carbon technologies allowing them to reduce their carbon footprints (Saberi et al., 2018). Advanced technology and energy improvement plans can be applied in different manufacturing systems. Advanced technology employed in low-emitting machines (LEMs) reduces the amount of energy these machines consume compared to high-emitting machines (HEMs). A case in point is the equipment driven by new energy-efficient motors which use less electricity. Hence, replacing HEMs with LEMs leads to considerable reduction in GHG emissions produced in industries (Wiebe, 2018; Wang et al., 2019).

Moreover, when it comes to environmental regulations, most research works studied the manufacturing systems regulated by the carbon tax. There has been little discussion about cap-and-trade which is one of the most business-friendly schemes at an operational level. The existing studies which focused on cap-and-trade have mostly addressed the effect of environmental regulations on production decisions minimizing total costs (e.g., He et al., 2015; Xu et al., 2016; Turki et al., 2018a; Zhang et al., 2019). Some studies have focused on how to comply with cap-and-trade and reduce GHGs generated from the production process (e.g., Du et al., 2016a; Zhou et al., 2016; Du et al., 2016b; Wang et al., 2017; Wang et al., 2018). However, far too little attention has been paid to developing allowance trading policies for the companies regulated by cap-and-trade. Production and trading control policies of unreliable manufacturing systems regulated by cap-and-trade scheme are still lacking which will be addressed in this thesis. For high emitting industries including concrete, steel, and car manufacturers, pulp and paper, as well as chemical facilities, it is a major challenge to rethink their operational decisions such as production quantities and carbon allowance trading under cap-and-trade. On the one side, it is important to know how to adjust the production plan considering the features of cap-and-trade. On the other side, it is important to know how to trade and decide whether and to what extent the carbon allowances should be sold or bought during the planning horizon to minimize total costs while decreasing emissions.

In case of inventory and production planning of closed-loop supply chains, some work studies paid attention to the environmental impacts of manufacturing/remanufacturing systems (e.g., Chang et al., 2015; Bazan et al., 2017; Singhal et al., 2019; Chen et al., 2020; Shekarian et al., 2021). However, they did not consider the stochastic and dynamic aspect of such systems like failures, repair times.

According to the literature, prior researchers that focused on production planning of failure-prone manufacturing/remanufacturing systems while considering environmental factors have not developed new production control policies. Turki et al., (2018a), Turki et al., (2018b), Hajej et al., (2019) and Ndhaief et al., (2020) used HPP and environmental hedging point policy (EHPP) that have been already developed by Ben-Salem et al., (2015a). Hence, there is a lack of production control policies for unreliable manufacturing/remanufacturing systems under carbon tax regulation aiming to control the GHG emissions. Furthermore, one major weakness of the existing studies is that there is no consideration of quality impact of returned products on emissions generated from manufacturing and remanufacturing systems. This key element will be considered in our thesis to better reflect the industrial reality. In today's business environment, many products are returned as they are defective, damaged, or exchanged. In many industry sectors such as aerospace, automotive, electrical and electronic equipment (EEE), mechanical engineering and medical equipment, remanufacturing is an effective method to minimize the consumption of resources and generation of waste by extending product's useful life (Zeballos et al., 2021). Regarding environmental concerns, many companies decided to practice reverse logistics by collecting used products and managing EOL products through decisions like recycling, remanufacturing, repairing, and disposing. In this vein, hybrid manufacturing/remanufacturing systems are designed to meet demand with both manufacturing of raw material and remanufacturing of returned products (Assid et al., 2021).

When it comes to energy intensive industries fuel switching is one of the most common strategies for decarbonization by reducing combustion emissions from energy sources. In cement industry, fuel switching from coal to natural gas can help reducing the carbon emissions and improving the environmental performance (Busch et al., 2022). The pulp and paper industry has responded to the need for energy transition by switching to bio-based fuels (Obrist et al., 2022). Replacing fossil fuels with hydrogen gaseous fuel and biofuels is a promising option to reduce GHG emissions from production process in global iron and steel industry (Fan and Friedmann 2021). According to the literature review provided for publications on fuel switching potentials in manufacturing systems, most studies discussed the environmental impact of fuel switching in different industries like power plants, iron and steel, cement, and material sector (e.g., Smyth et al., 2012; Rahman et al., 2013; Rehfeldt et al., 2020b). Among them, there are only a few studies determined the switching point between coal and NG for power plants (e.g., Delarue et al., 2008; Delarue and D'haeseleer 2008; Xin-gang et al., 2021). Moreover, consideration of environmental impact of fuel types at the operational level of decision-making is relatively new in the literature. Moreover, the fluctuation of natural gas price on production decisions will be considered in our study. In order to determine the switching point between coal and NG for power plants, Delarue and D'haeseleer (2008), considered a variable NG price. According to the literature, Onour (2009) analyzed the NG market and investigated the fluctuation of natural gas prices based on normal distribution and skewed-t distribution models. It is concluded that the normal distribution model better describes the dynamics of NG price volatility. Considering the fluctuation of NG price, here we assumed a variable NG price which follows a normal distribution.

1.6 General framework of the thesis

After providing the literature review in the previous sections, we focus in this section on defining the general framework of the thesis. Based on the analysis and criticism of the literature, we define the production system under study, research problem and objectives. Subsequently, the resolution approach and methodology, contribution as well as structure of the thesis are presented.

1.6.1 Production system under study

In this thesis, we focus on unreliable production systems in the context of environmental protection and control. Figure 1.2 shows the structure of the system under study. In the figure, each element is indicated by its name or function. The arrows symbolize the circulation of flows between entities including forward and reverse flow as well as emission flow.

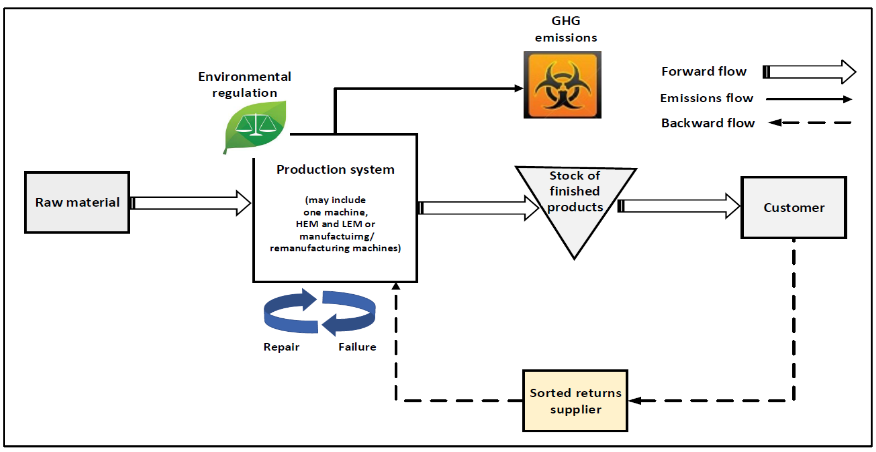

Figure 1.2 Structure of the system under study

The production system under study is subjected to random failures and repairs, producing a single type of product. Through this research, the production system may include one machine, or two machines (high-emitting machine (HEM) and low-emitting machine (LEM) or manufacturing/remanufacturing machines). The system is supplied by the infinite raw material. In case of manufacturing/remanufacturing system, the manufacturing machine produces using the raw material, and the remanufacturing machine produces using returns. Customer demand is met from inventory stock of finished products.

In practice, production often has serious impacts on the environment. Moreover, the system is enforced by environmental regulations (carbon tax or cap and trade). We therefore admit that the production process generates polluting GHG emissions which can result in additional costs for the company. As part of this work, the decision-making aspect is defined considering not only the level of inventory, but also the emissions generated by the system.

1.6.2 Research problem

After reviewing the literature, the issue of managing manufacturing systems in a context of environmental protection has not been sufficiently studied from an operational point of view. As a result, a number of questions have been raised in relation to this topic:

What production policies can adequately control a manufacturing system in a stochastic context considering the environmental aspect? What are the effects of considering this aspect on production/ inventory planning? When it comes to environmental issues, how companies can work with high-emitting machine (HEM) and gradually invest in low-emitting machine (LEM)? What is the most cost-effective plan to synchronize HEM and LEM? Is it better to use the HEM and LEM simultaneously or not? How much safety stock should be kept?

How can companies adapt their production plans and decide on trading in the carbon market to meet both environmental and economic goals? Which production control policy, under cap-and-trade regulation, can be the most effective in terms of cost and emissions reduction for managing failure-prone manufacturing systems? What is the best level of inventory to avoid backorders? What is the best trading strategy? In light of varying carbon prices, how much, when, and under what conditions should carbon allowances be sold or bought?

In a real industrial environment, what are the phenomena to be considered in closed-loop supply chain and which may have a direct link with generated GHG emissions? For example, can the quality of returned products have an impact on the emissions generated by the production system? What are production plans and decisions at the operational level to be taken in face of such a phenomenon (quality impact of returns on emissions)? How should the company manage the varying quality returns? What is the environmentally friendly, cost-effective plan for determining the condition and percentage of time manufacturing or remanufacturing should be employed to meet demand? When and at what rate should the system produce using manufacturing or remanufacturing machine, or both? When should remanufacturing switch between high-quality and low-quality returns? What are the optimal levels of safety stock for manufacturing and remanufacturing?

What are the challenges of companies consuming high-emitting fuels for production? How can they take advantage of switching option to a cleaner fuel to reduce emissions? What is an appropriate plan for the condition and percentage of time that each fuel type (high-emitting and low-emitting) should be used for production? How the fluctuation of NG price affects the production decisions? When and with what rate should the system produce using each fuel type? When and at which NG price should the system switch between high- and low-emitting fuels? What are the optimal safety stock levels for manufacturing?

In the following paragraph, we will present the objectives of our research project in order to answer these research questions.

1.6.3 Research objectives

The main objective of this research is to study unreliable manufacturing systems that generate emissions with consideration of environmental aspects. In a dynamic and stochastic context of failure-prone manufacturing systems, we will propose production control policies that take the emissions generated in the production process into account. Thus, this thesis includes in-depth studies that can help decision-makers at an operational level, to better adapt with environmental requirements, as follows:

First, we will study an unreliable manufacturing system that generates emissions under carbon tax regulation. a new production control policy structure will be proposed in order to gradually invest in the LEM minimizing total cost while simultaneously reducing GHG emissions. Our objective is to help the manager to synchronize HEM and LEM and define when to work with both machines and when to work with only one machine. Our developed policies support the manufacturing companies to transit from HEMs to LEMs.

Second, we will study failure-prone manufacturing systems regulated by cap-and-trade. Considering the random variation of carbon price, we will develop a new joint production and trading policy for such systems. Our objective is to guide the decision maker to jointly determine when to buy/sell carbon allowances or increase/decrease the production rate to minimize the total cost and reduce carbon emissions of the system.

Third, we will integrate the environmental considerations into failure-prone manufacturing/remanufacturing systems. This work considers the impact of returns' quality on the amount of GHG emissions generated by the system. Two new production control policies will be developed for unreliable manufacturing/remanufacturing systems considering variant emitting levels for high- and low-quality returns. Our objective is to help the manager in synchronizing manufacturing and remanufacturing together to minimize total costs while reducing GHG emissions, under carbon tax regulation.

Fourth, we will focus on the production problem of failure-prone companies which consume high-emitting fuel and have tendency to reduce emissions by switching to a cleaner fuel type. New joint production and fuel switching policies will be developed for such companies under carbon tax regulation to minimize total costs while reducing GHG emissions.

To solve the problem in each of the studies mentioned above, we used an experimental resolution approach which will be explained in detail in the following section.

1.6.4 Methodology and resolution approach

In the literature, several approaches have been developed to provide better control and management of unreliable manufacturing systems. Feedback policies are among the topics that have attracted the interest of several researchers. Among these, Kimemia and Gershwin (1983) introduced the concept of hedging point policy (HPP). Under this policy, an optimal level of inventory named the hedging point is maintained during times of system availability in order to hedge against future system capacity shortages caused by failures. Akella and Kumar (1986) obtained an analytical solution to the Hamilton-Jacobi-Bellman (HJB) equations in the case of a single machine that produces only one sort of product subject to random failure and repair times. They found the hedging point which minimizes total costs. Their work was limited to constant demand rates and exponential machine failure and repair time distributions. However, Gharbi and Kenné (2000) extended the HPP to non-exponential failure and repair time distributions and/or random demand rate models using a simulation-based experimental approach. The use of simulation has been justified by the difficulties of applying the classical control theory for the non-Markovian models. This approach was also used in the work of Gharbi et al., (2011).

The concept of HPP evolved in order to address more complex systems (several machines, several products and etc.) which makes analytical resolution very complicated. Indeed, it is difficult for analytical models to properly handle the detail and complexity of such failure-prone manufacturing systems. So, considering the mathematical limits of analytical resolution, development of other methods should be taken into account. Simulation optimization is also an important methodology to solve real problems that are generally more complex, of large size, dynamic and stochastic. In this regard, Kenné and Gharbi (2001) proposed a new simulation based-optimization resolution approach combining analytical model, simulation experiments, experimental design, and response surface methodology (RSM) for a multiple machine multiple product system with no restriction to constant demand rate and exponential failure and repair rates. As it was difficult to obtain the analytical resolution of the HJB equations, some researchers solved them using a numerical approach to determine the structure of the optimal production policies (e.g., Lavoie et al., (2007); Bouslah et al., (2013); Assid et al., (2020); Assid et al., (2021); Dhahri et al., (2022b)). They developed a stochastic dynamic programming model representing the system based on the control theory. Then, using a numerical approach, they solved the obtained HJB equations. Later, Bouslah et al., (2013a) and Assid et al., (2014), Ben-Salem et al., (2015a), Ben-Salem et al., (2015b), Ben-Salem et al., (2016), Afshar-Bakeshloo et al., (2018), Assid et al., (2019a) adapted the experimental approach by proposing heuristic near-optimal control policies based on the previous work. The approach has been shown to be effective in dealing with the control problems of unreliable manufacturing systems when analytical resolution is difficult to apply. Considering the complexity of our systems under study, we implement an experimental resolution approach combining simulation, experimental design, and response surface methodology in this thesis. The different stages of the approach are as follows:

- ✓ step 1: Production control policy description

The structure of the production control policy to be applied for the manufacturing system will be presented by mathematical equations.

- ✓ step 2: Simulation model and validation

A simulation model will be developed using “ARENA” software to display the dynamic behavior of the system. It is assumed that time to failure and time to repair follow exponential distribution where the system states can be described by Markovian processes. However, the simulation model as an effective way to mimic the behavior of the system is used to accept any probability distributions. The model is therefore applicable when studying real-world problems, as the simulation model can be adapted to represent most of the characteristics of the system in question without any mathematical limitations.

In theory, discrete event simulation can attain any precision level in performance measures. Increasing the length of the runs results in increased precision. Also, discrete event simulation does not require any restrictive assumptions, such as particular types of probability distributions of random processes. However, discrete simulation model is sometimes considered too time-consuming. In this thesis, for each control policy, we develop a combined discrete-continuous simulation model. The advantage of using a combined discrete-continuous model is to reduce the execution time compared with discrete models (Lavoie et al., 2007), and to model accurately the real production and inventory dynamics of the manufacturing system. The simulation model will use the control policy defined in the previous step as input to conduct experiments to assess the efficiency of the production system. Thus, for given values of the control factors, the total cost will be obtained.

- ✓ step 3: Design of experiment and the analysis of variance

The number of experiments and the levels for each independent variable will be defined to carry out several experiments. Then, analysis of variance (ANOVA) is implemented to indicate the effect of control parameters as well as their interactions on total costs in order to specify the main independent variables.

- ✓ step 4: Response surface methodology and optimization of control parameters

The response surface methodology will then be used to identify the impact of significant main control parameters, their quadratic effects as well as their significant interactions given in the previous step, on total costs. Using a combination of design of experiment (DOE), RSM and the regression analysis, the total costs approximation function will be provided. The model will be optimized to determine the best combination of the parameters of the control policy which minimizes the total cost.

- ✓ step 5: Validation of RSM model

To validate the RSM model, according to Myers et al., (2016), three steps are followed.

1. To begin, the adjusted R-squared coefficient is used to assess the RSM model's overall performance. The adjusted R-squared coefficient indicates how much of the total variation in total costs can be explained by the RSM model's independent variables. It is true that an adjusted R-squared close to 1 is preferable.

2. Second, a residual analysis is performed to ensure residual normality and homogeneity of variances.

3. Third, after optimising the RSM, we calculate a confidence interval of 95% and perform a Student's t-test to double-check the model's validity. We run the simulation model for a larger number of replications, using the optimal control parameter value as an input. Within the confidence interval, the optimal total cost should be found.

- ✓ step 6: Sensitivity analysis

Sensitivity analyses will be provided to evaluate our proposed control policy and the robustness of our considered resolution approach.

- ✓ step 7: Comparative study

To determine the most cost-effective and environmentally friendly production control policy, a comparison between the proposed control policy and an adaptation of the most relevant control policies from the literature for a broad range of system and cost parameters will be made.

1.6.5 Contributions and structure of the thesis

This thesis has provided original scientific contributions to the research on production planning and control for failure-prone manufacturing systems considering environmental aspects. In this sense, it has been the subject of three journal articles. The structure of the rest of the thesis consists of three chapters which form the heart of our work. Each chapter represents one of our articles.

In the second chapter, our article addresses the production planning problem of unreliable manufacturing systems including a high-emitting machine (HEM) which gradually invests in low-emitting machine (LEM). The main objective of this work is to establish new optimal control policies specifically designed for companies aiming to gradually invest in LEM to minimize total cost while simultaneously considering environmental aspects. under our new cost-effective control policies, the HEM and LEM are allowed to operate simultaneously, and the optimal solution defines when to work with both machines and when to work with only one machine. We aim to improve the availability of the system by increasing the LEM usage and improve the performance of the system by reducing the emission, backlog, inventory as well as total costs. This article is published in the Journal of Cleaner Production with the following citation:

Entezaminia, A., Gharbi, A., & Ouhimmou, M. (2020). Environmental hedging point policies for collaborative unreliable manufacturing systems with variant emitting level technologies. *Journal of Cleaner Production*, *250*, 119539.

In the third chapter, our article deals with the production planning and trading problem of failure-prone manufacturing systems regulated by cap-and-trade. Our contribution is to develop a new joint production and trading policy for the stochastic context of unreliable manufacturing systems considering the random variation of carbon price. Our policy helps the manager to use an effective dynamic plan to identify when to increase/decrease the production rate or sell/buy carbon allowances. Our proposed control policy has wide-range implications for the high emitting companies under cap-and-trade who are willing to simultaneously minimize total costs and reduce emissions. This article is published in the Journal of Cleaner Production with the following citation:

Entezaminia, A., Gharbi, A., & Ouhimmou, M. (2021). A joint production and carbon trading policy for unreliable manufacturing systems under cap-and-trade regulation. *Journal of Cleaner Production*, *293*, 125973.

In the fourth chapter, our article addresses the production planning problem of failure-prone manufacturing/remanufacturing systems with variate quality returns under carbon tax regulation. This article will find its originality by simultaneously integrating several key elements to better reflect industrial reality. These elements refer to the complexities related to returns (such as returns' quality), the quality impact of returns on generated GHG emissions as well as aspects associated with stochastic events (random failure and repair times). Our contribution is to provide an environmentally friendly cost-effective plan determining the condition and percentage of time manufacturing or remanufacturing should be used to satisfy the demand. Our new production control policy helps the decision maker in synchronizing manufacturing using raw material and remanufacturing using high- and low-quality returns together to minimize total costs while simultaneously reducing emissions generated. This article entitled “Environmental production planning of unreliable manufacturing/remanufacturing systems considering quality impact of returns under carbon tax regulation” was submitted in the Journal of Computers & Industrial Engineering, in May 2022.

In the fifth chapter, we focus on unreliable manufacturing systems that use high-emitting fuel (such as coal) and intend to reduce their GHG emissions by shifting to a cleaner fuel (such as natural gas (NG)). Although using a cleaner source of energy reduces carbon emissions, it comes at the cost of higher fuel prices. In our research, we also take into account the random fluctuations of NG price. We aim to develop environmental production control policies for failure-prone manufacturing systems with the possibility of fuel switching to minimize total costs while reducing emissions. In this vein, two production control policies are developed to achieve both economic and environmental goals. Based on our proposed policies, decisions on fuel switching depends on the market state including the random fluctuation of NG price, and the key elements of the system consisting of its state, inventory, and emissions level. Our proposed policy 1 could reduce emissions while minimizing total cost of the system including inventory, backlog, fuel, and emissions costs. An extension of policy 1 is also proposed, under which a lower inventory threshold level is considered for production using coal when emissions level is high. This article entitled “Production planning of failure-prone manufacturing systems in the context of emissions reduction by fuel switching” is submitted in The International Journal of Production Economics in September 2022.

We end this thesis with a general conclusion which summarizes the results of this work and presents the research perspectives.

1.7 Conclusion

A critical review of the existing literature was provided in this chapter. First, a general definition of flexible and unreliable manufacturing systems and the relevant production control policies were presented. We addressed the environmental aspects of manufacturing systems, environmental regulations, and green manufacturing. A literature of manufacturing systems considering environmental aspects and its limitations were provided. We also focused on a general definition of reverse logistics and closed-loop supply chain. Then, we studied the integration of manufacturing and remanufacturing, quality of returns, as well as environmental aspects of remanufacturing. A literature of manufacturing/remanufacturing systems considering environmental aspects and the existing gaps of this area were provided. Finally, the system under study is defined and research objectives, contributions, methodology and resolution approach as well as thesis' structure were discussed.

CHAPTER 2

ENVIRONMENTAL HEDGING POINT POLICIES FOR COLLABORATIVE UNRELIABLE MANUFACTURING SYSTEMS WITH VARIANT EMITTING LEVEL TECHNOLOGIES

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Paper published in *Journal of Cleaner Production*, March 2020

Abstract

As the main cause of environmental problems, GHG emissions generated by industrial activities are necessary to be reduced. In order to meet strict environmental regulations and make production cleaner, a large number of enterprises operating with high-emitting machines (HEMs) are gradually investing in low-emitting machines (LEMs) instead of undertaking costly replacements of all their HEMs. Recently, in a stochastic dynamic context, a control policy was developed to control such systems in which the HEM and LEM are not operating simultaneously (NOS). In this paper, as an extension to this base policy, we start by proposing a more efficient control policy for NOS systems. Our main objective is to develop new cost-effective and environmentally friendly control policy for the enterprises aiming to gradually invest in the LEM and help the manager to synchronize HEM and LEM together. So, we develop two new additional policies in which both HEM and LEM can operate simultaneously (OS) to increase the availability of the entire system and simultaneously reduce inventory, backlog and emissions generated. To determine the optimal parameters of these control policies, simulation modelling, an experimental approach, and response surface methodology are applied. Finally, several experiments are conducted to carry out comparisons between the policies based on a wide range of cost and system parameters. The results show that the new developed control policies for OS systems bring significant cost savings and GHG emission reductions as compared to the NOS systems.

Keywords: Control policy, environmental hedging point policy, unreliable manufacturing system, greenhouse gas emissions, low-emitting technology, simulation optimization.

2.1 Introduction

Worldwide, the last thirty years have seen an increase in awareness of the devastating impacts of global warming and greenhouse gas emissions (GHGs) on the environment and on the earth's climate system. Fundamentally, it is critical to control emissions and pollution to preserve the earth as well as its valuable resources. Faced with social and economic pressures, authorities try to limit GHG emissions of the industrial sector by enacting and enforcing strict rules and regulations. For their part, companies should focus on seeking new strategies to respond to environmental concerns and meeting green criteria in order to gain a competitive advantage (Shrivastava 1995).

Emission control approaches generally fall under various categories. According to Benjaafar et al., (2012) and Chen et al., (2013), emission control approaches can be divided into two categories, namely, regulatory and voluntary. With regulatory approaches, a specific limit is set by the government and authorities for GHG emissions generated by different industries to control their devastating effects. Interest in the implementation of voluntary approaches such as those involving environmental management systems and different voluntary programs to improve the scope and effectiveness of current regulations has increased in recent years (Lee and Yik, 2004). It is worth noting that voluntary approaches are attractive because they achieve environmental goals "in a more innovative manner" or "more quickly and at lower costs" than regulatory approaches (Brouhle et al., 2009).

There is no denying the fact that manufacturing systems have been among the biggest consumers of energy from unsustainable sources, resulting in such environmental issues caused by carbon dioxide and other greenhouse gas emissions (Shu et al., 2017). Applying greenness to production systems must therefore be prioritized. In this context, a commonly used approach to tackle environmental issues involves decreasing GHG emissions related to physical system processes. For instance, manufacturing companies are providing more environmentally-friendly facilities, using less polluting energy sources, providing energy saving policies, redesigning products and packaging based on green criteria (Chen et al., 2013).

In most industries, including electronics, pulp and paper and plastics, the manufacturing system consists of machines with a certain production capacity generating high levels of greenhouse gas emissions (Huisingh et al., 2015). Regarding the rules and regulations imposed by governments for each industry, many companies may need to apply green criteria to control the level of GHG generated. Companies such as Simons and Dell are willing to invest in green and low-carbon technologies allowing them to reduce their carbon footprints (Saberi et al., 2018). Advanced technology and energy improvement plans can be applied in different manufacturing systems. Advanced technology employed in low-emitting machines (LEMs) reduces the amount of energy these machines consume compared to high-emitting machines (HEMs). A case in point is the equipment driven by new energy-efficient motors which use less electricity. Hence, replacing HEMs with LEMs leads to considerable reduction in GHG emissions produced in industries (Wiebe, 2018; Wang et al., 2019).

Investment in new advanced technologies which are more energy efficient is costly for companies and replacing all HEMs with LEMs require significant investments. To achieve greenness, companies cannot simply replace all HEMs and transit to LEMs in one swoop because economic objectives must be considered alongside environmental ones. Moreover, some machines may not be fully depreciated, making replacing them economically unjustified. In such situations, it is more economical to continue using them and then make gradual investments in new low-emitting machines over an extended period of time. Companies will thus prefer to change the manufacturing system gradually, and to use a combination of the HEM and LEM. This therefore allows instruments of different forms to be used to provide significant environmental protection without dramatically increasing operating costs.
To emphasize the benefits of this transition, it should be noted that shifting to LEMs increases the LEM usage and provides greater production capacity. In this way, improvement in the system availability leads to a reduction in backlog and inventory costs. Moreover, as the usage

percentage of the LEM increases, the incurred emission decreases. Therefore, reduction in inventory, backlog and emission costs results in total cost decrease.

On the other hand, one of the key performance indicators for sustainable manufacturing evaluation is emissions generated by the manufacturing systems. Advanced green technologies like LEMs which are more energy-efficient are among the key ingredients in providing large-scale sustainable production (Sezen and Cankaya, 2013; Niaki et al., 2019). Transition to LEMs and reducing the GHG emissions helps the companies to reduce the environmental impacts and improve the sustainability performance of the system.

Among companies that gradually invest in LEM, one of the biggest challenges they must tackle is finding an effective plan for the condition and percentage of time that the LEM should be used for manufacturing. Production control policies are developed in order to help the manager to decide when to operate each machine and determine the speed of producing with each one. Producing with HEMs generates a huge amount of emissions; however, LEMs results in fewer GHG emissions. In this regard, control policies have direct impact on the emission generated by the manufacturing systems. However, operating the LEMs leads to higher production cost, higher maintenance time and cost and time and lower power (Augustine et al., 2011). That is the reason why developing optimal control policies is important to find the best periods that LEM should operate. Therefore, to achieve both their economic and environmental goals, such companies must therefore formulate best possible control policies to minimize total costs while simultaneously addressing environmental matters.

Most studies on the problem of production planning of manufacturing systems with environmental considerations focused on deterministic context without considering the unreliability of machines (Ma et al., 2010; He et al., 2015; Xu et al., 2016; Wang et al., 2017). Some of these research works focus on the dynamic and stochastic contexts of manufacturing systems (Ouelhadj and Petrovic, 2009; Barbosa et al., 2015; Framinan et al., 2019). However, when it comes to environmental and green issues, a gap exists in the field of unreliable manufacturing systems, and our paper takes that into account in a bid to provide more realistic and applicable solutions. Our study has potentially wide-ranging implications for the unreliable manufacturing systems that work with the HEM and aim to invest in the LEM in a gradual fashion. Consequently, the main research questions in our paper are as follows: What is the most cost-effective control policy to manage this unreliable production system? Is it better to use the HEM and LEM simultaneously or not? What is the optimal safety stock level (threshold level)? We aim to find the optimal control policy for the unreliable manufacturing system owned by enterprises that are willing to invest in the LEM gradually to minimize total cost.

The remainder of the paper is organized as follows: Section 2.2 presents the literature review. Section 2.3 is devoted to the problem statement. The formulation of a proposed control policy for the HEM and LEM not operating simultaneously (NOS) and a resolution approach are respectively provided in Sections 2.4 and 2.5. Simulation model is presented in Section 2.6. Description of proposed control policies for the HEM and LEM operating simultaneously (OS) is addressed in Section 2.7. Numerical results and comparison between policies are provided in Section 2.8. Finally, concluding remarks and future research work are presented.

2.2 Literature review

A summary and classification of the literature review related to our work, including the control policies for unreliable manufacturing systems (Class 1) and models for manufacturing systems considering environmental aspects (Class 2) are presented in Table 2.1. In Class 2, the manufacturing systems that consider the environmental aspects are classified into the deterministic context and stochastic context. The deterministic context is related to the manufacturing system models that do not consider unreliability of the machines and stochastic context is relevant to the models that consider failure-prone manufacturing systems.

Table 2.1 Overview of the state of the art for manufacturing system control policies and models considering environmental aspects

Authors	Hedging Point Policy (HPP)	Multiple Hedging Point Policy (MHPP)	Environmental Hedging Point Policy (EHPP)	Failure-prone/ Stochastic context	Regulatory environmental approach	Voluntary environmental approaches	NOS systems[1]	OS systems[2]	No constraint on hedging level
Class 1: Unreliable Manufacturing system control policies									
(Kimemia and Gershwin, 1983)	✓			✓					
(Akella and Kumar, 1986)	✓			✓					
(Kenné and Gharbi, 2000)	✓			✓					
(Gharbi et al., 2008)	✓	✓		✓					
(Pellerin et al., 2009a)	✓	✓		✓					
(Pellerin et al., 2009b)	✓	✓		✓					
(Gharbi et al., 2011)	✓	✓		✓					
(Hajji et al., 2011)	✓	✓		✓					
(Ouaret et al., 2013)	✓	✓		✓					
(Bouslah et al., 2013a)	✓	✓		✓					
(Bouslah et al., 2014)	✓	✓		✓					
(Polotski et al., 2017)	✓	✓		✓					
(Rivera-Gómez et al., 2018)	✓	✓		✓					
(Assid et al., 2019a)	✓	✓		✓					
Class 2: Manufacturing system models considering environmental aspects									
Category 1: Models with deterministic context without considering the unreliability of the machines									
(He et al., 2015)					✓	✓			
(Du et al., 2016a)					✓				
(Du et al., 2016b)					✓		✓		
(Xu et al., 2016)					✓	✓			
(Wang et al., 2017)					✓	✓			
(Dou et al., 2019)					✓				
Category 2: Models with stochastic context with considering unreliability of the machines									
(Ben-Salem et al., 2015a)	✓	✓	✓	✓	✓	✓			
(Ben-Salem et al., 2015b)	✓	✓	✓	✓	✓	✓			

Authors	Hedging Point Policy (HPP)	Multiple Hedging Point Policy (MHPP)	Environmental Hedging Point Policy (EHPP)	Failure-prone/ Stochastic context	Regulatory environmental approach	Voluntary environmental approaches	NOS systems[1]	OS systems[2]	No constraint on hedging level
(Ben-Salem et al., 2016)	✓	✓	✓	✓	✓	✓			
(Hajej et al., 2017a)				✓	✓				
(Hajej et al., 2017b)				✓	✓				
(Afshar-Bakeshloo et al., 2018)	✓	✓	✓	✓	✓	✓	✓		
(Hajej et al., 2019)				✓	✓				
This paper	✓	✓	✓	✓	✓	✓	✓	✓	✓

[1]NOS systems mean that at each moment, only one machine, either the HEM or LEM, can operate.
[2]OS systems mean that the HEM and LEM are allowed to operate simultaneously.

A comparison is made among relevant studies in the literature in terms of certain criteria, such as the type of control policies for manufacturing systems, failure-prone systems, environmental approaches, NOS and OS systems, and constraints on the hedging level. In the rest of this section, we focus on the literature review and underline our contributions.

When it comes to failure-prone manufacturing systems, there has always been an increasing interest in feedback control policies. Class 1 includes control policies developed for unreliable manufacturing systems. Based on the literature review, after the pioneering study by Kimemia and Gershwin (1983) over the past century this field of study has been investigated by many researchers. One of the most effective and widely used strategies in a dynamic stochastic environment is the hedging point policy (HPP) (Akella and Kumar, 1986). Hedging point policy aims to control the production rate based on the level of inventory as a function of the state of the system, and to build a specific safety stock level (threshold level) to satisfy customer demand during failure periods.

In recent years, considerable attempts have been made to extend this control policy to other manufacturing contexts. The multiple hedging point policy (MHPP) has been proposed in unreliable manufacturing systems integrating remanufacturing, subcontracting, quality control, etc., to control the production rate. Gharbi et al., (2008) proposed an MHPP model defined by two threshold levels related to two different repair rates. A Multiple Hedging Point Policy was also developed by Gharbi et al., (2011) and Hajji et al., (2011) for multiple state manufacturing systems. Pellerin et al., (2009a) considered the MHPP model for unplanned demand in multiple production rate remanufacturing systems to decide on partial or full replacement alternatives. Pellerin et al., (2009b) developed a sub-optimal MHPP for manufacturing and remanufacturing systems covering unplanned demand in order to devise an effective repair, replace, inspect-repair plan. Ouaret et al., (2013) presented an MHPP for hybrid unreliable manufacturing/remanufacturing systems under diffusion-type demand. Polotski et al., (2017) proposed an MHPP optimization in a stochastic dynamic environment for a one-part type hybrid manufacturing/remanufacturing facility with setup. Bouslah et al., (2013a) took into account the process and product quality integrated into production planning. MHPP was investigated by Bouslah et al., (2014) in order to determine the economic production and sampling policy. Rivera-Gómez et al., (2018) proposed a multiple hedging point policy to simultaneously deal with the production, subcontracting, and maintenance policies, and Assid et al., (2019a) developed a production control problem within hybrid manufacturing-remanufacturing systems.

Class 2 includes manufacturing system models that considered environmental aspects. In the first category, some studies considered the deterministic context for manufacturing systems, and applied green principles by following regulations imposed by authorities or different kinds of voluntary approaches. He et al., (2015) examined the production lot-sizing issues of a company under cap-and-trade and carbon tax regulations based on the economic order quantity (EOQ) model. Xu et al., (2016) studied the joint production and pricing problem of a manufacturing company under carbon tax regulations and cap and trade and compared the effects of these regulations on total profits and total carbon emissions. Du et al., (2016a) dealt with the impact of carbon footprint and low-carbon preference on the production decisions of emission-dependent companies in the cap-and-trade system. Du et al., (2016b) focused on manufacturers aiming to decide whether to reduce their emissions by employing low-carbon technologies. They found that cap-and-trade regulation would curb the total carbon emissions, in addition to promoting low-carbon production under specific conditions. Wang et al., (2017) focused on manufacturing/remanufacturing planning issues; they presented mathematical models to determine the optimal production quantities of a new and remanufactured product to maximize the firm's profits considering carbon emission cap and trade. Dou et al., (2019) proposed a two-period manufacturing/remanufacturing production planning under carbon tax regulation.

To deal with the stochastic and dynamic situations of manufacturing systems, different strategies have been developed. In that context, some works have focused on the analytical modeling of the stochastic production control problem. Hajej et al., (2017a) and Hajej et al., (2017b) proposed manufacturing strategies that integrate both economic and ecological aspects under carbon tax regulation. Hajej et al., (2019) presented a new production and maintenance strategy considering environmental aspect by proposing a solution based on subcontracting. However, feedback control policies can be considered as ranking among the most effective strategies. Of these policies, HPP is widely used to deal with random events (such as breakdowns, random demand, etc.). For several years, great effort has been devoted to studying the implementation of the hedging point policy in different aspects of manufacturing systems. However, there has been relatively little research into considering environmental issues in dynamic stochastic systems. In this regard, the second category focused on studies developed the environmental hedging point policies (EHPP) for unreliable manufacturing systems.

As part of the environmental hedging point policy (EHPP) proposed by Ben-Salem et al., (2015a), after exceeding the emission limit, they decreased the usage of the machine by reducing the threshold level in order to control the GHG level and minimize expected overall cost. In another study, Ben-Salem et al., (2015b) extended a production and preventive maintenance policy for the manufacturing system in which the emission rate increases due to degradation phenomena. Ben-Salem et al., (2016) extended the EHPP to tackle the issue of the

GHG limit being exceeded by stopping the main manufacturing system after a specific level of emissions and then outsourcing work to a green subcontractor. The closest work to our paper is Afshar-Bakeshloo et al., (2018), in which an environmental hedging point policy (EHPP) was developed for the HEM and LEM not operating simultaneously (NOS), with the constraint that the LEM threshold level should be less than that for HEM; when the total emission level exceeds its set limit, the policy stops the HEM and switches to the LEM.

The provided literature review focuses on two aspects. First, we addressed the unreliable manufacturing systems and the relevant control policies developed for such dynamic and stochastic context. In this regard, there are a few papers focused on environmental aspects to develop production control policies for failure-prone manufacturing systems. On the other hand, when we addressed the manufacturing system models considered environmental regulations like tax-based regulation and cap-and-trade, most of the studies focused on deterministic context without considering the unreliability of the machines. Therefore, according to the literature, still there is a gap of production control policies for unreliable manufacturing systems under environmental regulations aiming to reduce GH emissions.

The current studies which developed control policies for unreliable manufacturing systems considering environmental aspects focused on emission reduction by reducing the machine usage, stopping the high-emitting machine then calling green subcontractor, and stopping the high-emitting machine then operating with low-emitting one. According to existing policies the manufacturing system should stop operating with high-emitting machine after reaching a certain level of emission. None of the current developed control policies are appropriate for our problem which deals with the companies gradually invest in LEMs and need to synchronize HEMs and LEMs together.

Our contribution is to develop new optimal control policies specifically designed for companies aiming to gradually invest in the LEM to minimize total cost while simultaneously considering environmental aspects. New cost-effective control policies are developed in which the HEM and LEM are allowed to operate simultaneously (OS) until reaching a certain inventory level. Moreover, our developed control policies help the manager to synchronize HEM and LEM together to reach defined objectives, minimizing total costs and reducing emissions. The optimal solution defines when to work with both machines and when to work with only one machine. Our objective is to improve the availability of the system by increasing the LEM usage and improve the performance of the system by reducing the emission, backlog, inventory as well as total costs. Our developed policies support the manufacturing companies to transit from HEMs to LEMs. Based on the results, our policies could lead to considerable cost and emission reduction and outperform the current relevant policies which are not adapted to our system. Therefore, we develop more cost-effective and environmentally friendly production control policies for the companies operating with LEM and HEM.

2.3 Problem statement

2.3.1 Notations

The following notations are used in the rest of this paper:

$x(t)$	inventory/backlog level at time t
$e(t)$	emission level at time t
$\alpha_1(t)$	operational state of the HEM, equals 0 if the HEM is down and equals 1 if the HEM is up
$\alpha_2(t)$	operational state of LEM, equals 0 if the LEM is down and equals 1 if the LEM is up
$\beta_1(t)$	state of the HEM, equals 0 if the HEM is off (stopped) and equals 1 if it is on
$\beta_2(t)$	state of the LEM, equals 0 if the LEM is off (stopped) and equals 1 if it is on
$u_1(t)$	production rate for the HEM (product/time unit)
$u_2(t)$	production rate for the LEM (product/time unit)
u_m^1	maximum production rate for the HEM (product/time unit)
u_m^2	maximum production rate for the LEM (product/time unit)
d	demand rate
L	allowed standard limit of emissions
TTF_1	distribution function of time to failure for the HEM
TTF_2	distribution function of time to failure for the LEM
TTR_1	distribution function of time to repair for the HEM
TTR_2	distribution function of time to repair for the LEM
$MTTF_1$	mean time to failure for the HEM
$MTTF_2$	mean time to failure for the LEM
$MTTR_1$	mean time to repair for the HEM
$MTTR_2$	mean time to repair for the LEM

c^+	inventory cost for each product time unit ($/product/time unit)
c^-	backlog cost for each product per unit of time ($/product/time unit)
c^e	emission cost for each unit of violation ($/violation unit)
c_{P_1}	production cost for the HEM ($/product)
c_{P_2}	production cost for the LEM ($/product)
θ_1	emission index of the HEM
θ_2	emission index of the LEM
Av_1	availability of the HEM
Av_2	availability of the LEM
P_e	length of emission level monitoring period

Control factors

Z_i	hedging level for the HEM (*i*=1) and the LEM (*i*=2) in NOS system
S_1	hedging level for the HEM or LEM in OS system
S_2	safety stock for simultaneous operation of the HEM and LEM
R	ratio of Z_2 to Z_1
Y	voluntary emission limit

2.3.2 Model assumption

The main assumptions considered in this work are as follows:

- ✓ the rate of demand is considered to be known and constant.
- ✓ the planning horizon is infinite.
- ✓ it is assumed that there is no emission resulting from work-in-process (WIP) products.
- ✓ there is no setup time or cost for switching from the HEM to the LEM and vice versa.

2.3.3 Problem description

The investigated manufacturing system in Figure 2.1 includes failure-prone machines which produce one product type to meet customer demand. In this study, the manufacturing system consists of a high-emitting machine (HEM) and uses a low-emitting machine (LEM). The LEM generates lower emissions than the HEM ($\theta_2 < \theta_1$). The operation of the manufacturing system results in GHG emissions that are harmful to the environment, and the LEM generating a lower emission level is used to control the total amount of GHGs.

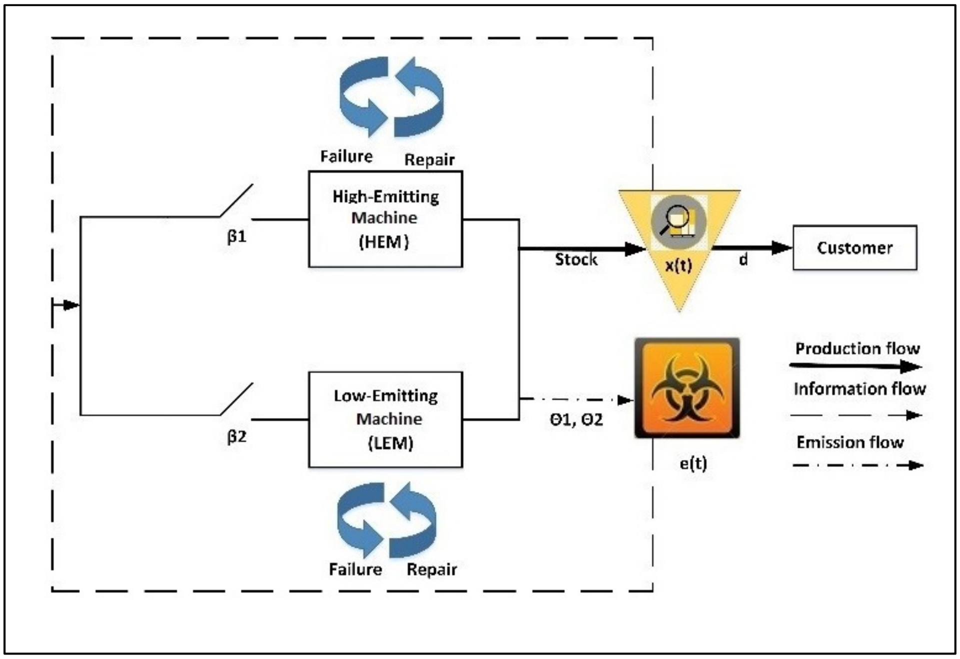

Figure 2.1 Production system under study

For the manufacturing system under study, $u_1(t)$ and $u_2(t)$ respectively denote the production rates of the HEM and LEM, which are prone to failures. Failure and repair duration are considered to evolve based on a stochastic process. The emission indexes for the HEM (θ_1) and for the LEM (θ_2) describe the quantity of pollution arising from producing one unit of product with each machine. Emission indexes follow the uniform distributions of $\theta_1 \sim [a_1, b_1]$ and $\theta_2 \sim [a_2, b_2]$. θ_2 is considered to be less than θ_1. The emission rates for the HEM and LEM are respectively equal to $u_1(t) \times \theta_1$ and $u_2(t) \times \theta_2$.
Some feedbacks are sent to the system once the inventory level exceeds the threshold level or the emissions exceeds its voluntary limit. The availability of the machines can be calculated as follows:

$$Av_1 = (MTTF_1)/(MTTF_1 + MTTR_1) \tag{2.1}$$

$$Av_2 = (MTTF_2)/(MTTF_2 + MTTR_2) \tag{2.2}$$

For any time t, $x(t), e(t), \alpha_1(t), \alpha_2(t), \beta_1(t),$ and $\beta_2(t)$ can describe the dynamic behavior of the system. In the discrete part, $\{\alpha_1(t), t > 0\} \in \{0,1\}$ and $\{\alpha_2(t), t > 0\} \in \{0,1\}$ take the value 0 if the machine is down and 1 if the machine is up. $\{\beta_1(t), t > 0\} \in \{0,1\}$ and $\{\beta_2(t), t > 0\} \in \{0,1\}$ take the value 0 if the machine is off, and 1 if the machine is on. Moreover, the continuous components for the state of the system are $x(t) \in R$, representing the inventory surplus level, and $e(t) \in R$ describing the emission level. $x(t)$ and $e(t)$ can be described by Equations (2.3) and (2.4). x_0 shows the initial surplus level.

$$\frac{dx(t)}{dt} = u_1(t).\alpha_1(t).\beta_1(t) + u_2(t).\alpha_2(t).\beta_2(t) - d \qquad x(0) = x_0 \tag{2.3}$$

$$\frac{de(t)}{dt} = u_1(t).\alpha_1(t).\beta_1(t).\theta_1 + u_2(t).\alpha_2(t).\beta_2(t).\theta_2 \tag{2.4}$$

The capacity constraint of the considered systems is given by the following equation:

$$0 \leq u_1(t) \leq u_m^1 \tag{2.5}$$

$$0 \leq u_2(t) \leq u_{\mathrm{m}}^2 \tag{2.6}$$

The following constraint is given to guarantee the feasibility of the system:

$$u_{\mathrm{m}}^1 \times Av_1 \geq d \tag{2.7}$$

$$u_{\mathrm{m}}^2 \times Av_2 \geq d \tag{2.8}$$

The considered cost consists of the inventory, backlog, production, and emission penalty costs. A regulatory control approach is imposed on the manufacturing system under study, and if the total emission level at the end of the emission control period exceeds the standard level, *L* announced by authorities, the difference is penalized with an emission cost (tax), c^e. At the beginning of each control period, the total emission level is reset to zero. *N* is the number of control periods for emission. The related equation can be defined as follows:

$$EC(t_i) = c^e \times max(0, e(t_i) - L) \qquad i = 1, \dots, N; \;\; t_i = i \times P_e; \;\; e(t_i) = 0 \tag{2.9}$$

The inventory and backlog cost can be calculated according to the surplus level, $x(t)$. The production cost is determined based on the production rate of the machines, $u_1(t)$ and $u_2(t)$. The inventory, backlog and production costs are defined as follows:

$$h(x(t)) = c^+ x^+ + c^- x^- \tag{2.10}$$

$$c(u_1, u_2) = c_{P_1}.u_1(t).\alpha_1(t).\beta_1(t) + c_{P_2}.u_2(t).\alpha_2(t).\beta_2(t) \tag{2.11}$$

$$g(x, u_1, u_2) = h(x) + c(u_1, u_2) \tag{2.12}$$

where $x^+ = max(0, x)$, $x^- = max(-x, 0)$, $c^+$and $c^-$are respectively the inventory and backlog costs. Using Equations (2.9) to (2.12), the average total cost could be defined as follows:

$$J(x, e, \alpha_1, \alpha_2, \beta_1, \beta_2) = \int_0^{N \times P_e} g(x, u_1, u_2)\, dt + \frac{1}{N \times P_e} \sum_{i=1}^{N} EC(t_i) \tag{2.13}$$

The optimal control policy seeks to minimize $j(.)$ subject to constraints (2.1) to (2.8), and to determine the production rate of machines as a function of $x(t), e(t), \alpha_1(t), \alpha_2(t), \beta_1(t)$, and $\beta_2(t)$.

2.4 Formulation of proposed control policy for NOS systems (PNOS-EHPP)

The system under study consists of a HEM that generates high levels of emissions, and a LEM, which is used to control the environmental emissions related to processes in the manufacturing system. In the policy presented by Afshar-Bakeshloo et al., (2018) (BNOS-EHPP), the production rate of machines relies on emissions and inventory feedbacks. At any time, the inventory level is compared with a threshold level, and the emission level is compared with voluntary emission limit (Y). If the emission level exceeds the voluntary limit, the HEM is stopped and the system switches to LEM. Moreover, the threshold level is considered in determining the production rate: if the inventory level is less than the threshold level, the production rate equals the maximum production rate; if the inventory is equal to the threshold, the production rate equals the demand rate, and when the inventory exceeds the threshold, the machine is stopped.

In the EHPP presented by Afshar-Bakeshloo et al., (2018), Z_2 is considered to be less than Z_1. However, imposing this constraint is not realistic, especially when the available production capacity of the LEM is less than that of the HEM ($u_{\mathrm{m}}^1 \times Av_1 > u_{\mathrm{m}}^2 \times Av_2$). Subsequently, when such system works with the LEM which has a lower available production capacity, the system is more likely to experience a shortage. Hence, the policy must increase the threshold level to deal with the shortage, and then Z_2 should be greater than Z_1. As has been shown in many previous works on HPP mentioned in the literature review section, when the available production capacity of the manufacturing system ($u_m \times Av$) decreases, the threshold level (Z) increases. After exceeding the emission limit, the manufacturing system can control the emission level by using the LEM (less the emission index) or reduce its threshold level. However, it is not necessary to impose the constraint of $Z_2 < Z_1$ on the policy for all situations, and the policy should be capable of increasing the LEM threshold level to deal with backlogs. Our work aims to find a wider and more general policy that is close to real-life contexts. Hence, in our proposed policy, the constraint for the LEM threshold level ($Z_2 < Z_1$) is relaxed, and this level is taken into account as a free decision variable.

The behavior of the proposed NOS system environmental hedging point policy (PNOS-EHPP) is described according to the following equations:

if $e(t) < Y$:

Apply HPP with a threshold level of Z_1 using only HEM (β_1= 1, β_2= 0), $\beta_1 . \beta_2 = 0$

$$u_1(t) = \begin{cases} u_m^1 & if\ x(t) < Z_1 \\ d & if\ x(t) = Z_1 \\ 0 & if\ x(t) > Z_1 \end{cases} \tag{2.14}$$

if $e(t) > Y$:

Apply HPP with a threshold level of Z_2 (free) using LEM (β_1= 0, β_2= 1), $\beta_1 . \beta_2 = 0$

$$u_2(t) = \begin{cases} u_m^2 & if\ x(t) < Z_2 \\ d & if\ x(t) = Z_2 \\ 0 & if\ x(t) > Z_2 \end{cases} \tag{2.15}$$

For a better understanding of the dynamics behavior of the system under PNOS-EHPP, readers can consult Figure 2.4 provided in Sub-section 2.6.1.

2.5 Resolution approach

We aim to minimize the total cost expressed in Equation (2.13) for the system that is driven by control policy provided in Equations (2.14) and (2.15). It is proven to be difficult to obtain the analytical solution for such complex problem in stochastic and dynamic context. Therefore, instead of using analytical approach, an experimental resolution approach combining a simulation technique, a design of experiment (DOE) and a response surface methodology (RSM) is used in order to solve the problem and estimate the optimal value of cost and control parameters. We adapted this approach to our case to deal with complexity of this kind of problems considered by studies such as (Afshar-Bakeshloo et al., 2018), (Ben-Salem et al., 2015a), (Ben-Salem et al., 2015b), (Ben-Salem et al., 2016), (Bouslah et al., 2013a), (Bouslah et al., 2014), (Gharbi et al., 2008), (Gharbi et al., 2011), (Kenné and Gharbi, 2000), (Pellerin et al., 2009a), (Pellerin et al., 2009b), (Rivera-Gómez et al., 2018). The main steps of the approach presented in Figure 2.2 are as follows:

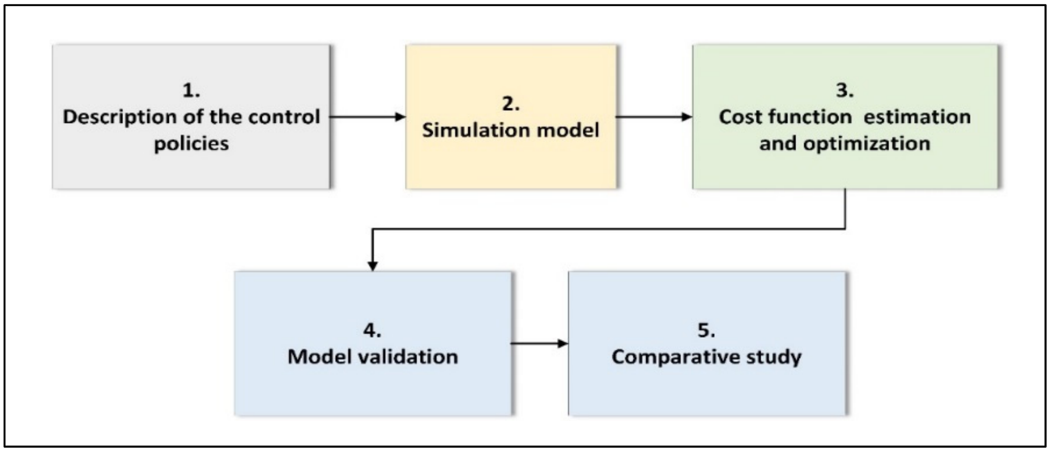

Figure 2.2 Proposed approach

- ✓ step 1: Control policy description

The structure of proposed policy is provided and expressed by mathematical Equations (2.14) and (2.15) in previous section.

- ✓ step 2: Simulation model

The simulation model is designed to represent the dynamic behavior of the system based on considered control policy. The policy could be taken into account as inputs in order to carry out experiments and evaluate the cost and system performance. In Section 2.6, our developed simulation model is presented in detail.

- ✓ step 3: Cost function estimation and optimization with DOE and RSM

The number of experiments and the level of each independent variable and the variation extent of each considered factor are defined in the experimental design approach. Then, in order to specify the main independent variables and their interactions that significantly affect the total cost (dependent variable), the analysis of variance (ANOVA) is used. Subsequently, RSM is implemented to determine the relationship between the dependent variable, the main factors, and their significant interactions. A quadratic approximation function of the expected total cost using a combination of DOE, regression analysis and RSM (Myers et al., 2016) is called the response surface and should take an equation as follows:

$$F \cong \beta_0 + \beta_1 Z_1 + \beta_2 Z_2 + \beta_3 Y + \beta_{11} Z_1^2 + \beta_{22} Z_2^2 + \beta_{33} Y^2 + \beta_{12} Z_1 Z_2 + \beta_{13} Z_1 Y + \beta_{23} Z_2 Y + \varepsilon \tag{2.16}$$

With, β_0, β_i and β_{ij} $(i, j \in \{1,2,3\})$ are unknown parameters (coefficients) to be estimated from the collected simulation data, and ε is a random error. The obtained model is then optimized to find the best combination of main factors (control parameters) which can result in the minimum cost.

- ✓ step 4: Model validation

In order to validate the regression model, we use three steps, such as in (Myers et al., 2016). First, the overall performance of the model is evaluated by the adjusted R-squared coefficient which represent the proportion of total variation explained by the regression model. The value of adjusted R-squared should be close to 1. Second, a residual analysis need to be done to check the homogeneity of the variances and the residual normality. Third, once the optimization is performed on the regression model, a Student's t-test is conducted to crosscheck its validity. We determined a confidence interval at 95% to crosscheck the validity of the model. The results should confirm that the cost falls well within the 95% confidence interval obtained using specific replications of the simulation model.

- ✓ step 5: Comparative study

The objective of this section is to make a comparison between developed control policies for a wide range of cost and system parameters and determine the best control policy in terms of cost and emission. In Section 2.8, numerical results and comparison between policies are provided in detail.

2.6 Simulation model

For each control policy, a combined discrete-continuous simulation model is developed using Arena software. Figure 2.3 represents the simulation model under the considered control policies.

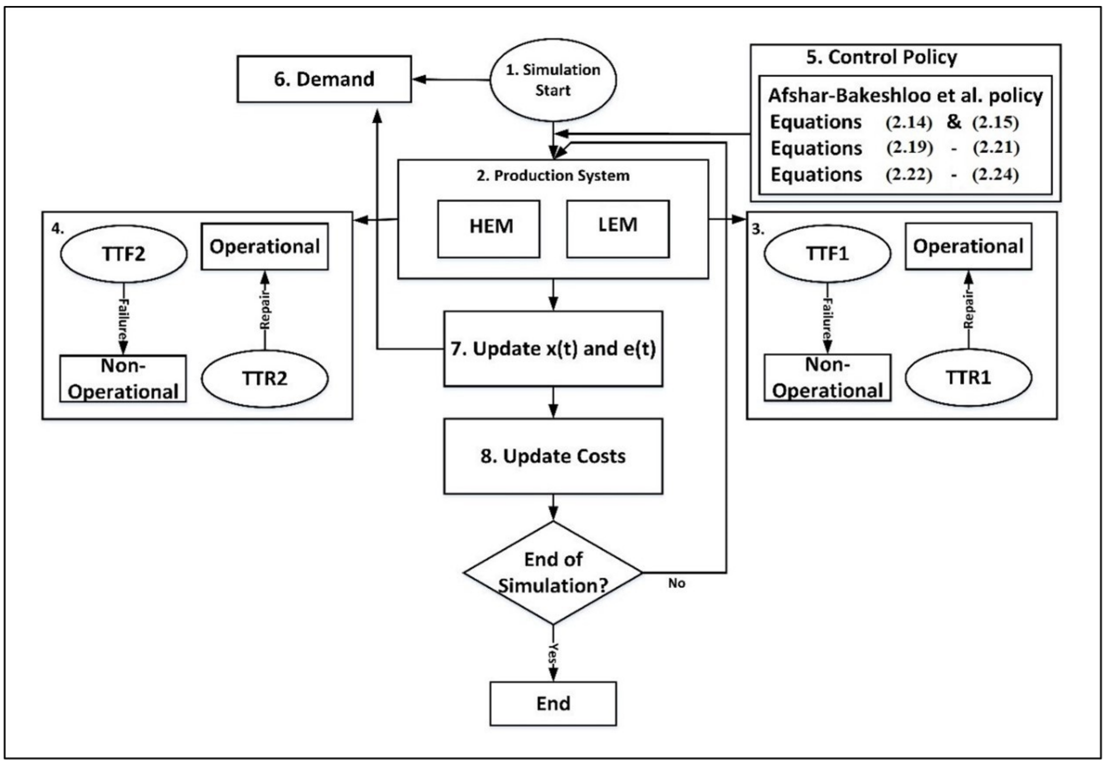

Figure 2.3 Diagram of the simulation model

As can be seen from the figure, in Block 1, the model will start with simulation inputs and parameters ($Z_1, Z_2, u_{\mathrm{m}}^1, u_{\mathrm{m}}^2, d,$ etc.). Blocks 2 to 4 show that the production system including the HEM and LEM is prone to random failures and repairs. The production system works based on each developed control policy shown in Block 5 to meet the demand shown in Block 6. Block 7 depicts the surplus inventory level variation and the generated emission level according to the Equations (2.3) and (2.4). Finally, the inventory, backlog, production, and emission costs are calculated as shown in Block 8.

2.6.1 Computational results and simulation validation

To check the accuracy of the simulation model, a dynamic testing is conducted to monitor its data evolution and behavior. As an example, the dynamic of the system using the PNOS-EHPP (Equations (2.14) and (2.15)) is provided over time in Figure 2.4.

The system parameters applied for the simulation validation are provided in Table 2.2. The manufacturing process depends on the emission level $e(t)$, the inventory level $x(t)$ and state of the machines based on $\alpha_1(t), \beta_1(t), \alpha_2(t)$ and $\beta_2(t)$. According to the considered policy, the HEM and LEM cannot operate simultaneously. For ease of reading, the symbol "Y.Ⓧ" is used to emphasize the phenomenon shown by the part X illustrated in Sub-Figure 2.4.Y. For example, a.① in Figure 2.4 represents the phenomenon shown by the part 1 illustrated in Sub-Figure 2.4.a. This symbol has the same meaning for all following figures.

As can be seen in a.①, when the emission level is less than *Y*=612,274, the production system works only with the HEM, $\beta_1 = 1$ (c.②), and the LEM is off, $\beta_2 = 0$. The manufacturing rate is equal to the maximum production rate of the HEM (u_{m}^1=130) since the inventory level is less than the threshold level of the HEM, Z_1=165.02 (b.③). The inventory level increases at the rate of $u_{\mathrm{m}}^1 - d$ (b.③) and the emission level increases at the rate of $u_{\mathrm{m}}^1 * \theta_1$ (a.①). Then, according to c.④, there is a failure in HEM. So, the production rate is equal to zero, and there is no increase in the generated emission level (a.⑤). According to b.⑥, the stock level drops at the rate of -*d*= -100. After repair, the production rate is at its maximum. Based on b.⑦, as soon as the stock reaches threshold level of the HEM (Z_1=165.02), the production rate is equal to demand and emissions rise at the rate of $d * \theta_1$ (a.⑧). As shown by a.⑨, when the total emission level exceeds 612,274, the production system switches from the HEM to the LEM (d.⑩). As the inventory level is less than the LEM threshold level (Z_2=290.44), the production rate is equal to u_{m}^2=115 (b.⑪) and there is an increase in the whole generated emissions but at a lower rate of $u_{\mathrm{m}}^2 * \theta_2$ (a.⑫).

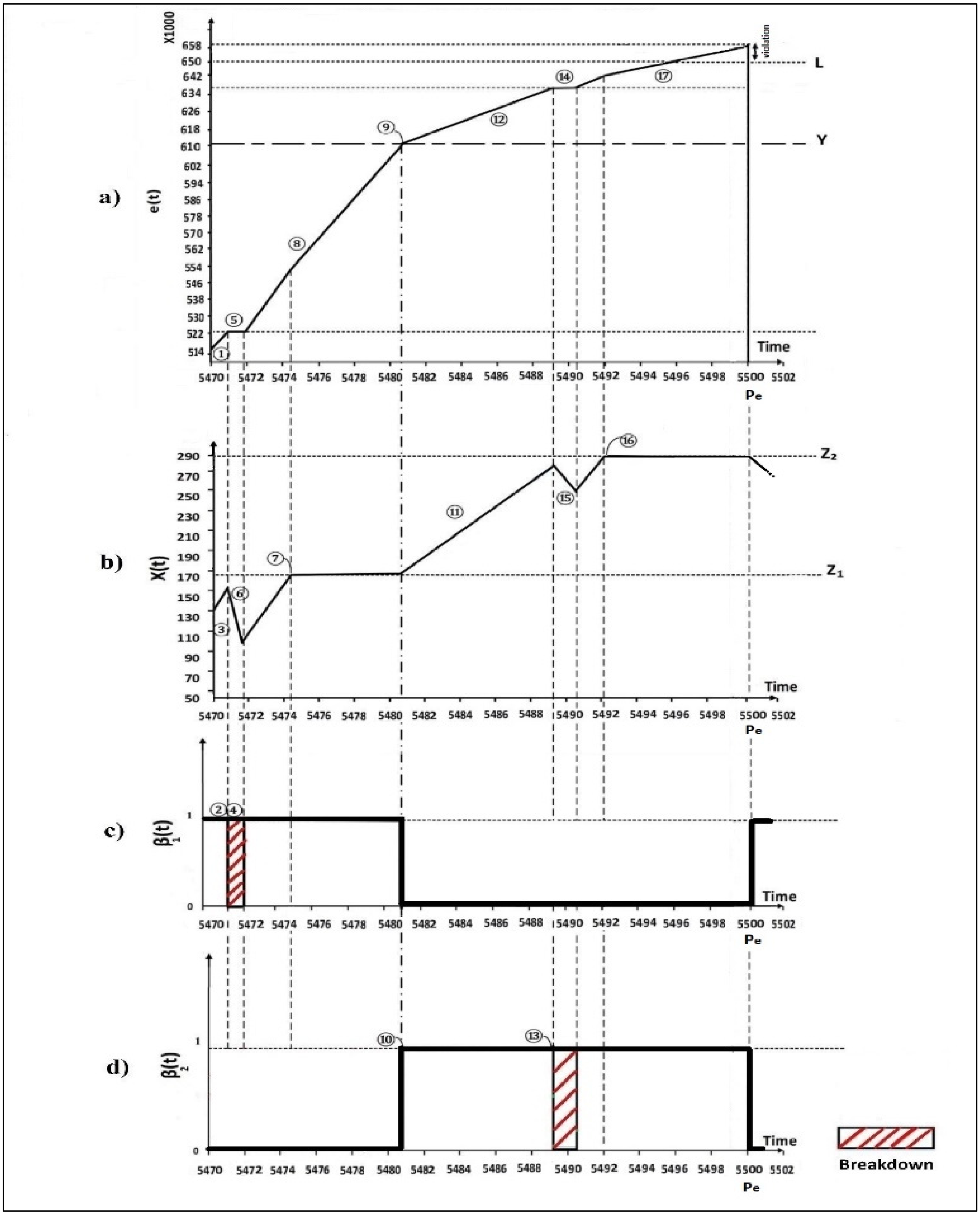

Figure 2.4 Dynamics of operations for simulation run of PNOS-EHPP

Based on d.⑬, there is a failure in the LEM, so production rate is equal to zero. There is no rise in the amount of emissions (a.⑭), and there is a reduction in the stock level at the rate of -*d*= -100 (b.⑮). When the machine is up, the production rate is equals to the maximum amount. When the inventory level reaches the LEM threshold level, Z_2=290.44 (b.⑯), the production rate is equal to demand and the emission level goes up at the rate of $d * \theta_2$ (a.⑰). At the end of the emission level monitoring period (Pe), the total emission level is reset to zero. The system stops LEM and can operate only with HEM. But because of the high level of inventory which is higher than HEM threshold level (Z_1), the system uses this inventory to satisfy the demand and does not operate HEM till reaching Z_1.

2.6.2 Design of experiment and response surface model

The optimization model is built following the design of experiment and the response surface methodology. Different simulation experiments are carried out to find the admissible region, including the optimal control parameters values. The system parameters applied are summarized in Table 2.2.

Table 2.2 The system parameters

Parameter	d	u_m^1	u_m^2	TTF_1	TTF_2	TTR_1	TTR_2	θ_1
Value	100	130	115	Exp(7)	Exp(10)	Exp(0.6)	Exp(0.7)	[0.5,2]
Parameter	θ_2	L	c^+	c^-	c^e	c_{P_1}	c_{P_2}	P_e
Value	[0.1,0.4]	650,000	1	25	5	2	8	5,500

A full-factorial design with three factors at three levels (3^3) is applied to separately estimate each interaction. Using five replications for each combination of control factors, 135 (5×3^3) simulation runs are performed for each design. The simulation length is 500,000 units of time to ensure a steady state condition. A substitute parameter $r = Z_2/Z_1$ is defined. Depending on simulation output, the statistical software STATGRAPHICS is used to conduct a multi-factor analysis of variance (ANOVA) and obtain the effect of independent variables (Z_1, r, Y), their interactions, and the quadratic effect on total cost. The ANOVA analysis for PNOS-EHPP summarized in Table 2.3 shows that except for Y^2, all main factors, their interactions and quadratic effects are significant at a 99.35% level of significance. The adjusted R-square obtained states that the RSM model accounts for more than 99% of the variability in expected total cost.

Table 2.3 ANOVA results of PNOS-EHPP

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value	Signification
A: r	84,958.9	1	84,958.9	136.46	0.0000	S
B: Y	202,769	1	202,769	325.69	0.0000	S
C: Z	926,944	1	926,944	1,488.85	0.0000	S
AA	3,427.29	1	3,427.29	5.50	0.0206	S
AB	7,492.1	1	7,492.1	12.03	0.0007	S
AC	2,915.45	1	2,915.45	4.68	0.0324	S
BB	26.8199	1	26.8199	0.80	0.8359	N.S
BC	3,985.67	1	3,985.67	5.65	0.0127	S
CC	3,516.771	1	3,516.771	5.57	0.0204	S
Total error	75,956.2	125	622.592			
Total (corr.)	1.3099E6	134				
$R^2 = 99.35\%$						

The response functions obtained are as follows:

$$Cost_{BNOS-EHPP} = 827.28742 - 90.6637\times r - 0.00064479\times Y - 3.19942\times Z_1 + 11.5940\times r^2 + 0.026226\times Z_1^2 + 0.859989\times 10^{-4}\times r\times Y + 0.342\times 10^{-6}\times r\times Z_1 + 0.857373\times 10^{-6}\times Y\times Z_1 \quad (2.17)$$

$$Cost_{PNOS-EHPP} = 726.1175483 - 89.3423\times r - 0.00061713\times Y - 3.13401\times Z_1 + 11.4797\times r^2 + 0.025988\times Z_1^2 + 0.842235\times 10^{-4}\times r\times Y + 0.335\times 10^{-6}\times r\times Z_1 + 0.83967\times 10^{-6}\times Y\times Z_1 \quad (2.18)$$

The projection of the cost response surface on two-dimensional planes for PNOS-EHPP is provided in Figure 2.5. Also, the minimum total cost and optimal control parameters obtained for BNOS-EHPP and PNOS-EHPP are presented in Table 2.4.

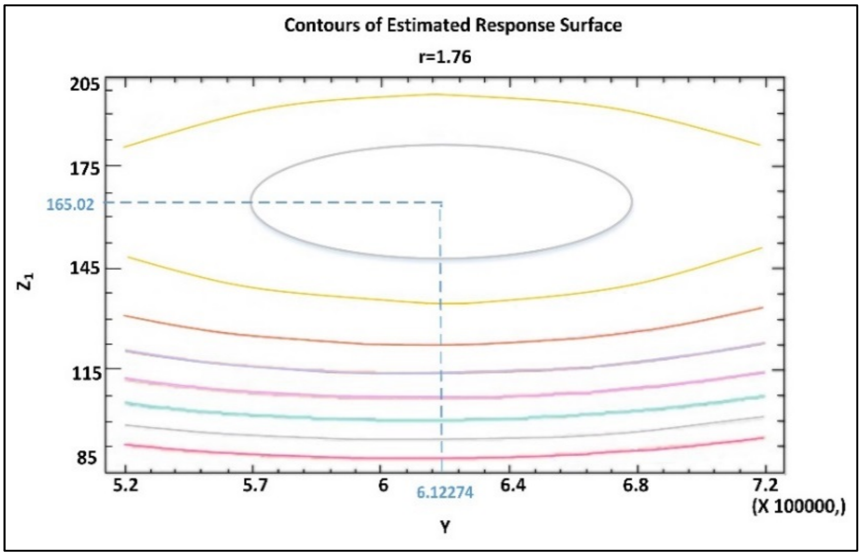

Figure 2.5 Projection of cost response surface on two-dimensional planes for PNOS-EHPP

Table 2.4 Optimization results for BNOS-EHPP and PNOS-EHPP

Control policy	Z_1*	Z_2*	Y*	LEM usage %	HEM usage %	
BNOS-EHPP	163.79	127.832	602,583	25	75	
PNOS-EHPP	165.02	290.44	612,274	26	74	
Control policy	Backlog Cost*	Inventory Cost*	Emission Cost*	Production Cost*	Total Cost*	Confidence Interval (95%)
BNOS-EHPP	88.26	145.09	171.47	201.05	605.87	[605.56, 606.18]
PNOS-EHPP	60.35	152.34	173.62	204.67	590.98	[590.12, 591.86]

The optimization results for BNOS-EHPP and PNOS-EHPP based on selected system parameters show that the optimal value of Z_2 (LEM threshold level) for PNOS-EHPP is higher than that of BNOS-EHPP. Based on the results, the PNOS-EHPP without constraint of $Z_2 < Z_1$

is more advantageous than the BNOS-EHPP with a 2.45% cost reduction (from 605.87 to 590.98). When the available production capacity of the new machine with the LEM is less than the HEM, the LEM threshold level should be more than Z_1. Therefore, the constraint has been relaxed to improve the policy. This improvement results from the ability of the policy to better monitor the production system and face backlog with the help of the LEM and increasing the total availability of the system. We take a closer look at the behavior of the system to prove this improvement in the next section.

2.6.3 Comparison between BNOS-EHPP and PNOS-EHPP

To draw a comparison between the two policies and find out how PNOS-EHPP can bring more benefits for the system by reducing cost, different values for the ratio of $u_m^2 \times Av_2$ to $u_m^1 \times Av_1$ have been considered by changing the availability and maximum production rate of the LEM in Figure 2.6.

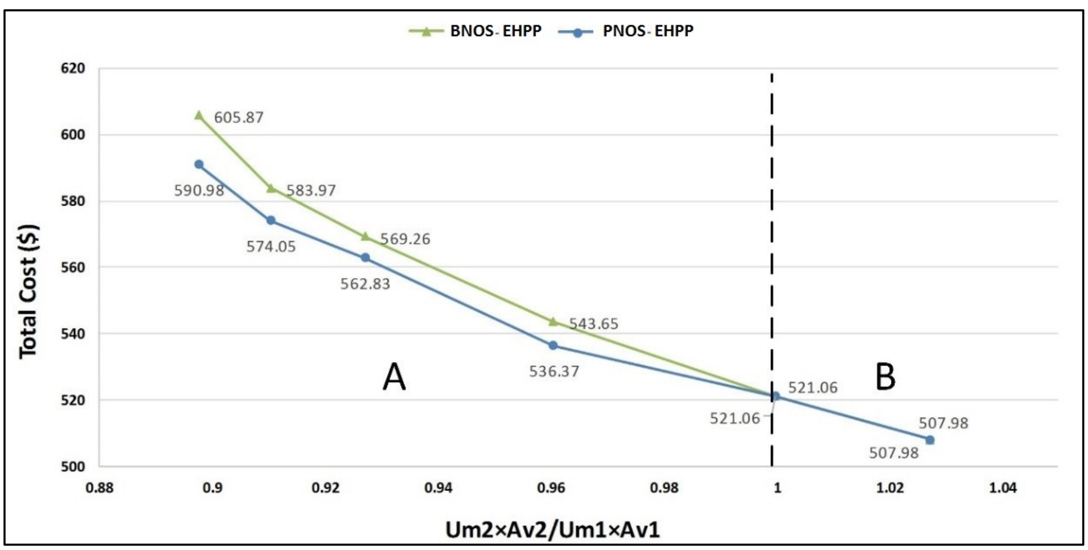

Figure 2.6 Comparison between BNOS-EHPP and PNOS-EHPP

Different values of $u_m^2 \times Av_2$ for the LEM have been taken into account. As can be seen in the figure, by increasing the $u_m^2 \times Av_2$ for LEM, there is a reduction in total cost because the available production capacity of the manufacturing system increases. Regarding comparisons between the two policies, it can be seen in section A that when the available production capacity of the LEM is less than that of the HEM ($u_m^2 \times Av_2 < u_m^1 \times Av_1$), our proposed policy is more efficient and can result in cost reduction as compared with BNOS-EHPP.

Therefore, in this case, in order to provide a more realistic policy, it is not valid to impose the constraint of $Z_2 < Z_1$. When the available production capacity of the LEM is increased such $u_m^2 \times Av_2 = u_m^1 \times Av_1$, both machines have the same available production capacity ($Z_2 = Z_1$). After this point, as can be seen in section B, the available production capacity of the LEM is greater than that of the HEM ($u_m^2 \times Av_2 > u_m^1 \times Av_1$). So, the behavior of the system and the minimum total cost under both policies, BNOS-EHPP and PNOS-EHPP, are the same.

2.6.4 Discussion about simultaneous operation of the HEM and LEM

The PNOS-EHPP helps the system control the generated GHGs by switching from the HEM to the LEM after a certain voluntary level of GHGs is reached, allowing the system to produce less emissions during the remainder of the period. However, based on the results, the emission, backlog and inventory costs are still considerably high for PNOS-EHPP. Consequently, we are therefore looking for a solution allowing the reduction of the aforementioned costs and minimizing the total cost of the production system.

In the manufacturing system in which the HEM and LEM can operate simultaneously (OS), availability is low, and as a result, the backlog is therefore high. Moreover, when the availability is low, the system needs to increase the inventory level in order to meet demand, meaning the inventory cost will increase. Emissions are still high in this case, because the LEM is only used after exceeding the voluntary GHG emission limit. Using only the HEM before this limit can lead to too excessive greenhouse gas emissions being generated. Based on PNOS-EHPP, the LEM is stopped for the great part of production period. We aim to benefit from the unused capacity of the LEM in our manufacturing system. Our objective is to increase the LEM usage and then decrease the backlog, inventory, and emission costs by increasing the availability of the whole system. To achieve such goals, two new policies are developed for OS systems in the next section.

2.7 Proposed environmental hedging point policies for OS systems

2.7.1 Proposed OS system-EHPP-I (POS-EHPP-I)

In the system in which HEM and LEM are not allowed to work at the same time, the backlog is high. There is no denying to the fact that using both HEM and LEM simultaneously provides the advantage of increased availability and decreased backlog and inventory. In the considered OS system, the probability of both machines breaking down at the same time is reduced, and as a result, there is a significant increase in the system availability. This greater availability leads to a lower backlog level, and in addition, the system needs a lower threshold level to satisfy demand, which could result in a lower inventory level. On the other hand, the longer LEM is operational during production, the more emissions will decrease. Therefore, ensuring greater system availability and lower emissions by using both low- and high-emitting machines simultaneously would significantly improve the previous control policies.

POS-EHPP-I is represented by Equations (2.19) -(2.21). In this policy, a specific hedging level, S_1, is taken into consideration for both machines to determine the production rate. Moreover, the proposed policy OS systems is intended to take advantage of the unused capacity of the LEM to improve the system availability and reduce inventory, backlog, and emission costs. To avoid backlog, when the inventory level is lower than a specific safety stock level, S_2 ($S_2<S_1$), we have to provide more production capacity for the system. So, we allow the system to simultaneously produce with both LEM and HEM until it reaches the inventory level of S_2. When the inventory level is lower than S_2, we use both HEM and LEM, and when we exceed S_2, only one machine (HEM) can be used. When the manufacturing system generates a high amount of GHG emissions such that the total emission exceeds the voluntary emission limit, we have to stop producing with HEM and start producing only with LEM to control the emission level.

if $e(t) < Y$ and $x(t) < S_2$: then use both HEM and LEM (β_1= 1, β_2= 1)

$$u_1(t) = u_m^1 \text{ and } u_2(t) = u_m^2 \tag{2.19}$$

if $e(t) < Y$ and $x(t) > S_2$:

Apply HPP with threshold level S_1 using only HEM (β_1= 1, β_2= 0)

$$u_1(t) = \begin{cases} u_m^1 & if\ x(t) < S_1 \\ d & if\ x(t) = S_1 \\ 0 & if\ x(t) > S_1 \end{cases} \tag{2.20}$$

if $e(t) > Y$:

Apply HPP with threshold level S_1 using only LEM (β_1= 0, β_2= 1)

$$u_2(t) = \begin{cases} u_m^2 & if\ x(t) < S_1 \\ d & if\ x(t) = S_1 \\ 0 & if\ x(t) > S_1 \end{cases} \tag{2.21}$$

An illustrative evolutionary diagram of POS-EHPP-I is presented in Figure 2.7. Before reaching S_2, when the emission level is less than its voluntary limit (Y), machines can operate simultaneously (d.①). Initially, both machines start to operate to meet demand, and the remaining products are stocked to increase the inventory level. In this context, the level of inventory rises according to $u_{\mathrm{m}}^1 + u_{\mathrm{m}}^2 - d$ (a.②), and the level of emissions increases according to ($u_{\mathrm{m}}^1 \times \theta_1 + u_{\mathrm{m}}^2 \times \theta_2$), (b.③). S_2 is considered as a safety stock level in making decisions as to whether or not to use both machines simultaneously. Once $x(t)$ reaches S_2 (a.④), the system stops the LEM (d.⑤) and works only with the HEM. To control the emission level in the POS-EHPP-I, when the emission level exceeds the limit of Y (b.⑥), the system stops the HEM (c.⑦) and can use only the LEM based on the classical HPP.

In POS-EHPP-I, the condition of using both machines simultaneously, is only applicable when the inventory level is less than S_2 and the emission level is lower than the set limit. To control total emissions, after the emission limit is exceeded, the system stops the HEM and only uses the LEM. In this way, because of the low capacity and availability of the system working only with the LEM, the emissions can thus be reduced, but the backlog and inventory is still considerable. Therefore, the possibility of using the HEM even after the set emission level is exceeded, could be the main point of our discussion.

If the HEM is used more, the inventory and backlog cost will decrease as availability will increase. Because the production cost when using the HEM is less than that incurred when using the LEM, the total production cost will decrease. Although the emissions generated will increase, minimizing the total cost is our objective which includes the emission cost. Therefore, it is not necessary to force the system to stop the HEM and produce only with the LEM. Consequently, by operating the HEM, which has a higher production rate, even after the emission limit is reached, the model will be able to reduce the backlog, inventory, production, and total cost.

As our aim is to find a control policy to minimize total cost, what would happen if we enabled the model to be able to use the HEM even after exceeding the emission limit? What would happen if we provided even higher system availability? Will that lead to cost savings for our manufacturing system? Could we decrease the total cost in this manner and keep emissions at a suitable level? In the next subsection, the POS-EHPP-II is presented, and addresses these questions.

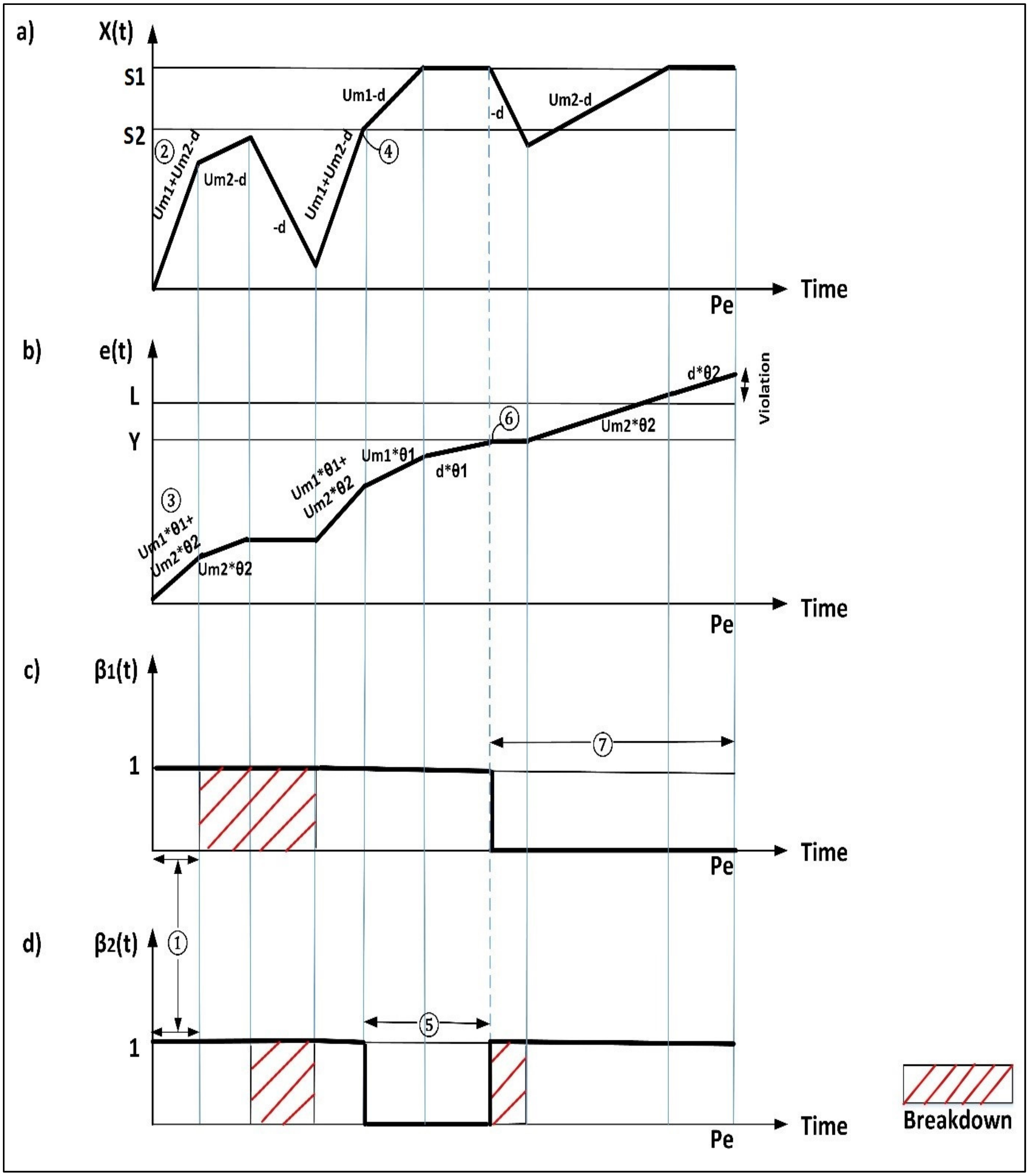

Figure 2.7 Inventory surplus and emission level evolution based on POS-EHPP-I

2.7.2 Proposed OS system-EHPP-II (POS-EHPP-II)

According to POS-EHPP-II, before the voluntary emission limit Y is exceeded, the behavior of the system is the same as with POS-EHPP-I. However, after exceeding the voluntary emission limit, it is not always necessary to switch to the LEM and use only this machine type for the rest of the period.

To increase the system availability and reduce the backlog, inventory and production costs, the HEM and LEM will operate simultaneously when the inventory level drops below the safety stock level S_2. When the inventory level reaches S_2, the system is not allowed to work with both machines. After S_2 is exceeded, if the emission level is less than its limit, the system stops the LEM and works only with HEM. If the total emission is greater than Y, then to control the GHG emissions, the HEM is stopped, and the system produces only with LEM. POS-EHPP-II is shown by Equations (2.22) –(2.24) as follows:

if $x(t) < S_2$: then use both HEM and LEM ($\beta_1 = 1$, $\beta_2 = 1$)

$$u_1(t) = u_m^1 \text{ and } u_2(t) = u_m^2 \tag{2.22}$$

if $x(t) > S_2$ and $e(t) < Y$:

Apply HPP with threshold level S_1 using only HEM ($\beta_1 = 1$, $\beta_2 = 0$)

$$u_1(t) = \begin{cases} u_m^1 & if\ x(t) < S_1 \\ d & if\ x(t) = S_1 \\ 0 & if\ x(t) > S_1 \end{cases} \tag{2.23}$$

if $x(t) > S_2$ and $e(t) > Y$:

Apply HPP with threshold level S_1 using only LEM ($\beta_1 = 0$, $\beta_2 = 1$)

$$u_2(t) = \begin{cases} u_m^2 & if\ x(t) < S_1 \\ d & if\ x(t) = S_1 \\ 0 & if\ x(t) > S_1 \end{cases} \tag{2.24}$$

Figure 2.8 presents an illustrative evolutionary diagram of POS-EHPP-II. According to a.①, the inventory level exceeds the required safety stock level, S_2. As the total generated emission is less than *Y*, the system stops the LEM and works with the HEM at a production rate $u_{\mathrm{m}}^{1}$to reach the threshold level of S_1. After reaching S_1 (a.②), the production rate of the HEM is equal to demand. According to b.③, as soon as the emission level exceeds the limit of *Y*, the system stops the HEM (c.④) and works only with the LEM to control emission. There is a failure in the LEM (d.⑤), so the inventory decreases at a rate of -*d* until a.⑥.

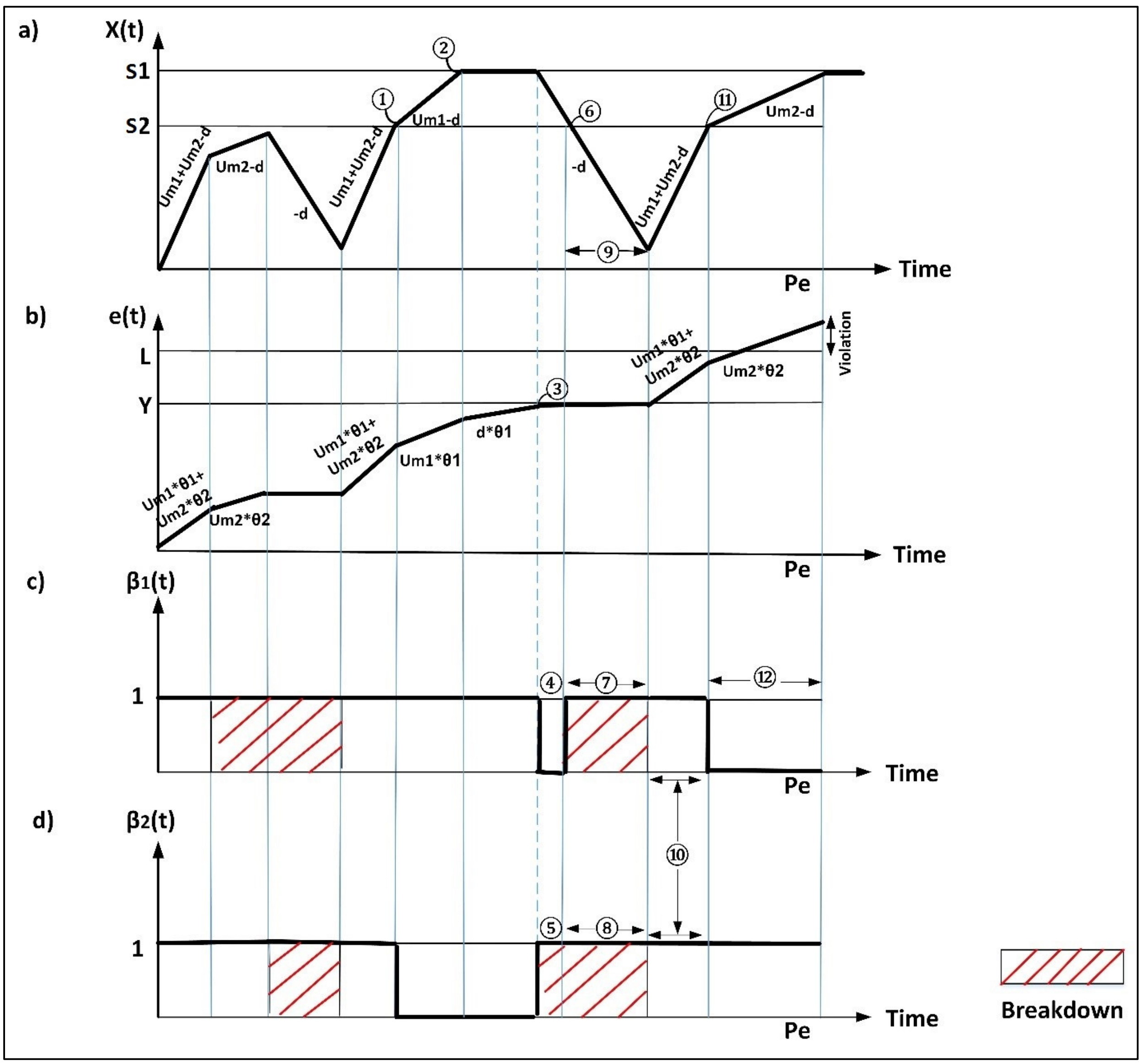

Figure 2.8 Inventory surplus and emission level evolution based on POS-EHPP-II

When the inventory decreases to the amount of S_2, it is time to use both machines simultaneously. However, there is failure in both machines (c.⑦ and d.⑧), and the inventory continues to decrease at a rate of $-d$ (a.⑨). When both machines are repaired, they start to work at the same time (d.⑩). Again, after building enough safety stock and exceeding S_2 (a.⑪), the system stops the HEM (c.⑫) and works with only one machine (the LEM) because the emission level is higher than Y at this point.

Optimization results are presented, and comparisons are carried out in the next section to confirm that the proposed control policies for OS systems give better results in terms of incurred cost.

2.8 Numerical results and comparison between policies

The optimal control parameters and costs for each policy are given in Table 2.5. Based on the results, PNOS-EHPP, which is able to provide a higher LEM threshold level to deal with backlogs, results in a cost reduction as compared with BNOS-EHPP. According to POS-EHPP-I, before reaching the emission limit, the LEM is allowed to simultaneously operate with the HEM until reaching a safety stock level equal to S_2. A comparison between the results of PNOS-EHPP and POS-EHPP-I shows that improving the system availability leads to a reduction in backlog and inventory costs. Moreover, as the usage percentage of the LEM increases, the incurred emission cost decreases. Although the production cost increases as compared with PNOS-EHPP, the incurred excess production cost is offset by reductions in backlog, inventory and emission costs, and leads to a total cost reduction for POS-EHPP-I as compared with PNOS-EHPP. So, based on the results, POS-EHPP-I provides more advantages than PNOS-EHPP in terms of cost reductions.

Table 2.5 Optimization results for considered policies

Control policy	Z_1*	Z_2*	Y*		LEM usage %	HEM usage %
BNOS-EHPP	163.79	127.832	602,583		25	75
PNOS-EHPP	165.02	290.44	612,274		26	74
Control policy	S_1*	S_2*	Y*		HEM usage %	HEM usage %
POS-EHPP-I	76.12	41.56	595,139		47	53
POS-EHPP-II	65.26	32.04	588,648		44	56
Control policy	Backlog Cost*	Inventory Cost*	Emission Cost*	Production Cost*	Total Cost*	Confidence Interval (95%)
BNOS-EHPP	88.26	145.09	171.47	201.05	605.87	[605.56, 606.18]
PNOS-EHPP	60.35	152.34	173.62	204.67	590.98	[590.12, 591.86]
Control policy	Backlog Cost*	Inventory Cost*	Emission Cost*	Production Cost*	Total Cost*	Confidence Interval (95%)
POS-EHPP-I	42.05	68.11	70.93	288.51	469.20	[468.77, 469.69]
POS-EHPP-II	24.75	40.13	81.12	275.85	421.85	[421.18, 422.41]

According to POS-EHPP-II, during the entire production period, the manufacturing system is allowed to stimulatingly use the HEM and LEM to build enough safety stock level equal to S_2. A comparison between the results of POS-EHPP-I and POS-EHPP-II shows that providing more system availability leads to a decrease in backlog and inventory costs. As the usage percentage of the HEM increases, the production cost decreases. Although the incurred emission cost increases as compared with POS-EHPP-I, the excess emission cost is offset by reductions in backlog, inventory, and production costs, and leads to a total cost reduction for POS-EHPP-II as compared with POS-EHPP-I.

As can be seen from Table 2.5, both POS-EHPP-I and POS-EHPP-II considerably reduce the total cost and generated emissions as compared with BNOS-EHPP and PNOS-EHPP. However, POS-EHPP-II is the most appropriate and cost-efficient policy.

2.8.1 Comparison of policies for a wide range of cost parameters

In order to comparatively assess the evolution of the policies another for a wide range of cost parameters, a comprehensive comparison is performed in Figure 2.9. The figure shows the influence of different cost parameters such as inventory (c^+), backlog (c^-), emission (c^e), and production costs (c_{p_1} and c_{p_2}) on total cost for the control policies.

As can be seen in Figure 2.9 (a) and (b), for a wide range of inventory costs (c^+) and backlogs (c^-), there is a sizeable difference between the total cost of PNOS-EHPP and the total cost of the proposed policies for OS systems, and this difference increases as c^+ or c^- goes up. This is because when the system availability increases, there is a reduction in backlog, and less inventory is needed in POS-EHPP-I and POS-EHPP-II to meet demand. So, the impact of c^+ (or c^-) on the total inventory/backlog cost and on the total cost of OS systems is less than its impact on the inventory/backlog cost and total cost of NOS systems (the slope of the figure for OS systems is less than NOS ones). Similarly, POS-EHPP-II provides more advantages than POS-EHPP-I as it improves the system availability for a wide range of inventory costs.

From Figure 2.9 (c), when there is an increase in emission costs (c^e), POS-EHPP-I and POS-EHPP-II lead to lower total cost than does PNOS-EHPP for a wide range of emission costs. This is because in OS systems, the usage percentage of the LEM is higher than BNOS-EHPP and PNOS-EHP, and the total generated emissions are lower. Therefore, the impact of c^e on the emission and total costs of NOS systems is greater than its impact on the emission and total costs of OS systems. Up to a certain value of c^e, there is a reduction in total cost for POS-EHPP-II as compared with POS-EHPP-I. In this case, although the usage percentage of the LEM in POS-EHPP-II is less than that with POS-EHPP-I, the incurred excess emission cost is covered by reductions in backlog and inventory costs, and can lead to reduction in total cost for POS-EHPP-II in comparison with POS-EHPP-I. However, after a certain level of c^e, it is not worthwhile for POS-EHPP-II to allow the system to use the HEM after the emission limit is reached, and so both POS-EHPP-I and POS-EHPP-II will lead to the same total costs.

Again, in Figure 2.9 (d), for different values of the HEM production cost (c_{p_1}), the total cost for POS-EHPP-I and POS-EHPP-II is less than that for PNOS-EHPP because based on the proposed policies for OS systems, it is possible to use both machines simultaneously even before reaching the emission limit, and the usage percentage of the HEM is lower than for PNOS-EHPP. Before a certain level of c_{p_1}, although the usage percentage of the HEM in POS-EHPP-II is greater than that of POS-EHPP-I, the total cost for POS-EHPP-II is lower because other cost components such as inventory and backlog costs for POS-EHPP-II are still much lower than for POS-EHPP-I. However, after a certain level of c_{p_1}, POS-EHPP-II does not allow the system to work with the HEM after the emission limit, and both POS-EHPP-I and POS-EHPP-II lead to the same results. Similarly in Figure 2.9 (e), when there is an increase in the production cost of the LEM (c_{p_2}), there is an increase in total costs for all policies. Although the usage percentage of the LEM in POS-EHPP-I and POS-EHPP-II is higher than for PNOS-EHPP, reductions in inventory, backlog and emission costs can overweight on the incurred production cost and result in cost reductions for a wide range of the LEM production costs.

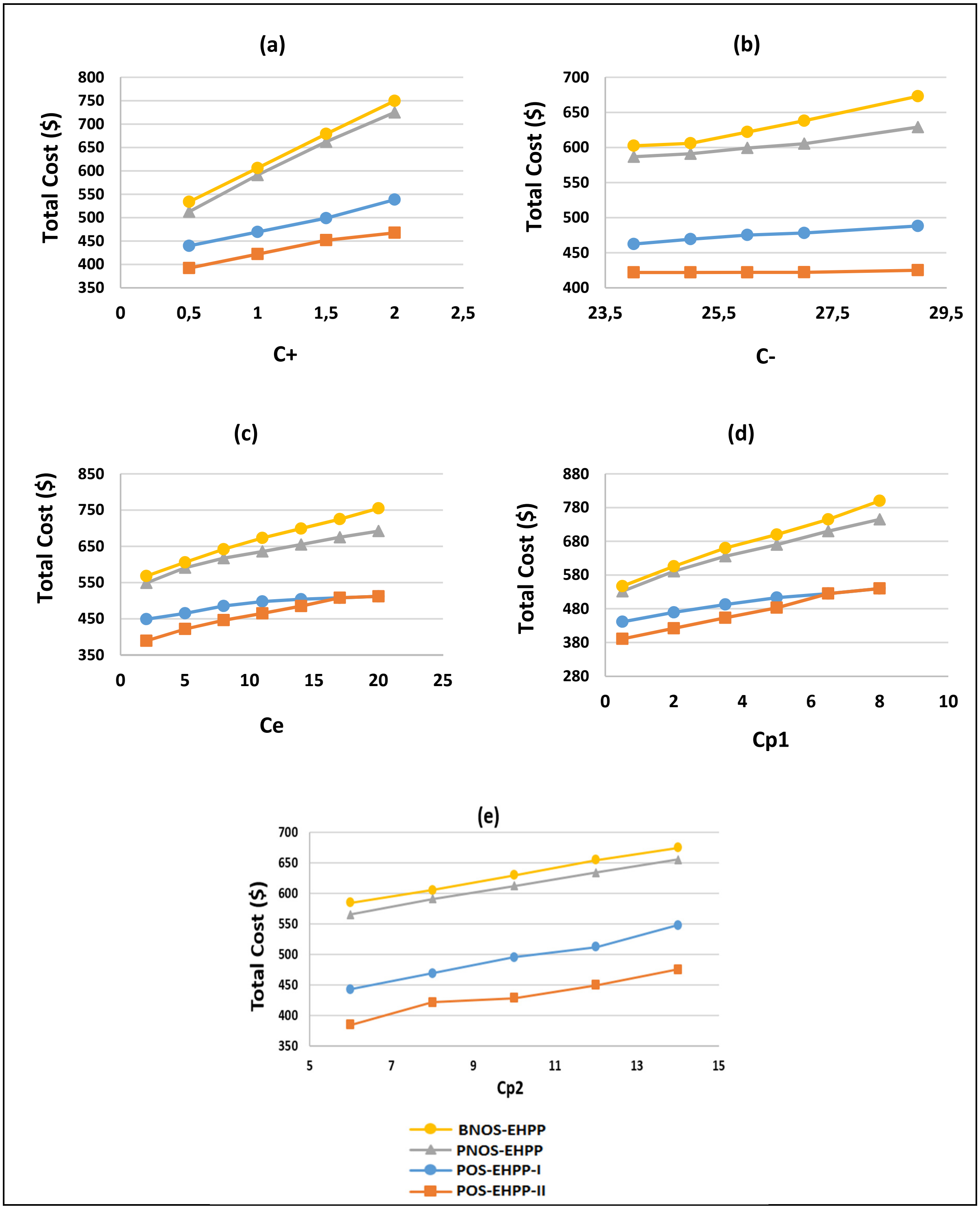

Figure 2.9 Effect of cost parameters (a): c^+: inventory cost, (b): c^-: backlog cost, (c): c^e: emission cost, (d): c_{p_1}: HEM production cost, (e): c_{p_2}: LEM production cost on the incurred total cost for control policies

2.8.2 Comparison of policies for a wide range of system parameters

Figure 2.10 shows the effect of some system parameters on the incurred total cost for the control policies. As is clear from Figure 2.10 (a), when there is an increase in availability of the HEM (Av_1), the total cost decreases because the available production capacity of the HEM will increase and leads to reductions in inventory and backlog and total costs. Based on the figure, by increasing the value of Av_1, the PNOS-EHPP is more efficient in terms of total cost as compared with BNOS-EHPP. By increasing the availability of the HEM, the difference in availability between the two machines increases, and so the impact of PNOS-EHPP on cost reduction is more pronounced.

From the figure, for the considered range of Av_1, the total cost of POS-EHPP-I and POS-EHPP-II is lower than the cost of PNOS-EHPP because OS systems can still lead to significant reductions in inventory and backlog as compared with NOS systems. As the usage percentage of the HEM in POS-EHPP-II is greater than POS-EHPP-I, by increasing the availability of the HEM, the slope of reduction in total cost for POS-EHPP-II is greater than OS-EHPP-I.

Similarly, according to Figure 2.10 (b), when the availability of the LEM (Av_2) increases, the available production capacity of the LEM rises, and so the backlog, inventory and total costs decrease. Hence, before a certain value of $(u_m^2 \times Av_2)/(u_m^1 \times Av_1)$, PNOS-EHPP is more efficient than BNOS-EHPP for NOS systems, and after this point, the total costs for both are the same. When there is a rise in availability for the LEM, using the LEM and HEM simultaneously in POS-EHPP-I and POS-EHPP-II can provide more system availability and cost reductions in comparison with PNOS-EHPP.

In summary, based on all results and comparisons made between the policies, POS-EHPP-I and POS-EHPP-II are the best policies in terms of cost saving and GHG emission performances for a wide range of cost and system parameters. However, POS-EHPP-II is the most appropriate and cost-efficient production control policy for the enterprises aim to invest in the LEM in a gradual fashion.

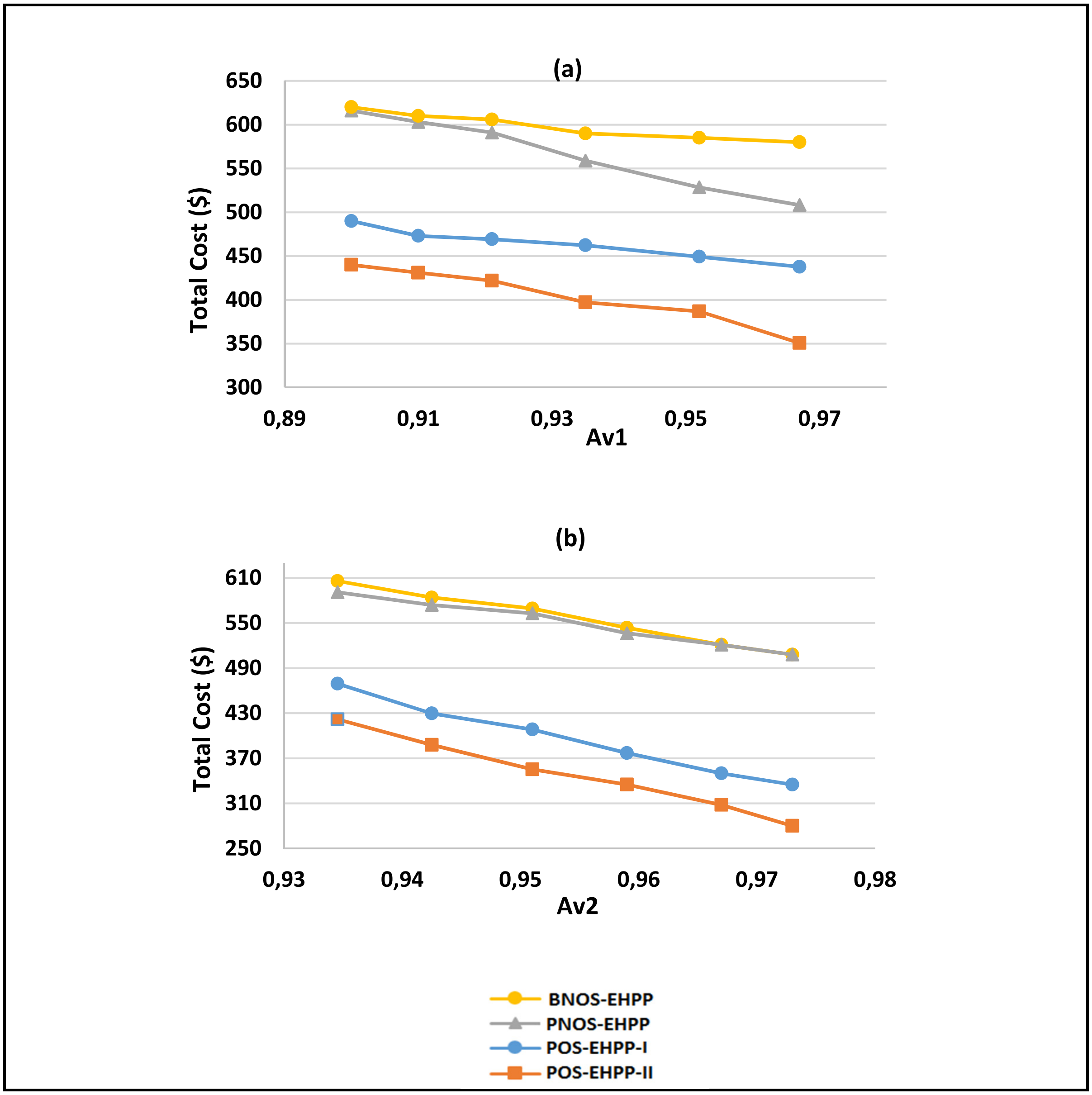

Figure 2.10 Effect of system parameters on the incurred total cost for control policies (a): Av_1 availability of the HEM, (b): Av_2: availability of the LEM

2.8.3 Managerial Insight and Practical Implementation

We developed the most cost-efficient environmentally friendly control policy designed for companies aiming to gradually invest in the LEM. For such companies, the biggest challenge they must tackle is finding an effective plan for the condition and percentage of time that the LEM should be used for manufacturing. The advantage of producing under our developed control policy for the manager is that it can considerably reduce the total cost and generated emissions as compared with other existing policies.

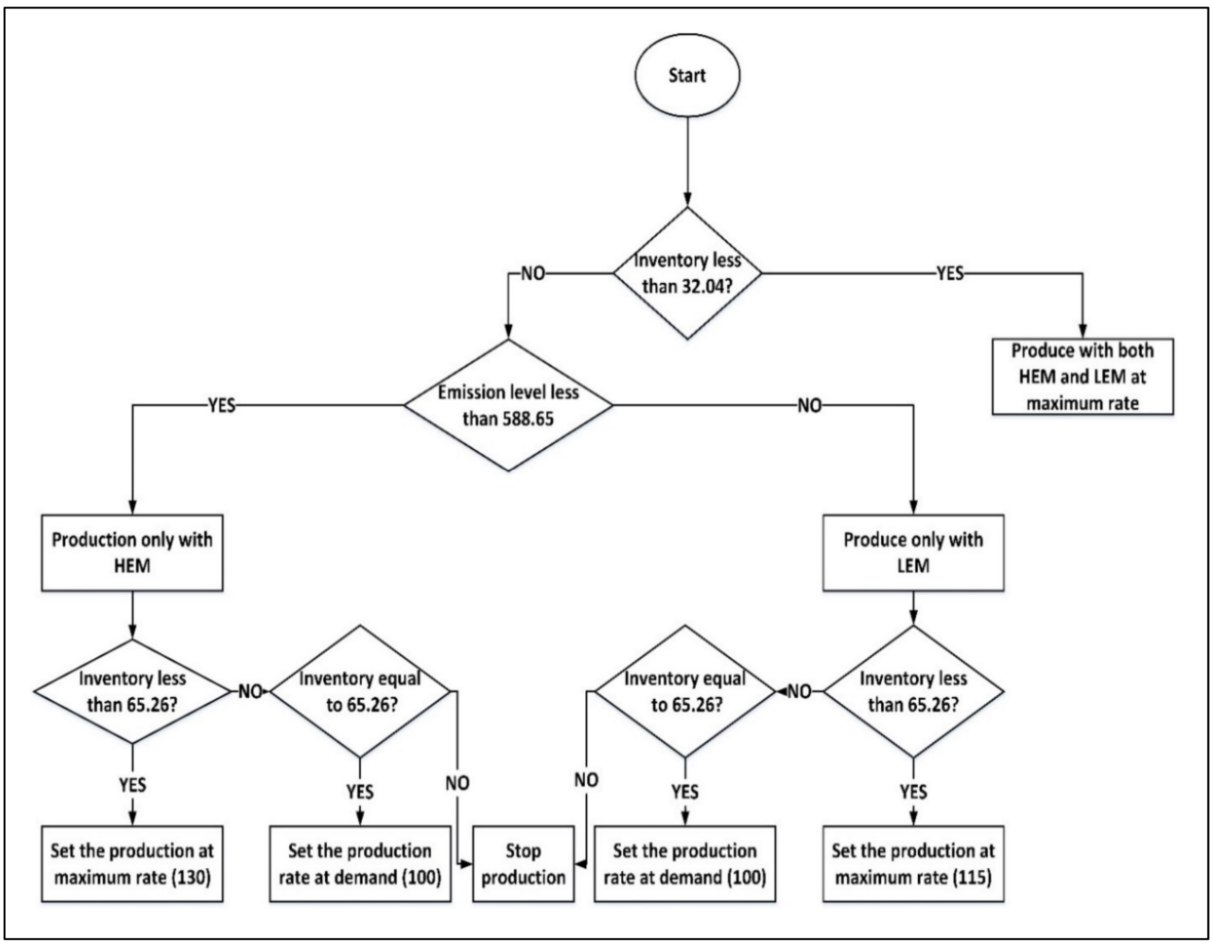

Figure 2.11 Implementation logic chart of POS-EHPP-II

Moreover, our developed control policy allows the manager to synchronize the HEM and LEM to reach defined objectives, minimizing total costs and reducing emissions. Under this policy, he is able to decide which machine (LEM/HEM) should operate and at which speed should produce, at any given time. In this way, the inventory and emission level are required to be monitored by the manager. As an illustration, Figure 2.11 represent a logic chart that guides the process of decision-making.

Based on the Figure, first the manager should monitor the inventory position. If the inventory level is less than 32.04, the manufacturing system should operate with both HEM and LEM at their maximum production rates. As long as the system build the safety stock equal to 32.04, the manager should observe the state of the emission generated by the manufacturing system. If the total emission generated is less than voluntary emission limit (588.65), he should stop the LEM and produce with only HEM. If the total emission generated exceeds 588.65, he should stop the HEM and produce with only LEM.

2.9 Conclusion

This paper deals with the problem of production planning for unreliable manufacturing companies that use high-emitting machines (HEM), and which, in order to decrease their GHG emissions, decide to gradually invest in low-emitting machines (LEM) instead of engaging in a single costly replacement of all machines. Recently, an environmental hedging point policy (BNOS-EHPP) was presented in which the system stops the HEM after the emission limit is exceeded, and then produces only with the LEM. Also, it was considered that the LEM threshold level is less than that for the HEM. However, in real manufacturing systems, the available production capacity of the LEM is less than HEM, and this unrealistic constraint increases the incurred backlog. First, a control policy (PNOS-EHPP) is proposed in this paper by relaxing the LEM threshold level constraint to present a more realistic policy. A comparison of the two policies shows that when the available production capacity ratio of the LEM to HEM is below a certain level, our proposed policy, PNOS-EHPP, is more cost-efficient than BNOS-EHPP. Our objective is to increase the LEM usage and availability of the system and reduce the inventory, emission, and backlog costs. We also developed two new control policies (POS-EHPP-I and POS-EHPP-II), in which the system is allowed to produce with both HEM and LEM simultaneously to reach a certain safety stock level. In POS-EHPP-I, the HEM and LEM are allowed to operate simultaneously only before reaching the emission limit. However, in POS-EHPP-II, the HEM and LEM can produce simultaneously during the entire production period until reaching a certain safety stock level.

Based on simulation optimization, optimal values of control parameters are determined using an experimental approach and response surface methodology. The results show that policies of PNOS-EHPP, POS-EHPP-I and POS-EHPP-II bring significant cost and GHG emission reduction advantages as compared with the BNOS-HPP. Also, a comparison between policies for a wide range of cost and system parameters reveals that POS-EHPP-II is the most cost-effective policy.

In conclusion, the findings from this study support the companies willing to gradually invest in new low-emitting technologies and replace HEMs with LEMs. Our developed control policies can help the manager to synchronize HEM and LEM together.

Future works to follow up on this research should consider the manufacturing system under other environmental regulations such as cap-and-trade approach. Also, the non-linearity of the emission rate could be taken into account to give more flexibility to the emission model. It would be interesting to consider degradation phenomena in which machine availability decreases over time and the emission rate increases. Finally, as an extension of our paper, future works can propose new control policies considering quality control and preventive maintenance in the manufacturing system.

2.10 Acknowledgements

This research has been supported by Natural Sciences and Engineering Research Council of Canada (NSERC) under grant number: RGPIN-2015-06026.

CHAPTER 3

A JOINT PRODUCTION AND CARBON TRADING POLICY FOR UNRELIABLE MANUFACTURING SYSTEMS UNDER CAP-AND-TRADE REGULATION

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Paper published in *Journal of Cleaner Production*, April 2021

Abstract

Manufacturing systems are one of the largest emitters of carbon emissions. Governments enforce environmental regulations to control and reduce such emissions. Cap-and-trade is one of the most efficient and widely-used regulations in which a tradable initial allowance is given to each emitter to sell or buy in the carbon market. In this study, we address the trading and production planning problem for unreliable manufacturing systems under cap-and-trade regulation. Regarding the carbon price which randomly changes in the market, it is challenging and complex for companies to know how to determine their production rate and trading quantity to take advantage of the carbon market. We aim to develop a new joint production and trading control policy for unreliable manufacturing systems considering the stochastic and dynamic context. Our objective is to guide the managers to jointly determine when to buy/sell allowances or increase/decrease the production rate to minimize the total cost and reduce carbon emissions of the system. The policy is specifically designed for the cap-and-trade regulation to minimize total costs consisting of emission, backlog, inventory, trading, and transaction costs. Simulation modelling, experimental design, and response surface methodology are implemented to optimize parameters of our proposed control policy. Finally, sensitivity analysis as well as comparative study are carried out to show how our proposed joint policy brings significant cost saving and emissions reduction in comparison with existing policies adapted from the literature.

Keywords: Unreliable manufacturing system, joint production and trading policy, greenhouse gas emissions, cap-and-trade, simulation optimization.

3.1 Introduction

In the last decades, there has been a considerable increase in the greenhouse gas (GHG) emissions caused by industrial activities in different services and production operations. Given the negative environmental impacts of GHGs, many environmental regulations have been developed by countries to mitigate the emissions caused by manufacturing companies. Carbon taxes and cap-and-trade schemes are two market-based approaches for curbing emissions (Benjaafar et al., 2012, Zakeri et al., 2015).

Under the carbon taxes scheme, companies are charged for their emissions at a constant level of tax rate (Xu et al., 2016). On the other side, based on the cap-and-trade scheme, a limited amount of tradable carbon allowances (cap) is considered for distribution among emitters. They are permitted to trade allowances with other emitters, government agencies or brokers (Ji et al., 2017). At the compliance period end, companies which generate emissions more than the allocated allowances are penalized by significant fines or need to purchase allowances from companies which generate emissions less than the allowed level (Kuiti et al., 2020). Indeed, cap-and-trade as one of the most business-friendly schemes has been implemented in North America, Europe, Australia and various regions in the world (Xu et al., 2016).

For high emitting industries including concrete, steel, and car manufacturers, pulp and paper, as well as chemical facilities, it is a major challenge to rethink their operational decisions such as production quantities and carbon allowance trading under cap-and-trade. On the one side, it is important to know how to adjust the production plan considering the features of cap-and-trade. On the other side, it is important to know how to trade and decide whether and to what extent the carbon allowances should be sold or bought during the planning horizon. At each moment, the manufacturer can decide whether to sell or buy carbon allowance in the market in which trading prices vary randomly. Carbon allowance trading combined with a cost-effective production policy can help the companies to reduce generated GHG emissions and reduce the total costs (Gong and Zhou 2013). Consequently, it is important to develop the optimal joint production and trading policy considering varying carbon price to minimize total costs and decrease emissions of such manufacturing systems.

It is worthwhile to note that the large part of the studies on manufacturing system models under cap-and-trade have focused on deterministic contexts and supposed that the manufacturing system is perfect and reliable. In these previous research works, time to failure and time to repair defining the system availability is not taken into account (Zhang et al., 2019; Dou et al., 2019). Indeed, system availability has a considerable impact on the performance of the system particularly when time to failure and repair are random. Unreliable manufacturing system is a failure-prone system subject to random breakdowns and repair times. Due to the stochastic repair time during which there is no production, the system may face backlog if there is no inventory to satisfy the demand. To provide more applicable and realistic solutions, the stochastic and dynamic context of manufacturing systems is considered in our study.

All things considered, to fit in with the cap-and-trade scheme, the companies face major challenges of adjusting their production policies and deciding how to trade in the carbon market to achieve both environmental and economic goals. Subsequently, the most important research questions of this study can be stated as follows: Under cap-and-trade regulation, which production control policy can be the most effective one with regards to cost and emissions reduction to manage failure-prone manufacturing systems? What is the optimal inventory threshold level to face backorders? What is the optimal trading policy? How much, when and under what conditions carbon allowances should be sold or bought considering varying carbon price? Accordingly, our objective is to develop a new optimal joint production and trading policy for unreliable manufacturing systems under cap-and-trade regulation, reducing carbon emissions and minimizing total cost which includes emission, inventory, backlog, trading, and transaction costs. Our new developed policy should help the managers to jointly decide on allowance trading and production rate in order to benefit from the carbon price variation while respecting environmental and manufacturing constraints.

The rest of this paper is structured as follows. A literature review is presented in Section 3.2. The problem statement is discussed in Section 3.3. Our resolution approach is presented in Section 3.4. A new joint production and trading policy formulation is provided in Sections 3.5. Section 3.6 presents the simulation model and validation. Numerical results, response surface methodology (RSM) model, optimization and sensitivity analysis are provided in Section 3.7. Comparative study and managerial insights are provided in Sections 3.8 and 3.9. Finally, conclusion and future research work are reported.

3.2 Literature review

In this section, we review the most relevant research works to our study, manufacturing system models and control policies under environmental regulations, which are divided into two categories of deterministic and stochastic context. In Table 3.1, a comparison has been made among related studies in terms of stochastic/deterministic context, type of environmental regulation (carbon tax or cap-and-trade), production and inventory policy (economic order quantity (EOQ), economic production quantity (EPQ), and hedging point policy (HPP)), developing carbon trading policy, considering varying carbon price.

The first category of the research investigates the manufacturing system models under cap-and-trade regulation. The majority of these studies have addressed the manufacturing system models without considering the machine failures. In this deterministic context, analytical models have been commonly developed to solve these optimization problems. Letmathe and Balakrishnan (2005) presented a mathematical model in order to obtain optimal production quantities for manufacturing systems with one operation procedure for producing each product under carbon tax regulation and cap-and-trade. They conducted several what-if scenarios and analyzed the effect of changes in emission tax and emission cap.

Table 3.1 Literature review of manufacturing system models and control in the light of environmental aspects

Authors	Unreliable Manufacturing Systems	Environmental Regulation		Production and Inventory Control Policy			Carbon Trading Policy	Varying Carbon Price
		Carbon Tax	Cap & Trade	Stochastic Context	Deterministic Context			
				HPP	EOQ	EPQ		
Category 1: Manufacturing system models under environmental regulations with deterministic context								
(Zhang et al., 2019)			✓			✓		✓
(Wang et al., 2018)			✓			✓		
(Yang et al., 2018)			✓			✓	✓	
(Xu et al., 2017a)			✓			✓	✓	
(Xu et al., 2017b).			✓			✓	✓	
(Wang et al., 2017)			✓			✓		
(Du et al., 2016a)			✓			✓		
(Du et al., 2016b)			✓			✓		
(Xu et al., 2016)		✓	✓			✓		
(Zhou et al., 2016)			✓			✓		
(He et al., 2015)		✓	✓		✓			
(Gong and Zhou, 2013)			✓		✓		✓	✓
(Hua et al., 2011)			✓		✓			
(Letmathe and Balakrishnan, 2005)		✓	✓			✓		
Category 2: Manufacturing system models under environmental regulations with stochastic context								
(Entezaminia et al., 2020)	✓	✓		✓				
(Hajej et al., 2019)	✓	✓		✓				
(Turki et al., 2018a)	✓		✓	✓				
(Afshar-Bakeshloo et al., 2018)	✓	✓	✓	✓				
(Hajej et al., 2017a)	✓	✓		✓				
(Hajej et al., 2017b)	✓	✓		✓				
(Ben-Salem et al., 2016)	✓	✓		✓				
(Ben-Salem et al., 2015a)	✓	✓		✓				
(Ben-Salem et al., 2015b)	✓	✓		✓				
This paper	✓		✓	✓			✓	✓

Hua et al., (2011) investigated the inventory management problem of firms under the carbon allowance trading mechanism. The optimal order quantity is obtained and the effect of carbon trade, carbon price and carbon cap on ordering decisions is examined. Gong and Zhou (2013) proposed optimal production and carbon emissions trading policies for a single product manufacturing system to minimize total costs. The optimal allowance trading policy is a target interval policy including two thresholds decreasing with the inventory level. The problem of lot-sizing in production based upon the economic order quantity (EOQ) was addressed by He et al., (2015) for a company under carbon tax regulation as well as cap-and-trade. A multi-stage dynamic optimization model was developed by Zhou et al., (2016) to obtain the optimal solutions for operational decisions of the manufacturing systems regulated by cap-and-trade including decisions on purchasing carbon credit, carrying over surplus emissions. Xu et al., (2016) focused on the problem of production and pricing for multi-product production companies under carbon tax and cap-and-trade.

Du et al., (2016a) studied the multi-product pricing and production problem on condition that environment-concerned consumers value the low-carbon products higher than ordinary products. Du et al., (2016b) analyzed the effect of carbon emissions and low-carbon preference on demand, market supply as well as production decisions and developed an optimization model for the production decisions of companies under cap-and-trade. Wang et al., (2017) examined the problem of manufacturing/remanufacturing planning under cap-and-trade and applied a downward substitution strategy to obtain the optimal quantities of production. Xu et al., (2017a) focused on the problem of pricing and production problem for an upstream manufacturer producing two products under cap-and-trade. Xu et al., (2017b) addressed the production and emissions reduction decisions of a manufacturer and retailer in a Market-To-Order supply chain under cap-and-trade.

Yang et al., (2018) formulated a mathematical model under cap-and-trade to help generating companies to decide on the green technology investment, emission permit trading. Wang et al., (2018) proposed a mathematical model to deal with the impact of cap-and-trade on production planning of companies. They used cost-benefit analysis to identify the optimal emissions reduction strategy to choose between alternatives of buying carbon credits and conducting the low-carbon technology. Zhang et al., (2019) developed the models of evolutionary game between manufacturers and governments under dynamic carbon trading price.

On the other hand, the second category studies the failure-prone manufacturing system models under environmental regulations. In this stochastic context, simulation optimization has been usually used to solve these problems as the analytical models are unable to solve such complex problems except some cases when assumptions are added to be the problem to make it analytical tractable. In regards to unreliable manufacturing systems, hedging point policy (HPP) is among the most common and effective strategies dealing with stochastic dynamic context of the production systems (Kenné and Gharbi 2000). According to HPP, the production rate is controlled by the inventory level to make a certain level of safety stock for failure duration to meet the demand (Akella and Kumar 1986). HPP is extended to various aspects of production systems. Nevertheless, little attention has been paid to the environmental aspect of stochastic and dynamic systems.

Environmental Hedging Point Policy (EHPP) as a new extended structure of HPP was proposed by Ben-Salem et al., (2015a) for unreliable systems under carbon tax regulation. Beside inventory level feedback, an additional emissions level feedback is taken into account to decide on production quantities. The manufacturer needs to have an emissions limit beyond which he decides to stop the production process to control total emissions. Ben-Salem et al., (2015b) proposed an EHPP for controlling maintenance, production as well as emission rates considering the degradation phenomena in the system. A production and subcontracting control policy was developed by Ben-Salem et al., (2016) for unreliable manufacturing systems producing under carbon tax. The system can partially satisfy the demand by an unreliable green subcontractor to control total generated emissions of the system.

Afshar-Bakeshloo et al., (2018) developed an EHPP for an unreliable manufacturing system under which employs low-emitting technology after exceeding a certain emission limit. They examined carbon tax regulation as well as cap-and-trade by implementing their proposed policy. Entezaminia et al., (2020) developed two new production policies addressing unreliable systems consisting of high-emitting machines as well as low-emitting ones under carbon tax. Operating both machines simultaneously, increases the entire system availability and decreases the costs including emission, backlog and inventory costs. Turki et al., (2018a) investigated an optimal manufacturing/remanufacturing and inventory planning under cap-and-trade regulation considering random demand, random machine failures, and carbon constraint. Considering a fixed carbon allowance price, if the carbon emitted is less than cap the manufacturer sells the extra allowances. Otherwise, he is obliged to buy carbon allowance. Based on the results, a high allowance trading price or/and lower cap persuade the system to collect returned products, remanufacture and reduce emissions.

Some studies have addressed analytical modelling of stochastic and dynamic production control problems. In this regard, Hajej et al., (2017a) developed an optimal control policy of maintenance and production regulated by carbon tax considering the influence of system deterioration to minimize total costs of production, emission, inventory, and maintenance. Hajej et al., (2017b) proposed an ecological production, subcontracting and maintenance policy for a failure-prone production system regulated by carbon tax which is subject to degradation. An optimal maintenance and production policy was developed by Hajej et al., (2019) for closed-loop unreliable systems with subcontracting regulated by carbon tax. To mitigate total emissions, the subcontractor is considered to help either the manufacturing system or the remanufacturing system during the production process. The economic plan for manufacturing, remanufacturing, subcontracting and preventive maintenance is obtained by minimizing total costs.

According to the provided literature review, it can be seen that most manufacturing system models under cap-and-trade have focused on the deterministic context. On the other hand, most research works dealing with stochastic and dynamic aspects of the manufacturing systems focused on carbon tax regulation. Thus, studies on stochastic and dynamic context of unreliable manufacturing systems regulated by cap-and-trade scheme are still lacking.

In addition, the literature published on manufacturing system models considering cap-and-trade have mostly addressed the effect of environmental regulations on production decisions to minimize total costs (e.g., He et al., 2015; Xu et al., 2016; Turki et al., 2018a; Zhang et al., 2019). Some studies have focused on how to comply with cap-and-trade and reduce GHGs generated from the production process (e.g., Du et al., 2016a; Zhou et al., 2016; Du et al., 2016b; Wang et al., 2017; Wang et al., 2018). However, there are a few papers dealing with developing allowance trading policies for the companies regulated by cap-and-trade. These papers combined the production and trading policy in the deterministic context of manufacturing systems.

When it comes to trading policies, Yang et al., 2018 compared the total expected emitted carbon with the carbon cap and decide to sell or buy carbon allowances. By defining scenarios for a specific autoregressive process of the carbon price, they found one optimal period to sell/buy the entire amount of emission permit. To the best of our knowledge, Gong and Zhou (2013), Xu et al., (2017a) and Xu et al., (2017b) are the only studies dealt with developing trading policies during the compliance period. They focused on a target interval policy characterized by two threshold trading levels in which the optimal lower or upper bound for allowance level is determined to decide about trading. According to the literature, the key limitations of the existing research works is that they have not focused on developing a joint production and trading policy for unreliable manufacturing systems specifically designed for the cap-and-trade regulation and its features.

Moreover, when it comes to the carbon price variation, Zhang et al., (2019) dealt with the impact of cap-and-trade regulation on decisions of manufacturers under both static and dynamic trading price. Yang et al., (2018) considered fluctuating carbon prices following a first-order autoregressive process. Gong and Zhou (2013) considered carbon price as no-negative random variables. According to the literature, the existing research works are limited by considering a specific function or probability distribution for carbon price. No study can be found that address any random variation of carbon price in manufacturing system models under cap-and-trade regulation. However, to implement our proposed policy, the carbon price can follow any random variation. For illustrative purposes, we assumed that carbon price can follow any probability distribution.

Our contribution is to propose a new joint production and trading policy for the stochastic context of failure-prone manufacturing systems regulated by cap-and-trade. The random variation of carbon price is also taken into account in our study. Our policy allows the decision maker to jointly decide on both production and trading and determine when it is interesting to sell/buy carbon allowances or increase/decrease the production rate. Our proposed control policy has wide-range implications for the high emitting companies who are willing to find an effective dynamic plan for their production and conditions under which the carbon allowances should be sold or bought during the compliance period. By implementing our environmentally-friendly and cost-effective proposed policy, the manufacturers are able to simultaneously minimize total costs and reduce emissions.

3.3 Description of the problem

3.3.1 Notations

Notations employed in the paper are listed below. Here, tCO_2e means metrics tons of carbon dioxide equivalent.

$x(t)$	inventory/backlog level at time t
$A(t)$	remaining allowance level at time t
$P(t)$	carbon price ($/$tCO_2e$)
$\alpha(t)$	machine operational state, 0 means it is down and 1 means it is operational
$u(t)$	machine production rate (product/time unit)
U_m	maximum production rate (product/time unit)
d	rate of demand
IA	Initial allowance associated to the company
TTR	time to repair
TTF	time to failure

$MTTR$	mean time to repair
$MTTF$	mean time to failure
c^+	inventory cost of products ($/product/time unit)
c^-	backlog cost of products ($/product/time unit)
c^e	penalty cost of each tCO_2e violation at the compliance period end ($/$tCO_2e$)
c_{tr}	emission transaction cost ($/transaction)
θ	emission index of producing
Av	availability of the machine
P_c	length of compliance period

Control factors

Z_H	high inventory threshold level
Z_L	low inventory threshold level
Ss	carbon allowance level defining the comfort zone for selling (selling limit)
S_b	carbon allowance level to which the system is permitted to buy allowances (S_b>S_s)
σ	price fluctuation defining the good price for selling/buying The price which is more than μ+σ is good for selling The price which is less than μ-σ is good for buying

3.3.2 Problem description

Figure 3.1 represents our considered manufacturing system which consists of an unreliable machine producing one type of product to satisfy the demand. Moreover, the production process which generates a considerable amount of emissions is regulated by cap-and-trade.

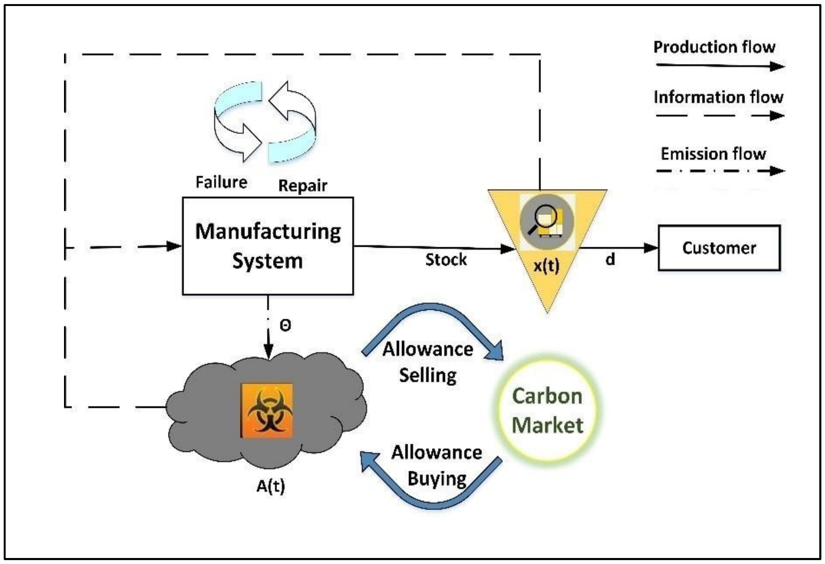


Figure 3.1 Considered production system

Figure 3.2 shows how companies trade in carbon market based on emission allowances under cap-and-trade. The company is given a specific quota of tradable carbon emissions from authorities that is defined as initial allowance (*IA*). This carbon allowance is permitted to be traded in the market.

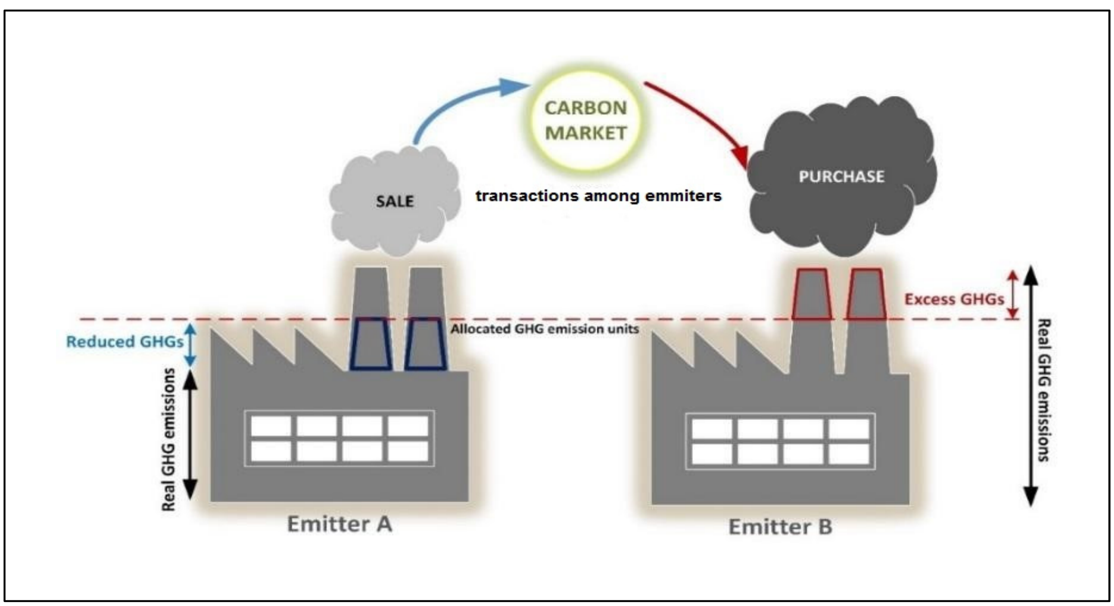


Figure 3.2 Carbon market for carbon allowances

At the end of the compliance period, if the companies emit more than their initial allowance, they have to purchase enough allowance from the market otherwise they have to pay an emission penalty. If they have surplus allowance, they can sell it in the market to make profits that reduce its costs. Under this regulation, we aim to find a joint optimal production and trading policy for such system to minimize the total costs of the unreliable manufacturing system including inventory, backlog, emission, transaction and carbon allowance costs (buying minus selling).

For the considered manufacturing system, $u(t)$ denotes production rates of the failure-prone machine. Duration of failure and repair are also taken into account. Emission index of the system, θ represents the pollution quantity generated by producing one product unit. Emission index is considered to follow a probability distribution.

Feedbacks on inventory level, allowance level and carbon price in the market are sent to system to decide on production rate and carbon trading. The machine availability can be calculated as follows:

$$Av = (MTTF)/(MTTF + MTTR) \tag{3.1}$$

At any time of t, $x(t), A(t),$ and $\alpha(t)$ present the system dynamic behavior. As a discrete component, $\{\alpha(t), t > 0\} \in \{0,1\}$ equals 0 when the machine is down and equals 1 when the machine is up.

Furthermore, continuous parts of the state of the system are $x(t) \in R$, which describes the inventory level, as well as $A(t) \in R$ which represents the remaining allowance level. $x(t)$ and $A(t)$ can be described by Equations (3.2) and (3.3). x_0 represents the initial level of inventory/backlog.

$$\frac{dx(t)}{dt} = u(t) \times \alpha(t) - d \qquad x(t_0) = x_0 \tag{3.2}$$

$$\frac{dA(t)}{dt} = -u(t) \times \alpha(t) \times \theta \tag{3.3}$$

The capacity constraint of the system under study is shown as follows:

$$0 \leq u(t) \leq U_m \tag{3.4}$$

The following constraint is provided to guarantee the system feasibility (production higher than customer's demand):

$$u_m \times Av \geq d \tag{3.5}$$

The system cost includes the emission penalty cost, backlog cost, inventory cost, allowance buying cost, allowance transaction cost, minus allowance selling revenue. The inventory and backlog costs are calculated based on the surplus level, $x(t)$ as follows:

$$h(x(t)) = c^{+}x^{+} + c^{-}x^{-} \tag{3.6}$$

Where, $x^{+} = (0, x)$, $x^{-} = (-x, 0)$. $c^{+}$is the inventory cost and c^{-} is the backlog cost. Based on the cap-and-trade regulation, if the company generates emissions more than the initial allowance and there is no chance to compensate the extra generated emissions, an emission penalty cost needs to be paid as follows:

$$EC(t_i) = c^{e} \times max(0, A(t_i) - IA) \qquad i = 1, \dots, N;\ \ t_i = i \times P_c;\ \ \ A(t_i) = IA \tag{3.7}$$

It is assumed that the system needs to check the carbon price every p units of time to decide on trading. Trading costs including transaction cost, allowance buying cost, and allowance selling revenue can be defined as follows:

$$TC(t_k) = c_{tr} + P(t_k) \times Trade(t_k) \qquad k = 1, \dots, M;\ t_k = k \times p \tag{3.8}$$

$Trade(t_k)$ can be positive showing buying costs or negative showing selling revenue. Using Equations (3.6) to (3.8), the average total costs can be given as below:

$$J(x, A, \alpha) = \int_0^{N\times P_c} h(x(t))\,dt + \frac{1}{N\times P_c}\left(\sum_{i=1}^{N} EC(t_i) + \sum_{i=1}^{M} TC(t_k)\right) \tag{3.9}$$

The optimal control policy seeks for minimizing $j(.)$ considering the constraints (3.1) -(3.5), in order to obtain production rate as a function of $\alpha(t), x(t), A(t)$.

3.4 Resolution approach

In this section we focus on our resolution approach and methodology used in the paper. To solve our complex problem and estimate optimal values for control parameters that minimizes total costs presented in Equation (3.9), an experimental resolution approach integrated with the design of experiment (DOE), the simulation technique, as well as the response surface methodology (RSM) is developed. Indeed, regarding the stochastic behavior of the considered manufacturing system and the complexity of the system dynamic represented by Equation (3.9), it is difficult to obtain an analytical solution (Afshar-Bakeshloo et al., 2018). Hence, to address the problem complexity, experimental resolution approach integrated with DOE, the simulation technique, and RSM is adapted to our study as in (Ben-Salem et al., 2016), (Afshar-Bakeshloo et al., 2018) and (Entezaminia et al., 2020). Seven steps of our resolution approach, are described as follows as briefly shown in Figure 3.3:

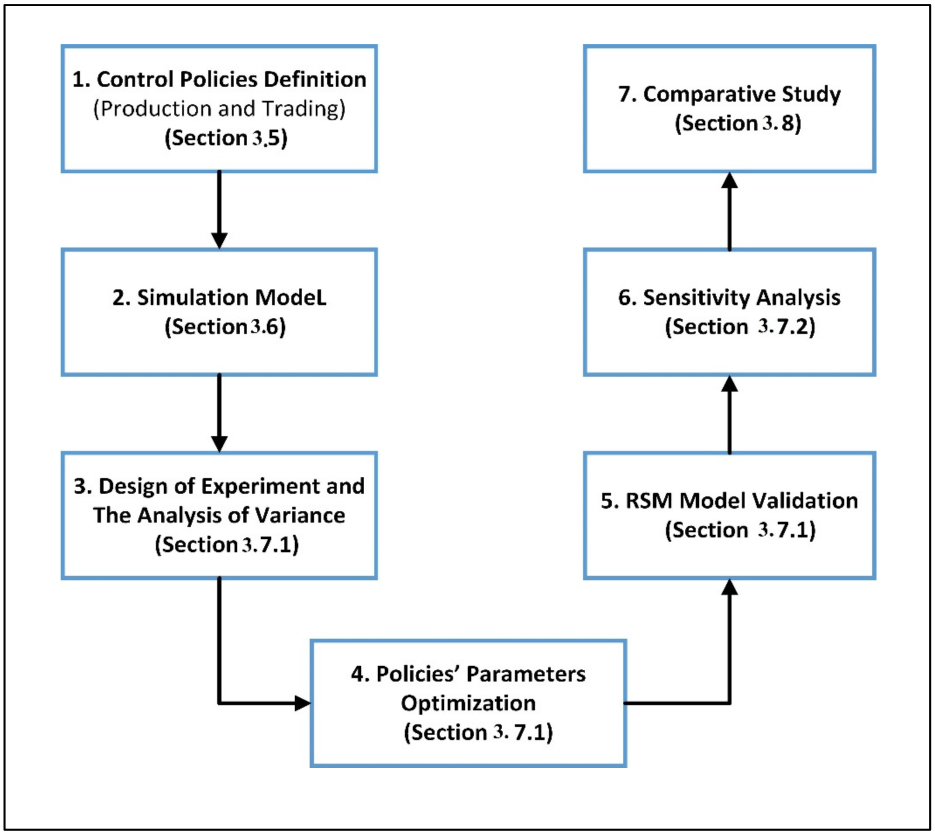


Figure 3.3 Experimental resolution approach

- ✓ step 1: Definition of the control policy

According to the figure, first the structure of the control policy presented by Equations (3.11) to (3.14) (see Section 3.5).

- ✓ step 2: Simulation model

A simulation model has been built to show system dynamics considering the control policy as the input and total costs as the output (see Section 3.6).

- ✓ step 3: Design of experiment (DOE) and the analysis of variance (ANOVA)

The number of experiments as well as the level of each independent variable are defined to conduct several experiments and then evaluate the system performance. We used the analysis of variance (ANOVA) to show effects of control parameters and their interactions on the total cost, as the response variable. In this way, main independent variables which significantly affect total costs are specified (see Section 3.7.1).

- ✓ step 4: Control parameters estimation and optimization

The response surface methodology (RSM) is used to establish the effect of significant control parameters, their quadratic effects and interactions on response variable. By implementing a combination of the experimental design, RSM as well as the regression analysis, we can provide the total cost (*TC*) approximation function as follows (Myers et al., 2016):

$$TC = \beta_0 + \beta_1 Z_H + \beta_2 Z_L + \beta_3 S_s + \beta_4 S_b + \beta_5 \sigma + \beta_{11} Z_H^2 + \beta_{12} Z_H Z_L + \beta_{13} Z_H S_s + \beta_{14} Z_H S_b + \beta_{15} Z_H \sigma + \beta_{22} Z_L^2 + \beta_{23} Z_L S_s + \beta_{24} Z_L S_b + \beta_{25} Z_L \sigma + \beta_{33} S_s^2 + \beta_{34} S_s S_b + \beta_{35} S_s \sigma + \beta_{44} S_b^2 + \beta_{45} S_b \sigma + \beta_{55} \sigma^2 + \varepsilon \tag{3.10}$$

Using data obtained from the simulation model, the estimated values of unknown coefficients, β_0, β_i and β_{ij} ($i, j \in \{1, 2, 3, 4, 5\}$), are provided. The random error is also shown by ε. Then, optimal values of main control parameters minimizing the total incurred cost are obtained (see Section 3.7.1).

- ✓ step 5: Model validation

Three steps are followed based on Myers et al., (2016) to validate the regression model.

- ➢ first, to evaluate the overall model performance, the adjusted R-squared coefficient is taken into account. It measures the proportion of variation in the dependent variable (total costs) explained by independent variables for our regression model. Indeed, the adjusted R-squared is more appropriate when it is close to 1.

- ➢ secondly, a residual analysis is performed in order to check the residual normality and homogeneity of variances.

- thirdly, a Student's t-test is carried out after optimizing the regression model in order to crosscheck the model validity. In this regard, a confidence interval (at 95%) is determined. Indeed, the optimal value of total costs needs to fall within the provided confidence interval by running the simulation model for a particular number of extra replications (see Section 3.7.1).

- ✓ step 6: Sensitivity analysis

Sensitivity analyses are conducted to evaluate our proposed joint production and trading policy and the resolution approach robustness (see Section 3.7.2).

- ✓ step 7: Comparative study

A comparison is made between our proposed joint production and trading policy and an adaptation of the most relevant existing control policies in the literature for a broad range of cost parameters (inventory, backlog, emission as well as transaction cost), and system parameters (system availability, initial allowance and carbon price) to specify the most effective control policy in terms of minimizing total cost and reducing carbon emissions (see Section 3.8).

3.5 Formulation of proposed Joint Production and Trading Policy for unreliable systems under cap-and-trade (JPTP)

In this section, we proceed to propose a new joint production and carbon trading policy for failure-prone manufacturing systems regulated by cap-and-trade. In our proposed policy we tend to find a cost-effective dynamic plan for the condition under which the allowances should be sold or bought during the compliance period. On the one hand, the level of remaining allowance can affect the trading decisions because it is important to know how much emissions the manufacturing system is still allowed to generate (Gong and Zhou 2013). In our proposed policy, if the remaining allowance level is high, the production manager is confident to sell the allowances till a specific level (S_s). Similarly, if the level of remaining allowance is low and we are likely to deplete our carbon allowances, the manager may decide to buy allowances till a specific level (S_b) in order to avoid emission penalty. Besides, the other significant factor which can be taken into account is the carbon price. We also consider the random variation of carbon price, so it is significant for the manager to buy allowances if the carbon price is rather low and sell allowances if the carbon price is high. In this regard, we defined the control factor of σ which is the price fluctuation ($\mu \pm \sigma$) determining the good price for selling or buying.

Moreover, the allowance level is impacted by both the trading and production policies. By producing, the manufacturing system generates carbon emissions which decreases the allowance level. For the unreliable manufacturing systems under cap-and-trade it is important to realize how to control the system production rate when the allowance level is changing by carbon allowance trading. When there are enough allowances in the system and the carbon price is not good for selling, the system can take advantage of staying in the allowance comfort zone to produce till reaching a high inventory threshold level of Z_H. When the allowance level is low and even the carbon price is not good for buying, the manufacturer should reduce emissions by producing less. The manufacturer should stop the production till reaching a low inventory threshold level of Z_L ($Z_L < Z_H$) in order to reduce emissions while minimizing backlog risk.

In this way, decisions on the production rate of the failure-prone manufacturing system under cap-and-trade are made based on the inventory level, allowance level, as well as carbon price. Therefore, our proposed joint production and trading policy designed for the failure-prone manufacturing systems regulated by cap-and-trade is as follows:

If $A(t) > S_s$:

If $P(t) < PU$ then Trade(t) =0

$$u(t) = \begin{cases} Um & if\ x(t) < Z_H \\ d & if\ x(t) = Z_H \\ 0 & if\ x(t) > Z_H \end{cases} \tag{3.11}$$

If $P(t) \geq PU$ then Trade(t) = -($A(t)$ - S_s)

$$u(t) = \begin{cases} Um & if\ x(t) < Z_L \\ d & if\ x(t) = Z_L \\ 0 & if\ x(t) > Z_L \end{cases} \tag{3.12}$$

If $A(t) \leq S_s$:

If $P(t) \geq PL$ then Trade(t) =0

$$u(t) = \begin{cases} Um & if\ x(t) < Z_L \\ d & if\ x(t) = Z_L \\ 0 & if\ x(t) > Z_L \end{cases} \tag{3.13}$$

If $P(t) < PL$ then Trade(t) = +(S_b- $A(t)$)

$$u(t) = \begin{cases} Um & if\ x(t) < Z_H \\ d & if\ x(t) = Z_H \\ 0 & if\ x(t) > Z_H \end{cases} \tag{3.14}$$

As can be seen from the Equation (3.11), when the allowance level is more than S_s, the system is in the comfort zone for selling carbon allowances in the market. If the carbon price is less than $PU = \mu + \sigma$, it is not high enough to sell the carbon allowances and the system will not trade any allowances. So, the system remains in the comfort zone for selling and the production system is confident to produce more and reach a high inventory threshold level of Z_H. However, based on the Equation (3.12) when the allowance level is more than S_s and the price is more than $PU = \mu + \sigma$ (high enough), the system is confident to sell allowances till reaching the carbon allowance level of S_s. After selling, the allowance level falls to S_s which is low. In this situation the manufacturing system needs to reduce generated emissions by stopping the production till reaching a low inventory threshold level of Z_L. According to Equation (3.13), when the allowance level is equal or less than S_s, it is time to buy allowances but not at any prices. If the price is not less than $PL= \mu\text{-}\sigma$, it is not low enough to buy allowances. So, there is no trade in this situation. In order to keep allowances the manager needs to reduce the generated emissions generated by production. In this situation, the manufacturing system needs to stop the production till reaching Z_L. As can be seen in the Equation (3.14), when the allowance level is less than S_s, it is time to buy allowances, so the carbon price needs to be checked. If it is less than $PL= \mu\text{-}\sigma$, (low enough), the system will buy allowances till the allowance level of S_b. So, the allowance level will go back to the comfort zone for selling and the manufacturing system is confident to produce more and build inventory till reaching the high threshold level of Z_H. In our policy, according to European Union emission trading scheme (EU ETS), it is assumed that at the compliance period end, if the system exceeds the dedicated initial allowances, it will be penalized by emission cost. If there are extra allowances at the end of the compliance period, a small portion (2.5%) of the initial allowances will be carried over and kept for the next compliance period and the rest is obliged to be sold in the market.

3.6 Simulation model and validation

In our system, there are both continuous and discrete events such as the continuous part of the inventory surplus level as well as the discrete part of the system state. Consequently, a discrete-continuous simulation model is designed for our proposed joint production and trading policy in Arena simulator software. Moreover, discrete-continuous simulation modeling reduces the computational time compared with discrete event simulation modeling (Lavoie et al., 2007). Figure 3.4 shows the simulation model for our proposed control policy.

As shown in the figure, the model started in Block 1 by defining inputs and parameters ($Z_L, Z_H, U_m, d,$ etc.). Then, Blocks 2 and 3 demonstrate that the manufacturing system is failure-prone. Block 4 shows the carbon price which randomly changes. Block 5 shows the manufacturing system works according to our proposed joint production and trading policy (JPTP) in order to satisfy the customer demand which is represented by Block 6. The variation of inventory surplus according to Equation (3.2), and the remaining allowance level according to the Equation (3.3) are demonstrated in Block 7. Then, the simulation time advances (Block 8) and as shown in Block 9, the model updates $x(t)$, the level of inventory surplus, and $A(t)$, the remaining allowance level. The emission, backlog, inventory, production, transaction and trading costs as well as revenues are calculated (Block 10).

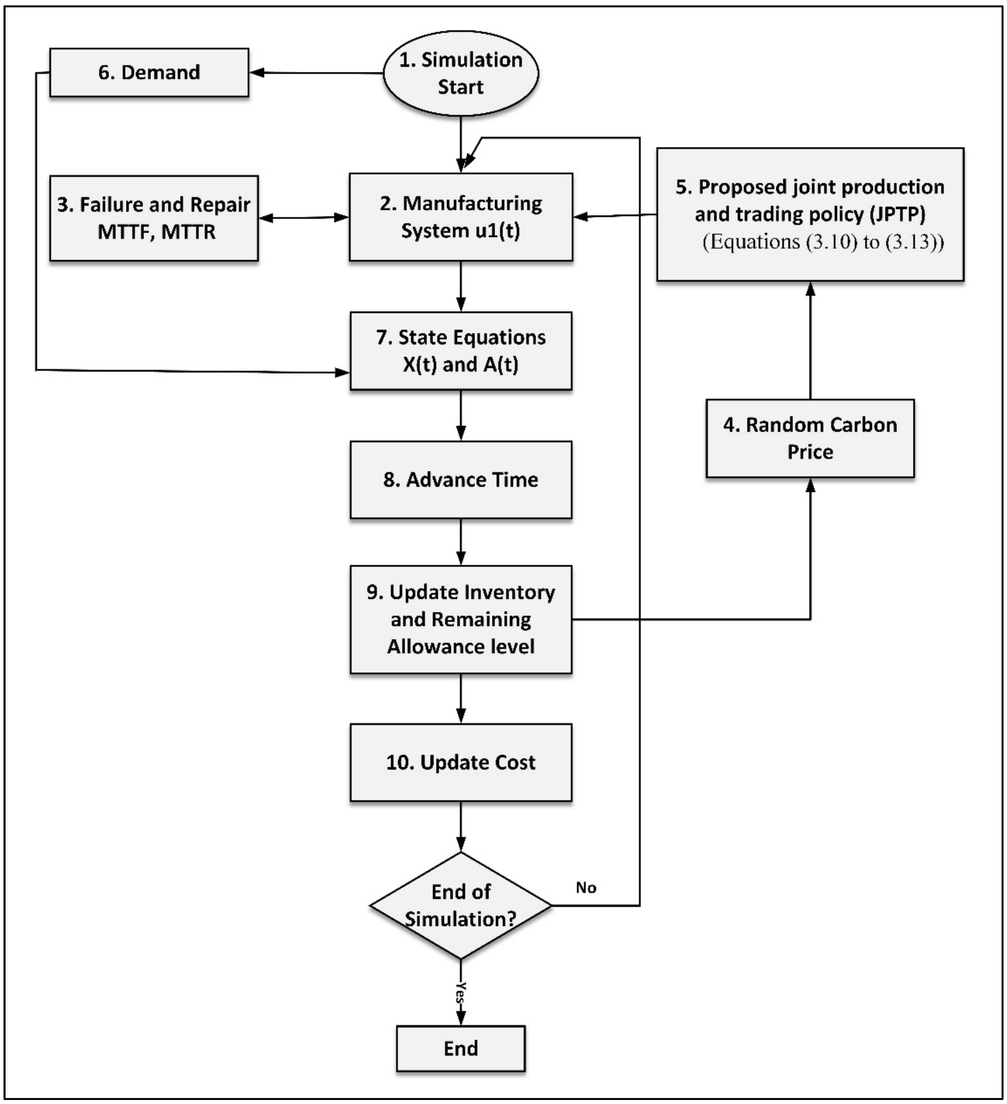


Figure 3.4 The simulation model diagram

To validate our simulation model, we run it using as the input our proposed joint production and trading policy (Equations (3.11) to (3.14)). As depicted in Figure 3.5 Our simulation model faithfully reproduces the behavior of the manufacturing system (shown in Figures 3.1 and 3.2) when it is controlled by our proposed policy. To make it clear, the symbol of "a.©" is used to represent the phenomenon indicated in part C of Sub-Figure 3.5.a). For instance, b.① in Figure 3.5 shows the phenomenon indicated by the part 1 of Sub-Figure 3.5.b).

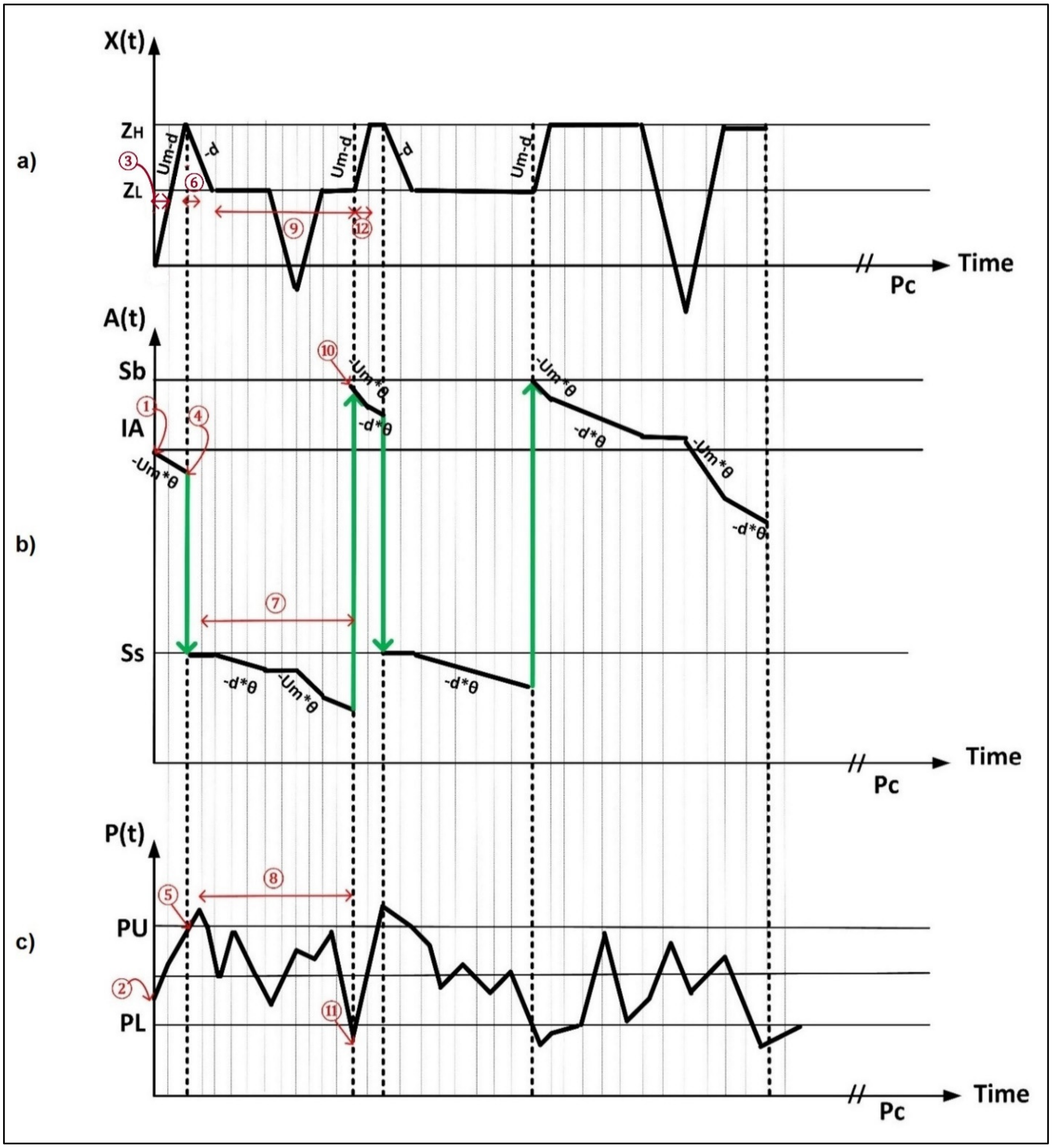


Figure 3.5 Proposed joint production and trading policy (JPTP)

According to the figure, when the manufacturing system starts to produce at the beginning of the compliance period, the allowance level is equal to the initial allowance level (b.①). The allowance level is more than S_s and the system is in the comfort zone for selling allowances. However, according to c.②, the carbon price is less than *PU* which is not high enough and the system will not sell allowances. The manufacturing system takes advantage of the considerable amount of allowances (>S_s) to produce more and build the high inventory till hedging level, Z_H. Since the inventory surplus level is lower than Z_H, the production rate equals its maximum rate (a.③). According to b.④ and c.⑤, the allowance level is still higher than S_s and the carbon price is more than *PU*. So, the system sells allowances till the level of S_s. After selling, the allowance level becomes low. Hence, in order to reduce generated emissions, the production system decides to stop the production till reaching the inventory threshold level of Z_L (a.⑥). Then, during the periods shown in b.⑦, the allowance level is less than S_s and the system needs to buy allowances. But the carbon price is not low enough (c.⑧). To reduce the generated emissions, the manufacturing system stops the production till reaching the inventory threshold level of Z_L (a.⑨). As can be seen in c.⑪, the carbon price is low enough and the manager buys carbon allowances till S_b (b.⑩). As the system goes back to the comfort zone for selling, the system takes advantage of these allowances and produces at maximum rate to build the high inventory to reach the threshold level of Z_H (a.⑫).

3.7 Numerical example

In this section, the resolution approach is used to obtain the optimal total incurred costs and the optimal values of control parameters defining our proposed joint production and trading policy. An illustrative numerical example, the relevant sensitivity analysis and comparative study are also provided. Considered operational and cost parameters are given in Table 3.2, as follows:

Table 3.2 The system parameter values

Parameter		D	U_m	*TTF*	*TTR*	θ	*IA*
Value		100	130	Exp (7)	Exp (0.4)	U[0.5,1]	650,000
Parameter		*C+*	*C-*	*Ce*	*Ctr*	P_c	$P(t)$
Value		5	50	500	5,000	5,760	NORM (20,1)

A Box-Behnken design with five control parameters of Z_H, Z_L, S_s, S_b and σ at three levels is applied for our proposed joint production and trading policy. To ensure the constraint of $Z_L \leq Z_H$, a substitute parameter $\alpha_1 = Z_L/Z_H$ is defined, with $0 \leq \alpha_1 \leq 1$. Also, to ensure the constraint of $S_s \leq S_b$, a substitute parameter $\alpha_2 = S_s/S_b$ is defined, with $0 \leq \alpha_2 \leq 1$. For each design, 320 simulation runs are carried out using five replications of each control factors combination. The simulation run time is considered to be 500,000 time units (TU) in order to ensure reaching the system steady-state. Table 3.3 presents levels of each control parameter.

Table 3.3 Levels of control parameter

Factors	Low	Medium	High
Z_H	35	82.5	200
α_1	0.01	0.5	0.99
S_b	0	325,000	650,000
α_2	0.01	0.5	0.99
σ	0.5	1.25	3

3.7.1 RSM model and optimization

“STATGRAPHICS” software is used to carry out the statistical processing of data and perform the analysis of variance. Thus, the effects of control parameters, their interactions as well as quadratic effects on the total cost are obtained as shown in Table 3.4. For considered parameters shown in Table 3.2, the correlation coefficients R-square adjusted equals 99.79%. The R-square (adjusted) is sufficiently high to judge the good quality of model. In the same way, we conducted an analysis of the residual normality as well as the homogeneity of variance in order to check the model conformity. To crosscheck the model validity, it is confirmed that the optimal value of total cost for the proposed joint production and trading policy falls within the confidence interval (at a 95% level of confidence). We obtain the confidence interval using *n*=40 replications of the simulation model.

The RSM model for the JPTP is as follows:

$$Total\ Cost = 1{,}157.62 - 4.0211 \times Z_H - 0.000755837 \times \alpha_1 - 3.5456 \times S_b + 2.01526 \times \alpha_2 + 0.0209802 \times \sigma + 4.07133 \times 10^{-7} \times Z_H \times \alpha_1 + 8{,}508.77 \times Z_H \times \sigma + 319.764 \times \alpha_1^2 + 0.0361398 \times \alpha_1 \times \sigma + 89.6714 \times {S_b}^2 - 0.000620997 \times S_b \times \alpha_2 + 0.02489656 \times S_b \times \sigma - 12.33166 \times \alpha_2 \times \sigma + 4.689 \times 10^{-7} \times \sigma^2 \quad (3.15)$$

Table 3.4 ANOVA for cost

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
A:*ZH*	3.00139E6	1	3.00139E6	155.90	0.0002
B:*ZL*_alfa1	2.88917E6	1	2.88917E6	152.57	0.0008
C:*Sb*	9.56276E9	1	9.56276E9	1839.25	0.0000
D:*Ss*_alfa2	9.01137E9	1	9.01137E9	1671.42	0.0000
E: Sigma	1.29465E10	1	1.29465E10	2080.28	0.0000
AA	382762.0	1	382762.0	20.24	0.0028
AB	442779.0	1	442779.0	25.39	0.0018
AC	1499.86	1	1499.86	0.08	0.9189
AD	4455.7	1	4455.7	0.13	0.7166
AE	226357.0	1	226357.0	18.36	0.0031
BB	200750.0	1	200750.0	16.80	0.0043
BC	5505.1	1	5505.1	0.20	0.6537
BD	5992.6	1	5992.6	0.26	0.6854
BE	412608.0	1	412608.0	35.33	0.0020
CC	178274.0	1	178274.0	14.82	0.0080

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
CD	2.11425E9	1	2.11425E9	767.76	0.0000
CE	1.11408E9	1	1.11408E9	632.73	0.0000
DD	1049.94	1	1049.94	0.05	0.9235
DE	1.161E9	1	1.161E9	641.82	0.0000
EE	1.41428E9	1	1.41428E9	662.66	0.0000
blocks	103292.	4	25823.1	0.08	0.9893
Total error	6.91511E7	205	337322.		
Total (corr.)	3.76552E10	229			

R-squared = 99.8164 percent

R-squared (adjusted for d.f.) = 99.7949 percent

Optimization results including the minimum total costs as well as optimal control parameters are provided as follows: $\text{Total Cost}^*_{\text{JPTP}}$= 4,343.19, Z_H^*= 83.17, α_1^*=0.91 (Z_L^*= 76.24), S_b^* = 719,989.2, α_2^*=0.25 (S_s^* = 180,244), σ*=1.52. The optimal cost for JPTP falls within the confidence interval (95%) of [4,340.78, 4,345.31]. This confidence interval is provided using 40 replications of the simulation model. Figure 3.6 represents the projections of the cost response surfaces.

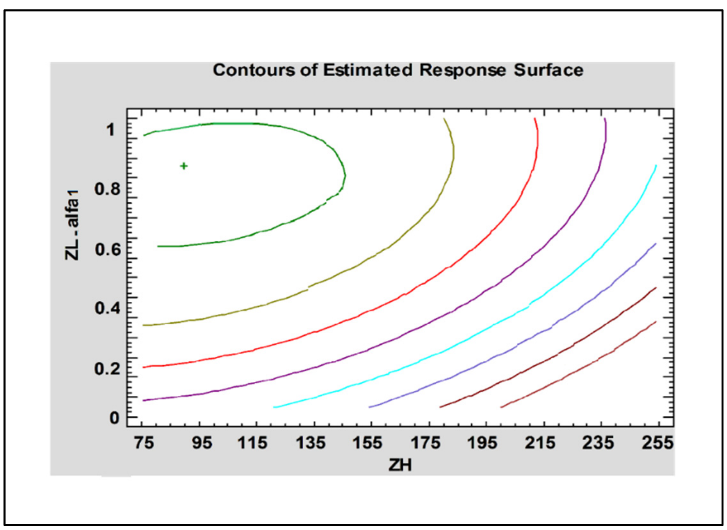


Figure 3.6 The estimated total cost response surface

3.7.2 Sensitivity analysis:

An extensive sensitivity analysis is carried out to confirm our proposed policy and resolution approach robustness. Variations of the control parameters (Z_H^*, Z_L^*, S_s^*, σ^*) of JPTP as a function of cost and system parameters (C^+/C^-, C^e, C_{tr}, Av, Θ) are provided in following subsections.

3.7.2.1 Variation of inventory, backlog (C^+/C^-), emission (C^e) and transaction cost (C_{tr}):

The variation of the control parameters of JPTP is shown in Figure 3.7 (a), when C^+/C^- varies. As can be seen from the figure, when there is an increase in C^+ (respectively, there is a decrease in C^-), the system will react by reducing values of optimal inventory threshold levels. So, there is a reduction in Z_H and Z_L. When high inventory cost leads to low values of Z_H and Z_L, this means that the manufacturing system produces less at its maximum production rate. In this way, the system generates less emissions. Hence, the system needs to buy less allowances and there is a reduction in the buying limit of S_b. Moreover, the system is confident to take advantage of carbon market and sell more allowances. The system reacts by reducing the value of S_s and increasing the comfort zone for selling allowances. To give the system more chance for selling, there is a slight reduction in the σ (reduction in *PU*) which increases the eligible prices for selling allowances.

Figure 3.7 (b) presents the variation of control parameters associated with JPTP when C^e is varying from 500 to 650. When there is a rise in the emission cost (C^e), the system reacts by generating less carbon emissions. Hence, there is a reduction in the inventory threshold levels of Z_H and Z_L, leading to less production at the maximum rate. Moreover, when C^e increases, the system has a tendency to keep more allowances in the system. Therefore, there is an increase in the optimal values of S_S to reduce the comfort zone for selling and there is an increase in S_b to buy more carbon allowances. Considering the increase of S_S, the system is mostly in need of buying allowances. So, in order to give the system more chance of buying allowances, there is a decrease in σ (increase in *PL*) which increases the eligible carbon prices for buying.

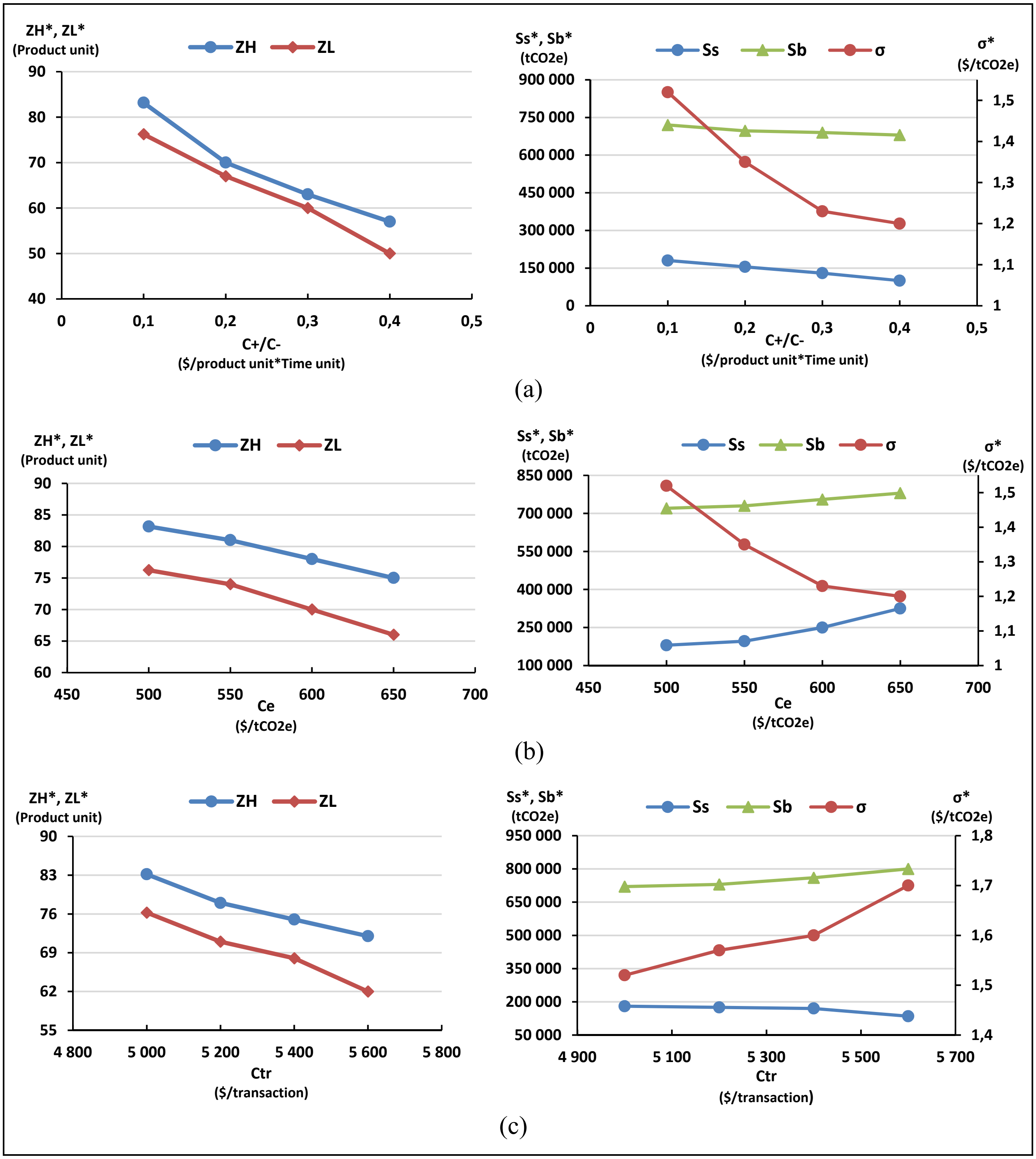


Figure 3.7 Variation of Z_H^*, Z_L^*, S_s^*, S_b^* and σ^* when varying C^+/C^-, C^e and C_{tr}

The variation of Z_H^*, Z_L^*, S_S^*, and σ* as a function of C_{tr} is shown in Figure 3.7 (c). When there is an increase in transaction cost (C_{tr}), the system has a tendency to reduce the number of times that allowances are sold or bought. So, as can be seen in Figure 3.7 (c), there is a rise in σ which reduces (increases in PU and decreases in PL) the number of eligible carbon prices for selling or buying. As expected, the results show that by increasing the transaction cost, the total number of transactions drops from 20,817 to 17,244. Moreover, by increasing the transaction cost, the system has a tendency to increase the trading quantity for each transaction. So, there is a reduction in S_S to sell allowances till a lower level and there is an increase in S_b to buy allowances till a higher level. According to the results, the average trading quantity for each transaction increases from 420,784.29 to 460,967.30 tCO_2e. Reduction in S_S expands the comfort zone for selling carbon allowances and leads to reducing allowances, so there is more pressure on the manufacturing system to reduce the carbon emissions generated by production. Consequently, the inventory threshold levels decrease resulting in less production at the maximum rate.

3.7.2.2 Variation of system availability (Av), emission index (Θ):

Figure 3.8 (a) represents the variation of control parameters when system availability (Av) increases from 0.94 to 0.97. By increasing the system availability, the probability of machine breaking down is reduced. In this way, there is a rise in the available production capacity, so the manufacturing system can meet the demand with the lower safety stock. As shown in Figure 3.8 (a), improving system availability results in a reduction in the inventory threshold levels of Z_H and Z_L. By reducing the inventory threshold levels, the production system works less with maximum production rate and then generates less carbon emissions. So, the system is confident to sell more allowances and buy less. There is a reduction in S_b to buy less allowances and there is a decrease in S_S to expand the comfort zone for selling. Also, in order to give the system more chance to sell carbon allowances, there is a decrease in σ (increase in PL) which increases the range of eligible carbon prices for selling.

Figure 3.8 (b) shows the variation of Z_H^*, Z_L^*, S_S^*, and σ^* when Θ (carbon emissions generated by producing each product) rises. As the manufacturing system generates more emissions by producing each product, the inventory threshold levels reduce in order to produce less at the maximum rate. As can be seen from Figure 3.8 (b), there is a decrease in Z_H and Z_L to control generated emissions. Generating more emissions results in less allowances, so there is an increase in S_b to buy more allowances. Moreover, the system reacts by rising S_S to limit the comfort zone for selling and keep more carbon allowances. Considering the expanded zone for buying, the system tends to decrease σ to increase eligible prices for buying.

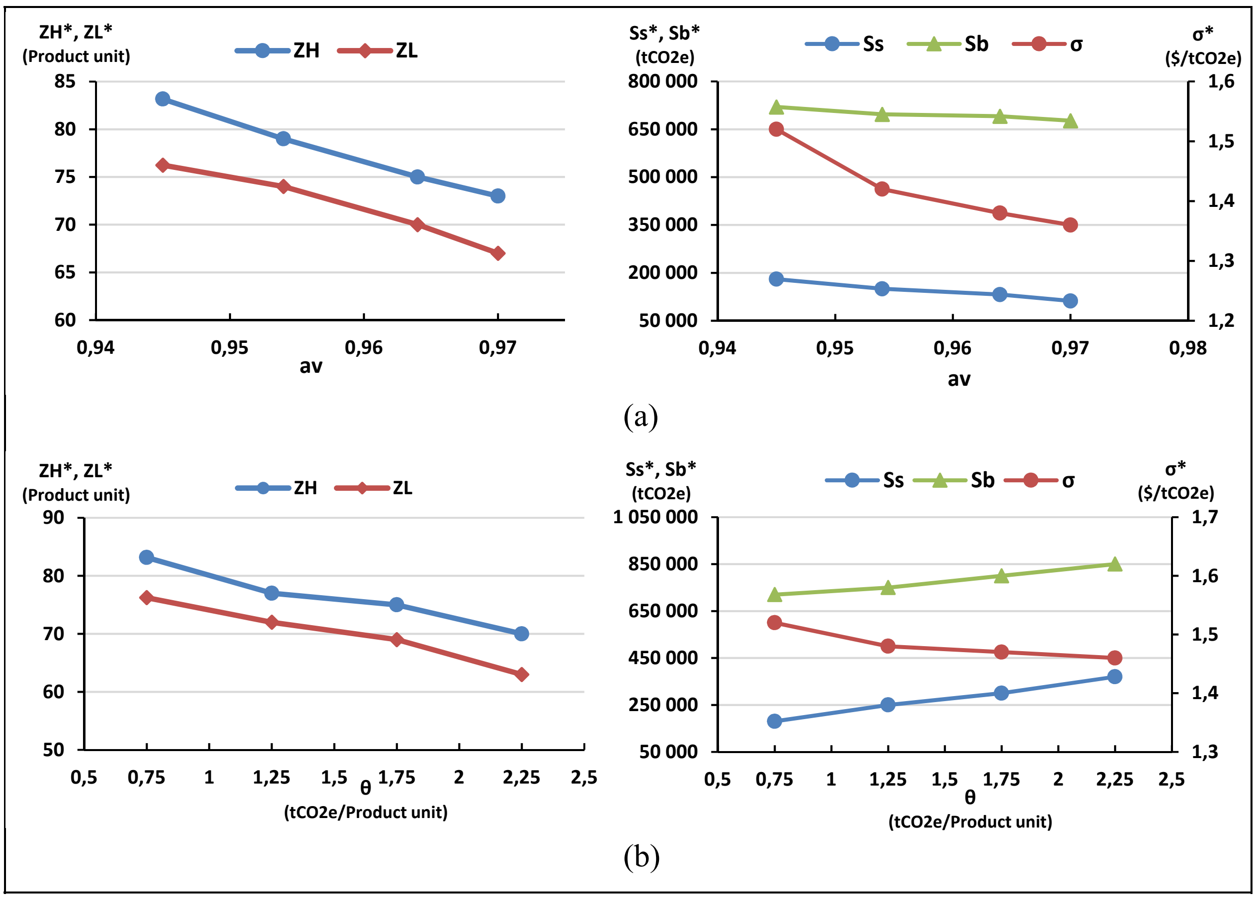


Figure 3.8 Variation of Z_H^*, Z_L^*, S_S^*, S_b^* and σ^* when varying Av and Θ

3.8 Comparative study

In this section, we present the existing control policies adapted from the literature and a simplified version of our joint production and trading policy. Then we compare these policies with our proposed policy, JPTP. To confirm that our policy outperforms the existing policies, a comparison is also provided for wide-range system and cost parameters.

3.8.1 Policies considered for comparison

In the following subsection we describe an adaptation of the most relevant existing policies to our work from the literature and a simplified version of our policy.

3.8.1.1 Two-threshold Trading Policy (TTP)

The two-threshold trading policy (TTP) developed for deterministic manufacturing systems (Gong and Zhou 2013; Xu et al., 2017a; Xu et al., 2017b). TTP is a target interval policy defined by two threshold trading levels in which the optimal lower or upper bounds for allowance level are determined for trading. If the allowance level is less than lower bound (AL), the system needs to buy the allowances to increase the level; if the allowance level is higher than the upper bound (AU), the system should sell the carbon allowances, and otherwise there is no need to trade. For the manufacturing system under TTP in which the machine failure is not considered, the production rate is set to be equal to the rate of demand.

3.8.1.2 Hedging Point Policy integrated with Two-threshold Trading Policy (HPP-TTP)

As our considered manufacturing system includes a failure-prone manufacturing system, the classical hedging point policy (HPP), as a common effective strategy for the stochastic and dynamic context of such systems is also integrated with the existing two-threshold trading policy (HPP-TTP) to be compared with our proposed policies. According to this policy, a certain safety stock level (Z_H) should be built to meet the demand during system failure (Akella and Kumar 1986). The production system starts to produce at maximum rate to build the inventory threshold level and after reaching Z_H, the production rate is set to be equal to the demand rate in order to keep this safety stock for failure duration.

3.8.1.3 Environmental Hedging Point Policy integrated with Two-threshold Trading Policy (EHPP-TTP)

Moreover, the Environmental hedging point policy (EHPP) for unreliable manufacturing systems regulated by carbon tax developed by Ben-Salem et al., (2015a) is integrated with the existing two-threshold trading policy (EHPP-TTP) and then it is compared with our proposed policies. According to EHPP, the manufacturer decides to produce at the maximum rate to reach a threshold level, Z_H. He decides to stop the production system when the emissions level becomes high (exceeds its limit, Y), and reduces the inventory threshold level to Z_L for minimizing the risk of facing backlog.

3.8.1.4 Simplified Joint Production and Trading Policy for failure-prone manufacturing systems under cap-and-trade (SJPTP):

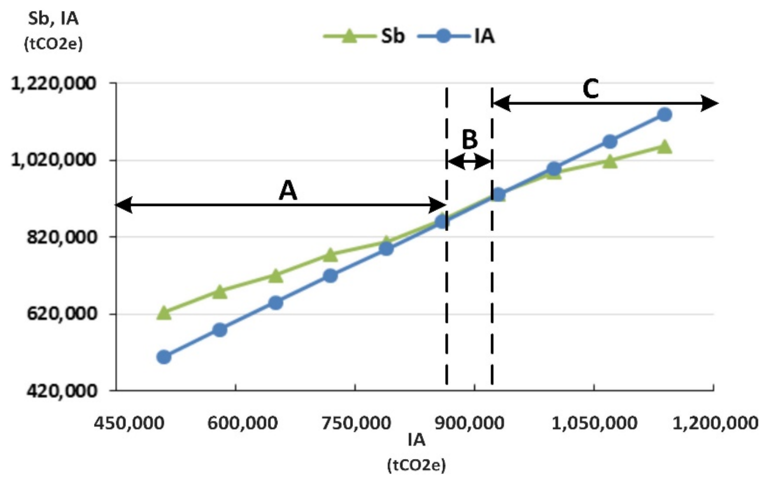
JPTP is a general comprehensive policy which can be implemented by unreliable manufacturing systems under cap-and-trade regulation. However, the initial allowance (IA) announced by the government should be a good indicator of the value of S_b. If IA is very high, it is costly for the system to buy allowances till IA when it is needed. Also, if IA is very low, it is not advantageous to limit the system and buy allowances only till IA. So, for a high or low level of IA, it is needed to get the optimal value of S_b. However, if IA is not very high or low, the system can buy allowances till IA and there is no need to use the variable S_b.

Our simplified joint production and trading policy (SJPTP) is a specific case of JPTP in which the system should buy allowances until the initial allowance level when buying is needed (replacing S_b by IA in Equation (3.14)). In this way, the buying limit, S_b gets a fixed value of IA. So, SJPTP with one less variable compared to JPTP is easier to be implemented by the companies. Reducing the number of variables in the policy make it easier to get the optimal values for control parameters.

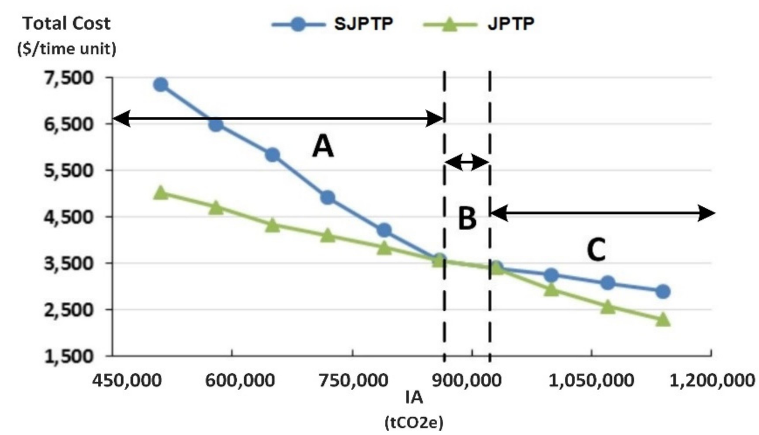
An analysis is performed in Figure 3.9 in order to show the initial allowance levels for which the simplified joint production and trading policy can be used. Figure 3.9 (a) shows the optimal value of S_b when IA varies. The optimal total cost of JPTP and SJPTP when varying IA is provided in Figure 3.9 (b).

As can be seen from Zone A in Figure 3.9 (a), for the low values of IA, the optimal values of S_b are higher than initial allowance level. In this way, the system under JPTP is permitted to buy a considerable amount of allowances to take advantage of the low carbon price in the market when buying allowances is needed and make profit by selling these allowances at high prices later. Consequently, for low values of IA, the total cost of JPTP is less than that of SJPTP as shown in Zone A of Figure 3.9 (b). Afterwards as shown in Zone C of Figure 3.9 (a), for high values of IA, the optimal values of S_b are less than initial allowance level. Indeed, the system is not obliged to buy allowances till a high level of initial allowance, which is costly. Buying a huge amount of allowances leads to a considerable amount of excess allowances at the end of the compliance period which is not profitable. Therefore, for high values of IA, the total cost of JPTP is less than SJPTP as shown in Zone C of Figure 3.9 (b).

As can be seen from Zone B of Figure 3.9 (a), for a specific range of IA (860,000 to 930,000 tCO_2e), the optimal value of S_b for JPTP takes almost the same value as IA, so behavior and total costs of the system under both proposed policies are the same as shown in Zone B of Figure 3.9 (b). Therefore, when IA is not too high or too low, SJPTP with one less variable than JPTP is easier to be implemented by the production systems under cap-and-trade regulation.



(a)



(b)

Figure 3.9 Variation of S_b^*, $\text{Cost}^*_{\text{JPTP}}$ and $\text{Cost}^*_{\text{SJPTP}}$ when varying IA

3.8.2 Comparison between proposed and existing control policies

We applied Steps 2 to 5 of our resolution approach in Section 3.4 as shown in Figure 3.3 to obtain the optimal value of parameters and total cost of each policy. The best policy is the one with the lowest optimal costs and carbon emissions. Table 3.5 and Table 3.6 present the optimal values of control parameters as well as optimal total costs of each control policy.

Table 3.5 Optimal values of control parameters for considered policies

Factor ------ Policy	Z_H (Product Unit)	Z_L (Product Unit)	Y (tCO2e)	AU (tCO2e)	AL (tCO2e)	S_s (tCO2e)	S_b (tCO2e)	Cumulative Emissions per Compliance Period (tCO2e)	Carbon Emissions (tCO2e/Time Unit)
TTP	-	-	-	328,454	67,478	-	-	687,110.4	119.29
HPP-TTP	110	-	582,216	343,426	81,137	-	-	713,664.0	123.90
EHPP-TTP	102	86	-	326,730	66,845	-	-	666,892.8	115.78
SJPTP	98	81	-	-	-	216,830	-	559,411.2	97.12
JPTP	83	76	-	-	-	180,244	719,989	532,454.4	92.44

Table 3.6 Optimal values of total cost for considered policies

Cost Policy	Inventory Cost ($/Time Unit)	Backlog Cost ($/Time Unit)	Emission Cost ($/Time Unit)	Trading Cost ($/Time Unit)	Transaction Cost ($/Time Unit)	Trading (Revenue) ($/Time Unit)	Optimal Total Cost ($/Time Unit)
TTP	-	4,773.7	655.12	3,820.85	11,523.29	(5,632.68)	15,140.28
HPP-TTP	496.54	329.68	789.39	4,205.98	11,685.79	(5,495.97)	12,011.41
EHPP-TTP	473.26	364.56	538.45	3,780.29	11,217.45	(5,762.08)	10,611.93
SJPTP	435.87	381.27	295.19	3,639.12	7,973.60	(6,877.57)	5,847.48
JPTP	388.4	414.71	261.82	4,127.48	8,405.44	(9,254.66)	4,343.19

Comparison between the TTP and HPP-TTP shows that implementation of hedging point policy (HPP) could result in a considerable reduction in backlog costs and consequently reduction in total costs. Based on the results, by reducing the inventory threshold level after exceeding a certain emission limit (*Y*), EHPP-TTP results in emissions reduction. Subsequently, keeping less inventory in the system under EHPP-TTP leads to less inventory cost and more backlog cost compared with HPP-TTP. Moreover, producing less at the maximum rate generated less carbon emissions, so the system has the chance to sell more allowances. There is a reduction in *AU* and *AL* to expand the selling zone and limit the buying zone of trading policy. As shown in Table 3.6, there is an increase in selling revenue of the system and reduction in the buying cost resulting in a decrease in total costs under EHPP-TTP compared to HPP-TTP.

As shown in the results, our proposed production and trading policies (JPTP and SJPTP) result in considerable cost reduction compared with all other existing policies. Under EHPP-TTP, if the allowance level is less than AL, the system will buy allowances till AL and if the allowance level is higher than AU, the system will sell till the level of AU. So, under this policy, there are plenty of transactions including buying at high prices and selling at low prices which is not profitable for the system. In our proposed policies, we take both allowance level and carbon price into consideration to decide on trading. By designing our policies to buy at low prices and sell at high prices, there is a considerable decrease in transaction cost, increase in the trading profit (difference between buying cost and selling revenue), consequently reduction in total cost under JPTP and SJPTP compared with EHPP-TTP. More selling and trading revenue under our proposed policies reduces the allowances in the system and puts more pressure on the manufacturing to produce less at maximum rate. So, as shown in Tables 3.5 and 3.6, there is reduction in inventory threshold levels under our proposed policies compared with EHPP-TTP resulting in less inventory cost and more backlog cost. According to SJPTP, if the allowance level is less than S_s and the price is low enough to buy, the system is permitted to buy carbon allowances till initial allowance level. On the contrary, according to JPTP, the system can decide on the buying limit (S_b) and make more profit. Accordingly, JPTP brings advantage of cost reduction (25.7%) for the system compared with SJPTP.

The results also show that both proposed joint production and trading policies (SJPTP and JPTP), considerably decrease total cost, and produced less carbon emissions in the system compared to other policies. Nonetheless, JPTP is the most cost-efficient environmentally friendly control policy developed for cap-and-trade regulation. Moreover, to confirm that our proposed policies outperform existing policies, a comparative study should be carried out for wide-range system and cost parameters.

3.8.3 Comparison between proposed and existing control policies for wide-range system and cost parameters

We performed a comparative study shown in Figure 3.10 to 3.12, based on the impact of cost parameters (inventory, backlog, emission, and transaction cost) and system parameters (standard deviation of carbon price and system availability) on total costs and emissions of our proposed policies (SJPTP and JPTP) and the existing control policies.

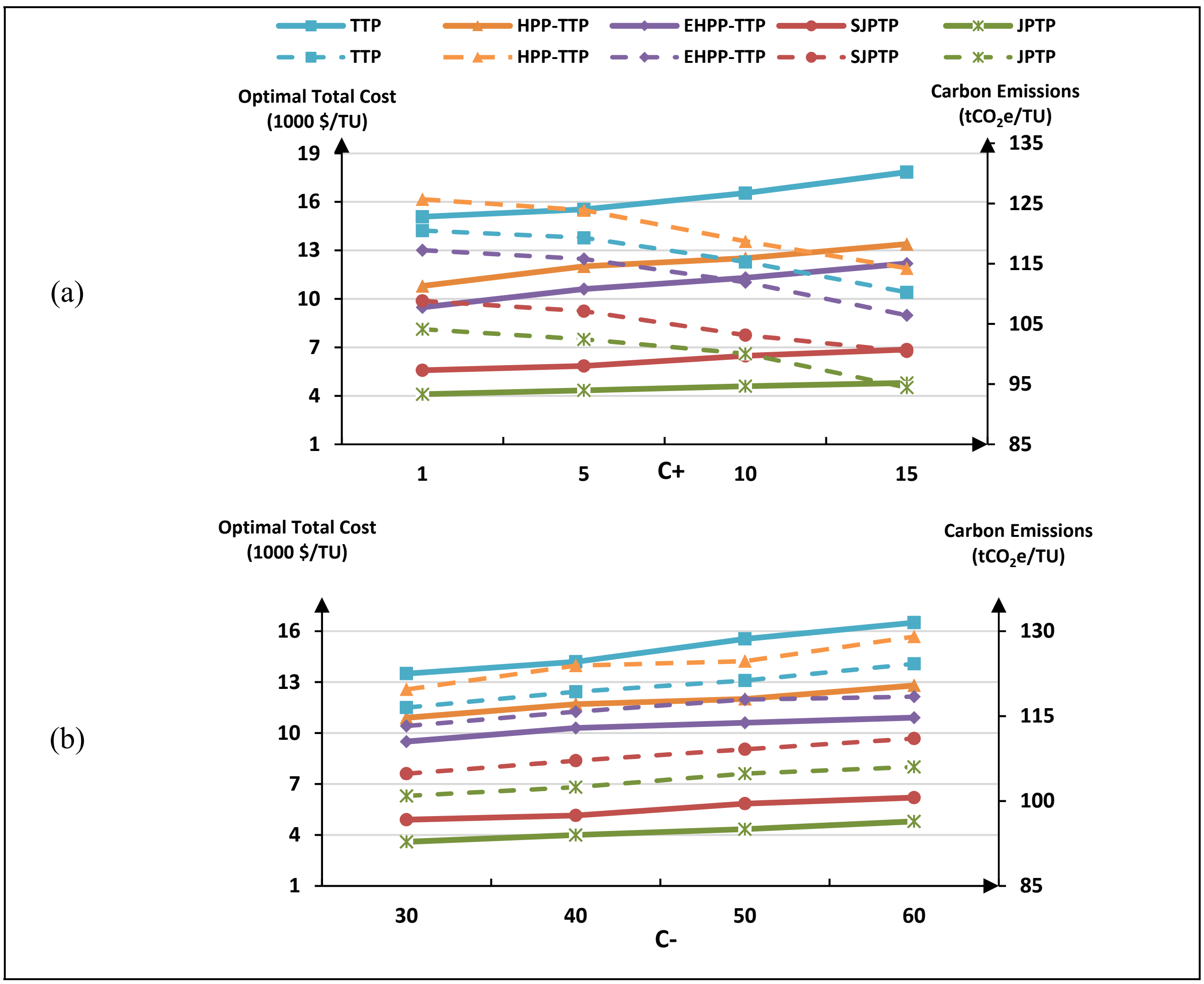


Figure 3.10 The impact of cost parameters (inventory and backlog cost) on optimal total costs and carbon emissions for considered policies

For each policy, solid line displays the optimal total cost and dash line represents the carbon emissions. TU means time units, here. The aim is to confirm that our proposed policies outperform existing policies adapted from the literature in terms of optimal total cost and carbon emissions reduction.

Our proposed policies provide more advantages than existing policies for a broad range of the inventory cost as the system under proposed policies need less inventory to meet the demand. From Figure 3.10 (a), we note that when there is a rise in the inventory cost (C^{+}), the difference between total costs of existing policies and that of proposed policies increases. Requiring less inventory for the system under our proposed policies also results in less production which generates less carbon emissions. Consequently, according to Figure 10.3 (a), by increasing C^{+}, the difference between emissions of existing policies and that of proposed policies increases.

Our proposed policies which need less inventory to satisfy the demand leads to more backlog. However, as shown in Figure 3.10 (b), the increase of the trading profit for the system under SJPTP and JPTP overweighs the incurred backlog cost, leading to a reduction in optimal total cost and carbon emissions.

Moreover, the results showed that the system under our proposed policies benefits from considerable carbon emissions reduction, so the impact of C^{e} on total costs of new proposed policies is less than its impact on the closest existing policies (generating more emissions). By increasing C^{e}, there is considerable carbon emissions reduction in the system under our proposed policies compared with the system under existing policies. Therefore, when C^{e} rises as shown in Figure 3.11 (a), the difference between proposed and existing policies increases regarding both optimal total costs and carbon emissions.

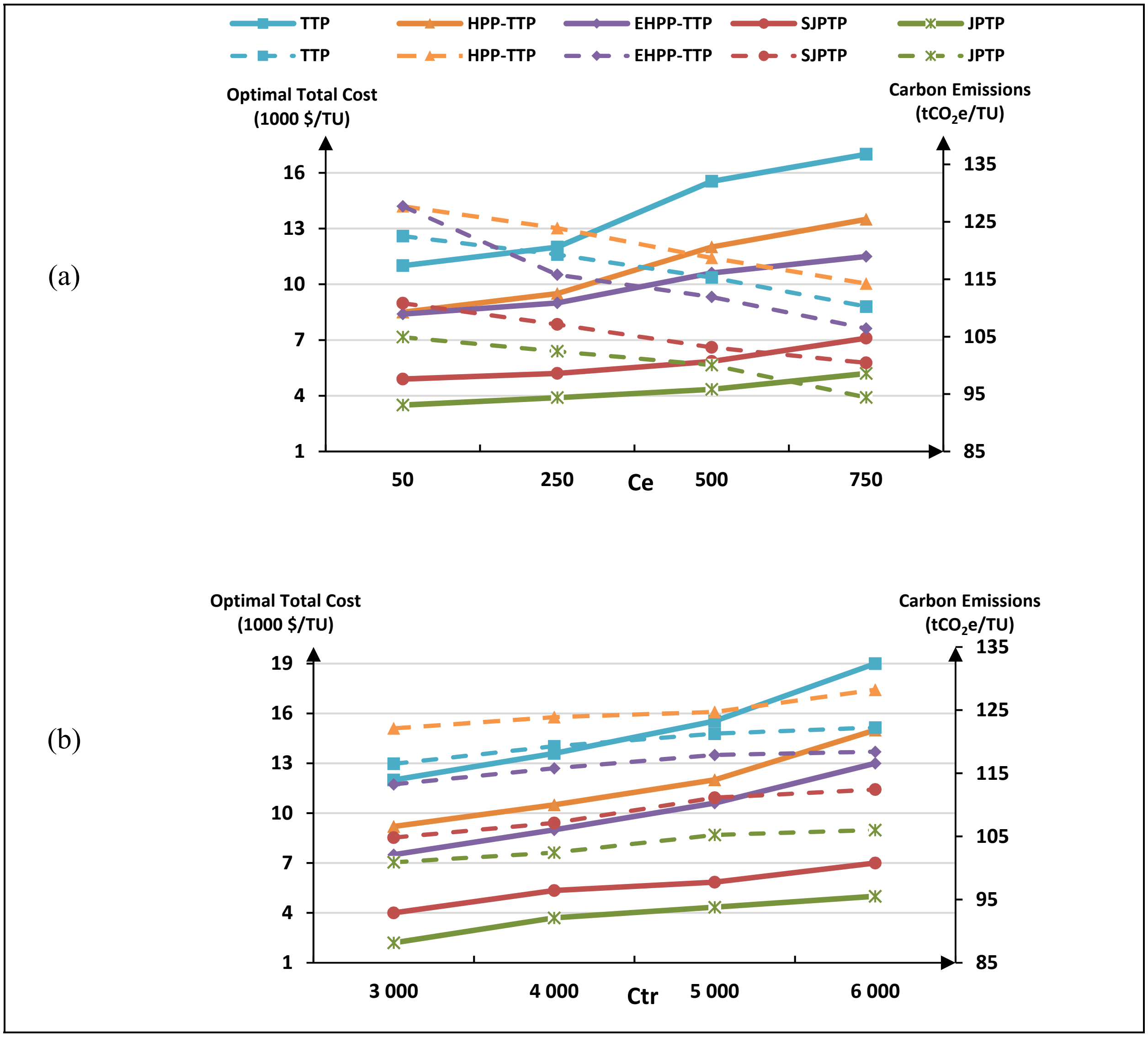


Figure 3.11 The impact of cost parameters (emission and transaction cost) on optimal total costs and carbon emissions for considered policies

Increasing in the transaction cost, reduces the number of transactions resulting in more allowance in the system. There is less pressure on the manufacturing system to control the emissions. Then, more production at maximum rate leads to a rise in the generated carbon emissions. However, proposed policies compared with existing ones result in considerable reduction in the number of costly transactions. Because under proposed policies the system decides on trading based on both allowance level and carbon price and makes a trade only if the price is good. As can be seen from the Figure 3.11 (b), when there is an increase in the transaction cost (C_{tr}), the difference between existing and proposed policies increases, when it comes to optimal total costs as well as carbon emissions.

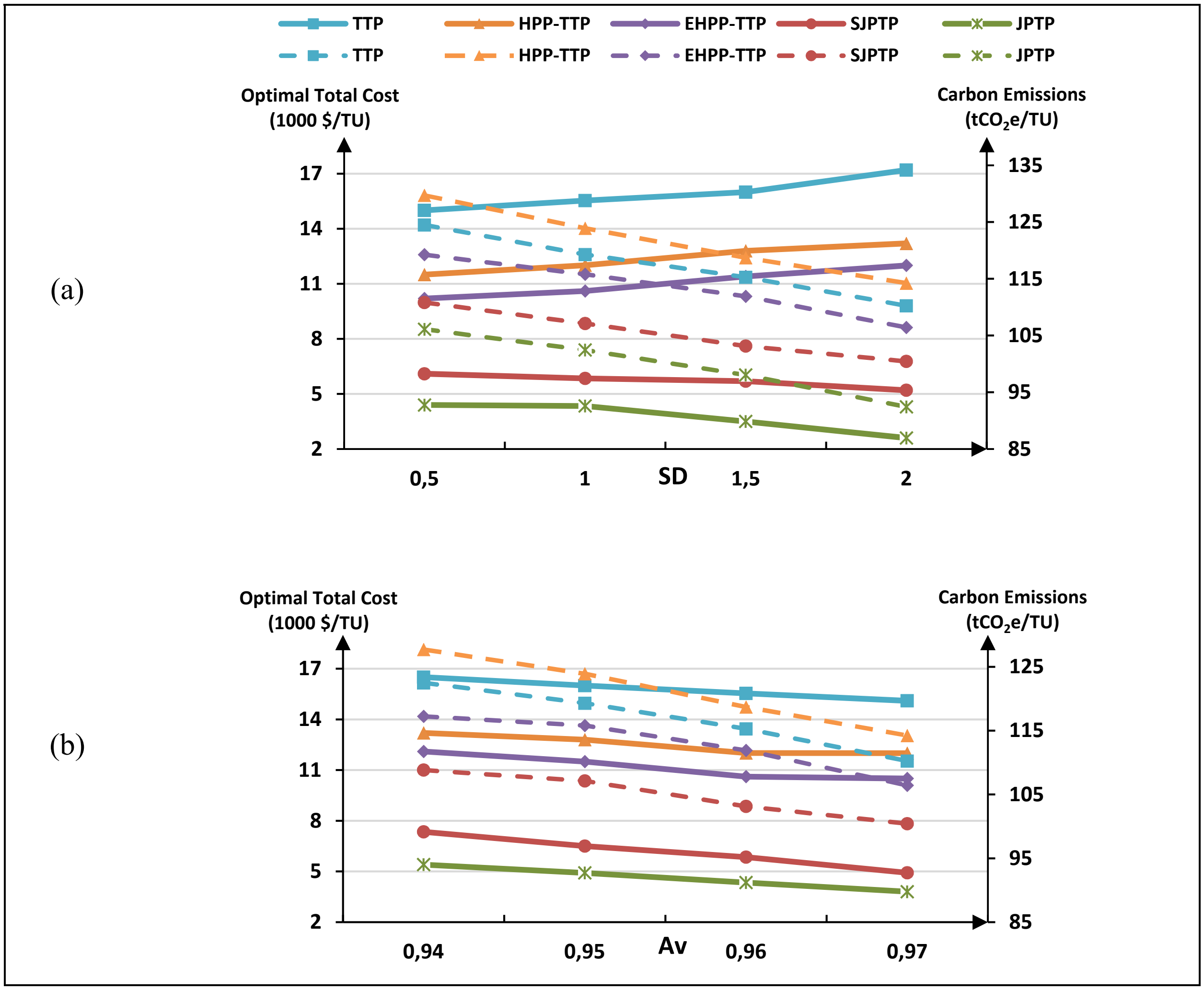


Figure 3.12 The impact of system parameters on optimal total costs and carbon emissions for considered policies

As the system under existing policies trades based on allowance level regardless of the carbon price, increasing the fluctuation of carbon price leads to more transactions at inappropriate prices. More transactions at appropriate prices under our proposed policies results in more allowance selling and more pressure on the manufacturing system to control the emissions. Reducing the production at maximum rate decreases the generated carbon emissions. In Figure 3.12 (a), it can be seen that by increasing in standard deviation of carbon price (*SD*), there is a bigger difference between proposed and existing policies in terms of optimal total costs and carbon emissions.

In Figure 3.12 (b), if there is a rise in the system availability (Av), the difference between total costs of existing policies and proposed policies increases. Because by increasing availability (Av), lower safety stock is needed to satisfy the demand and the system has more allowances to trade. By increasing the trading profit for the system under SJPTP and JPTP, our proposed policies overweigh the existing policies in terms of cost reduction. Moreover, requiring Less inventory leads to less production which generates lower carbon emissions in the system. So, our proposed policies also overweigh the existing policies in terms of carbon emissions reduction.

As shown in Figures 3.10 to 3.12, our proposed policies outperform existing ones adapted from the literature with regards to optimal total cost reduction for wide-range system and cost parameters. This confirms that our proposed joint production and trading policies simultaneously reducing optimal total cost and carbon emissions.

3.9 Managerial Insights and Practical Implementation

It is a major challenge for manufacturing systems under cap-and-trade to find the best production and trading policy to take advantage of the carbon trading market and reduce their total cost. Under the conditions where the carbon price is randomly changing in the carbon market, the biggest challenge for such companies is to decide on the production quantity and whether and to what extent the system should sell/buy the carbon allowances in the market. By implementing our proposed control policy, the manager can jointly decide on production and trading quantity and determine when to buy/sell allowances or increase/decrease the production rate in order to take advantage of the carbon trading market, reduce optimal total costs and carbon emissions of the system.

In this vein, the manager needs to monitor the allowance level, inventory level, and carbon price. When it comes to the trading policy, the manager should take the allowance level and carbon price into account. If the allowance level is high, the manager can be confident to sell the part of allowances under the conditions that the carbon price is high enough. When the level of carbon allowance is low, the manager needs to buy allowances subject to a carbon price which is low enough. When it comes to the production policy, if there are enough allowances in the system, the system is confident to produce more products. So, the manager can rise the inventory hedging level to avoid backlog. When the allowance level is low and the price is not good for buying, the manufacturing system should help to reduce carbon emissions by producing less. Therefore, the manager should stop the production till reaching the low inventory threshold level that simultaneously reduces carbon emissions and minimizes backlogs. Then, the inventory level needs to be checked by the manager to decide on the production rate. Also, when the inventory level is less than low inventory hedging level, the production rate should be set at its maximum rate. When the needed safety stock is built, the manager should produce at the rate of demand. Then when the level of inventory goes above its hedging level, he should stop the production.

Figure 3.13 shows the implementation logic chart of our proposed policy JPTP. Accordingly, first, the manager needs to monitor the allowance level. If the allowance level is higher than the selling limit (180,244 tCO2e), the carbon price needs to be checked to decide on trading. If the carbon rice is higher than 21.52 $/tCO2e, the system should sell allowances till the level of 180,244 tCO2e. After selling, the allowance level is low, and the manufacturer needs to stop the production till reaching the inventory level of 76 units in order to avoid backlog and reduce carbon emissions.

If the allowance level is higher than 180,244 tCO_2e but the carbon price is not high enough (not higher than 21.52 $/$tCO_2e$), the system should not sell any allowances and should continue producing at maximum rate (130) to reach the high inventory level (83 units). When the manufacturing system builds the needed safety stock, the manufacturer should set the production rate at demand (100). Then if the inventory goes above the hedging level, he should stop the production.

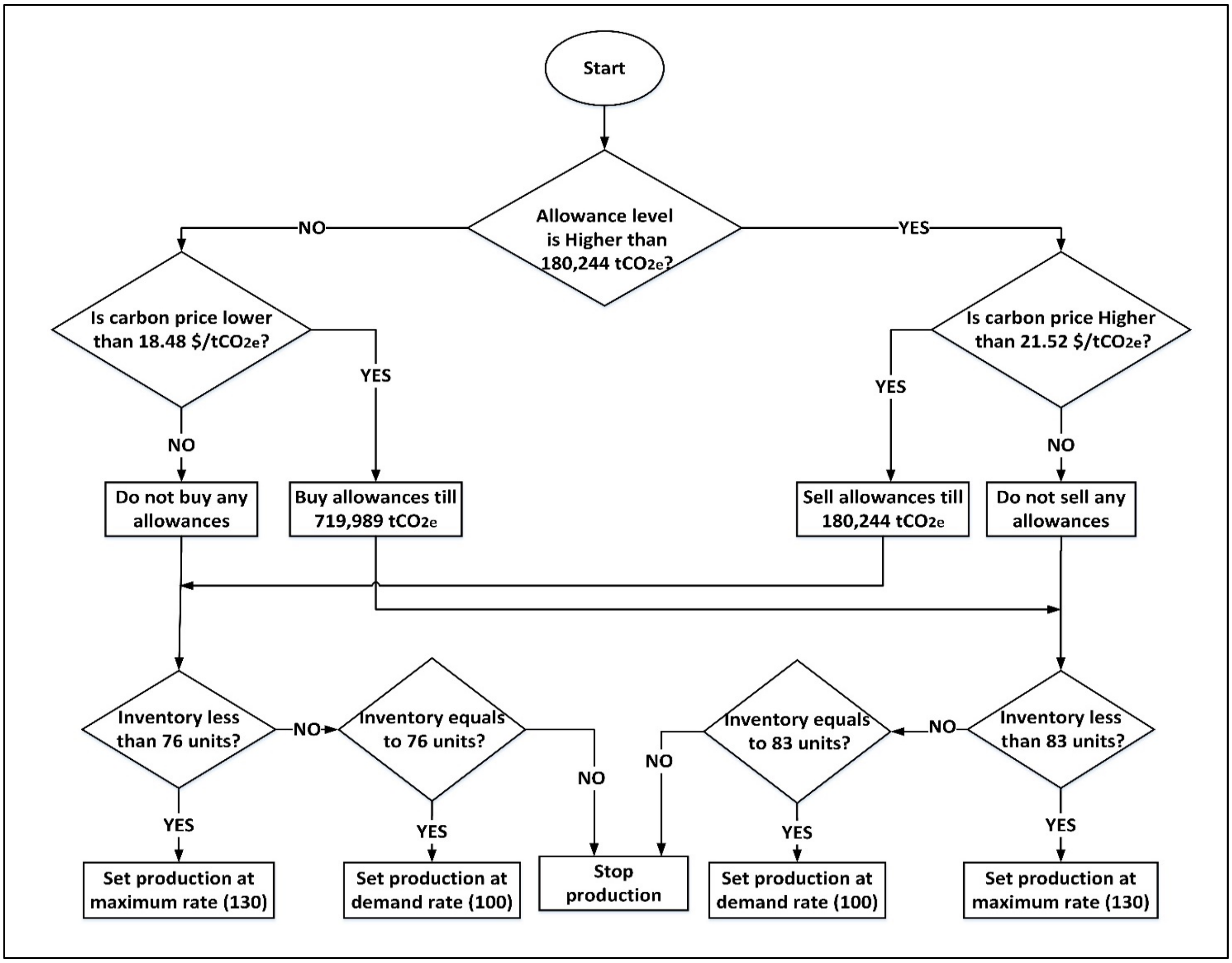


Figure 3.13 Implementation logic chart for JPTP

When the allowance level is lower than 180,244 tCO_2e, it is time to buy allowances. However, the price should be checked. If the carbon price is lower than 18.48 $/$tCO_2e$, the system should buy allowances till the level of 719,989 tCO_2e. After buying, the allowance level is high and the manufacturer is confident to produce more till reaching the inventory level of 83. If the allowance level is lower than 180,244 tCO_2e, but the carbon price is not low enough (lower than 18.48 $/$tCO_2e$), the system should not buy any allowances and should continue producing at maximum production rate (130) to reach the high inventory threshold level (76 units). As long as the inventory equals the threshold level, the manufacturer should produce at the rate of demand (100). If the inventory goes above the hedging level, the production should be stopped.

3.10 Conclusion

In this study, we addressed the unreliable manufacturing systems' production and trading planning for under cap-and-trade. As carbon prices randomly change in the market, determining the production rate and trading quantity is challenging and complex for companies regulated by cap-and-trade to take great advantage of the carbon market. Our aim was to develop a new joint production and trading policy for failure-prone manufacturing systems specifically designed for cap-and-trade regulation to minimize total incurred costs including emission, backlog, inventory, trading and transaction costs. According to our proposed policy, the system can jointly decide on the production rate and trading carbon allowances based on the inventory level, allowance level and carbon price. This policy helps the manager to determine when the production quantity should be increased or decreased and the allowances need to be sold or bought in the carbon market to bring great benefits to unreliable manufacturing systems.

To obtain the optimal value of parameters of the control policy, the experimental approach, simulation modelling, as well as response surface methodology are implemented. To confirm that our proposed policy outperforms existing policies, the sensitivity analysis is performed showing the variations of control parameters as a function of cost and system parameters. Based on the results under our developed policy, allowance level, carbon price and inventory level should be taken into consideration to decide on trading and production. Designing our policy to buy at low prices and sell at high prices results in considerable decrease in transaction cost, increase in the trading profit, consequently reduction in the optimal total cost and carbon emissions compared with other existing policies. More allowance selling under our proposed policies reduces the allowances in the system and puts more pressure on the manufacturing to produce less at maximum rate resulting in less inventory and emission. Overall, our policy is the most environmentally-friendly and cost-efficient control policy developed for cap-and-trade regulation, which decreases the optimal total cost and produces less carbon emissions compared to other policies.

Our analysis on initial allowance level showed that depending on how big the initial allowance is, the system can decide on the allowance level to which the carbon emissions should be bought. In this way, we proposed a simplified version of our proposed policy to be implemented by companies under cap-and-trade regulation when initial allowance is not too high or low. Finally, a comparative study is conducted to confirm that the proposed joint production and trading policy results in significant cost saving and emissions reduction in comparison with the existing policies in the literature for a broad range of system and cost parameters.

However, our policy has some limitations that, in turn, provide directions for future research. One of the limitations of our study is to consider one machine and one product type manufacturing system. Future studies on our research should deal with more complex manufacturing systems consisting of multi-products and multi-machines. Another limitation is to consider a linear emission rate of the machine, regardless of the degradation phenomena. According to degradation phenomena, as the age of the machine increases over time, the machine availability decreases and the emission rate of the machine increases, not necessarily linearly. Future investigations should consider the degradation phenomena and non-linearity of emission rate to provide more realistic emission models. As a gradual degradation due mainly to the lack of preventive maintenance activities, future studies should also address simultaneously the preventive and corrective maintenance in manufacturing systems. An optimal plan for preventive maintenance can be obtained to minimize total costs and reduce the emissions.

3.11 Acknowledgements

This research has been supported by Natural Sciences and Engineering Research Council of Canada (NSERC) under grant number: RGPIN-2020-05826

CHAPTER 4

ENVIRONMENTAL PRODUCTION PLANNING OF UNRELIABLE MANUFACTURING/REMANUFACTURING SYSTEM CONSIDERING QUALITY IMPACT OF RETURNS UNDER CARBON TAX REGULATION

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Paper submitted in *Computers & Industrial Engineering*, May 2022

Abstract

For many industries, high variation of returns' quality is one of the major problems making production planning of remanufacturing activities complicated. In this paper, we address the production planning of failure-prone manufacturing/remanufacturing systems with variate quality returns under carbon tax regulation. In the system under study, specific quality conditions (high- or low-quality) are assigned to returns. The impact of returns' quality on emission and production rates is also considered. We aim to develop production control policies that helps the manager in synchronizing manufacturing and remanufacturing considering simultaneously high- and low-quality returns to meet both environmental and economic objectives. Our proposed policy 1 reduces greenhouse gas emissions (GHGs) while minimizing the total costs including production, inventory, backlog, and emissions costs. Proposed policy 2, as an extension of policy 1, helps the system to reduce GHG emissions and increases the system availability by higher utilization of remanufacturing using high-quality returns. Optimal value of parameters for each policy is calculated using design of experiment, simulation, and response surface methodology. Our comparative study indicates that our proposed policy 2 outperforms both proposed policy 1 and the policies adapted from the literature in terms of both optimal total costs and GHG emissions reduction.

Keywords: environmental production control policy, remanufacturing, returns' quality, unreliable systems, greenhouse gas emissions, simulation optimization.

4.1 Introduction

In recent decades, concerns over environmental issues such as global warming and climate change have considerably grown. There is no denying the fact that manufacturing sector is one of the main sources of environmental issues including greenhouse gas emissions (GHGs), waste generation and resource depletion (Ramandi and Bafruei 2020). Environmental regulations like carbon tax and cap-and-trade put pressure on companies to limit their emissions and develop environmentally responsible systems. Moreover, many countries are struggling with the major problem of generating large quantities of waste. Waste-related regulations such as Waste Electrical and Electronic Equipment (WEEE) have been used by governments to force industries to take care of their End-of-Life (EOL) products (Zhang et al., 2021).

In today's business environment, many products are returned as they are defective, damaged, or exchanged. Remanufacturing is an effective method to minimize the consumption of resources and generation of waste by extending product's useful life (Zeballos et al., 2021). Regarding environmental concerns, many companies decided to practice reverse logistics by collecting used products and managing EOL products through decisions like recycling, remanufacturing, repairing, and disposing. In this vein, hybrid manufacturing/remanufacturing systems are designed to meet demand with both manufacturing of raw material and remanufacturing of returned products (Assid et al., 2021).

Regarding the complexities of managing returns such as uncertain returns' quantity and quality, it is more challenging to manage the production of manufacturing/remanufacturing systems than traditional manufacturing systems (Assid et al., 2021). Other stochastic events associated with the machine failures and repairs lead to more complexity, which are considered in our study. In fact, as returned products come from various sources such as damaged products and cancelled orders, the quality of returns is considerably variable. To manage this variability, categorization of returns based on their quality is used to assign specific quality conditions to returned products like high-quality or low-quality (Sonntag and Kiesmüller 2017). This return categorization is beneficial for providing advanced information on input quality and has become a necessary tool in the existing remanufacturing industry problem (Panagiotidou et al., 2013). In fact, the variability in the quality of returns is a serious challenge for production planning because the suitable remanufacturing effort (e.g., remanufacturing cost and lead time) is heavily influenced by the condition of the returns. In general, higher quality returned products take less time to process. This explains why the returns quality has such a significant impact on production capacity. For instance, because of the number of components that mist be replaced, remanufacturing a one-year-old transmission costs significantly more than remanufacturing a four-year-old one. Similarly, the remanufacturing processing time and cost of previously remanufactured automotive engine block are often greater since the remanufacturing must be done with tighter tolerance (Akçalı and Çetinkaya 2011). Moreover, when it comes to environmental aspects, remanufacturing using higher quality returned products generates less GHG emissions than remanufacturing using low-quality returns (Zhou et al., 2018). Therefore, taking the variation of returns' quality into account, especially in planning of production activities could result in efficiency improvement, cost saving and GHG emissions reduction. So, it is interesting to pay attention to the impact of returns' quality on the GHG emissions generated from the manufacturing/remanufacturing systems.

One of the biggest challenges for manufacturing/remanufacturing systems with variate quality returns is to provide an environmentally friendly cost-effective plan deciding on the condition and percentage of time manufacturing or remanufacturing should be used to satisfy the demand. In this regard, the main research questions of this study are as follows: When and at what rate should the system produce using manufacturing or remanufacturing machine or both of them? When should the remanufacturing switch between high- and low-quality returns? What are the optimal safety stock levels for manufacturing and remanufacturing? Our objective is to develop optimal production control policies for failure-prone manufacturing/remanufacturing systems with variate quality returns under carbon tax regulation. We aim to help the manager in synchronizing manufacturing using raw material and remanufacturing using high- and low-quality returns together to minimize total costs while simultaneously reducing emissions generated.

The rest of the paper is laid out as follows: Section 4.2 contains a review of the literature in the field. The problem statement and resolution approach are respectively provided in Section 4.3 and 4.4. The formulation of a proposed production control policies is presented in Section 4.5. Section 4.6 describes the simulation model and its validation. Numerical results and sensitivity analysis are addressed in Section 4.7. A comparative study is provided in Section 4.8. Finally, the managerial insights and conclusion are respectively presented in Section 4.9 and 4.10.

4.2 Literature review

A summary of the literature review relevant to this study is presented in Table 4.1 including the models for manufacturing/remanufacturing systems with and without consideration of environmental aspects. Each class is divided into two groups based on whether they considered machine failure. A comparison has been made among the publications in the literature in terms of specific criteria, such as inventory and production policy, developing a new policy, closed-loop supply chain network, quality-based class of returns, quality impact of returns on emissions, simultaneous operation of manufacturing and remanufacturing, environmental regulations, and voluntary environmental approach.

Group 1 of Class 1 consists of studies which focused on the production planning of manufacturing and remanufacturing systems regardless of environmental aspects and machine failure. In the relevant studies, the economic order quantity (EOQ) or economic production quantity (EPQ) are used as the inventory/production policy. In this context, Liu et al., (2018) presented a mathematical model for production and pricing strategies of a monopolistic manufacturing and remanufacturing system. The conditions under which the system should produce new items, or remanufactured items, or both are identified considering two-quality bins for returns.

Table 4.1 The relevant literature of models for manufacturing and remanufacturing systems with and without considering environmental aspects and machine failure

Publications	**Inventory/ production policy**			**Developing a new policy**	**Closed-loop supply chain network**	**Quality-based class of returned products**	**Quality impact of returns on emissions**	**Simultaneous operation of machines**	**Environmental regulations**	**Voluntary environmental approach**
	HPP*	**EPQ****	**EOQ*****							
Class 1: Models for manufacturing/remanufacturing systems without considering environmental aspects										
Group 1: Models without consideration of machine failure										
(Liu et al., 2018)		✓			✓	✓		✓		
(Farahani et al., 2020)		✓			✓	✓				
(Zheng et al., 2021)		✓			✓					
(Aminipour et al., 2021)		✓			✓			✓		
(Zhang and Chen 2022)		✓			✓					
Group 2: Models with consideration of machine failure										
(Turki et al., 2017)	✓				✓			✓		
(Polotski et al., 2017)	✓			✓	✓			✓		
(Polotski et al., 2019)	✓			✓	✓			✓		
(Assid et al., 2019b)	✓			✓	✓			✓		
(Assid et al., 2021)	✓			✓	✓	✓		✓		
Class 2: Models for manufacturing/remanufacturing systems considering environmental aspects										
Group 1: Models without consideration of machine failure										
(Bazan et al., 2017)		✓			✓			✓	✓	
(Chen et al., 2020)		✓			✓			✓	✓	
(Zhao et al., 2021)		✓			✓	✓			✓	
(Shekarian et al., 2021)		✓			✓			✓	✓	
(Liao and Li 2021)			✓		✓				✓	
Group 2: Models with consideration of machine failure										
(Salim et al., 2017)		✓			✓			✓	✓	
(Turki et al., 2018a)	✓				✓				✓	
(Turki et al., 2018b)	✓				✓	✓		✓	✓	
(Hajej et al., 2019)	✓				✓			✓	✓	
(Ndhaief et al., 2020)	✓				✓			✓	✓	
This paper	✓			✓	✓	✓	✓	✓	✓	✓

* Hedging point policy. ** Economic production quantity. *** Economic ordering quantity.

Farahani et al., (2020) proposed an optimal disposition policy for remanufacturing systems with variable quality returns. They aimed to provide a disposition decision-making model for a remanufacturing process with limited inventory capacity of recovered returns, constant demand, and a minimal quality grade level for the remanufactured product. Zheng et al., (2021) studied the production and pricing decisions for new and remanufactured products. They looked into the remanufacturing strategy's influence on the manufacturer, taking into account customer prejudice and accurate responses. In a two-stage model with and without remanufacturing, they characterise the optimal production and pricing decisions for new and remanufactured items. Aminipour et al., (2021) focused on integrating cyclic manufacturing and remanufacturing policies in a two-stage closed-loop supply chain. They generated an optimal production schedule minimizing the sum of setup as well as holding costs. Zhang and Chen (2022) investigated a closed-loop supply chain (CLSC) that includes a supplier of new and remanufactured critical components and a capital-constrained original equipment manufacturer. They addressed the optimal operational and financing portfolio strategies for the capital constrained CLSC.

Group 2 of Class 1 includes models and policies for manufacturing/remanufacturing systems without considering environmental aspects but with consideration of machine failures. To deal with the dynamic stochastic environment of unreliable manufacturing/remanufacturing systems, hedging point policy (HPP) is used by many researchers. HPP aims to determine the production rate according to the inventory level as a function of the system state and reach a specific safety stock level to meet the customer demand when there is a failure (Entezaminia et al., 2020). In this regard, Turki et al., (2017) focused on a manufacturing–remanufacturing–transport–warehousing closed-loop supply chain. They presented a hedging point policy in order to control manufacturing and remanufacturing, with preserving the coordination among manufacturing, remanufacturing, inventorying as well as return of end-of-life products. Polotski et al., (2017) focused on a hybrid manufacturing/remanufacturing system including one facility in which both raw materials and returned items are used in the production process. To plan the production effectively and reduce the manufacturing cost, they determined the optimal production and setup policies for failure-prone hybrid manufacturing/remanufacturing systems. Polotski et al., (2019) developed a joint manufacturing, remanufacturing as well as disposal control policy for failure-prone hybrid systems in which both raw material and returns are used to meet the demand. Assid et al., (2019b) dealt with the production planning of a failure-prone hybrid manufacturing/remanufacturing systems considering supply constraints. They developed joint control policies integrating simultaneously the production and disposal activities as well as the procurement of both returns and raw material. Assid et al., (2021) developed a production policy for hybrid manufacturing/remanufacturing systems to obtain both remanufacturing and manufacturing production rates and switch between remanufacturing modes. As it is becoming increasingly difficult to ignore the environmental impact of manufacturing/remanufacturing systems, one of the limitations of studies in Class 1 is that they do not focus on the environmental aspects of such systems.

According to Class 2, there are a few studies which dealt with the inventory and production planning of manufacturing/remanufacturing systems considering environmental aspects. In Group 1 of Class 2, machine failure is not taken into consideration by researchers. In this context, Bazan et al (2017) studied a two-level closed-loop supply chain model with a manufacturer and a retailer for remanufacturing of used/ returned items under carbon tax penalty. They minimised the sum of inventory related costs considering GHG emissions generated from production and transportation activities, as well as the extension of a product life through repetitive recovery. Chen et al., (2020) studied a monopolist remanufacturing system under both take-back and emissions capacity regulations. Optimal decisions of the remanufacturer to maximize the profit are determined, and the environmental and economic impact of regulations are investigated. Zhao et al., (2021) focused on production planning for remanufacturing both single and multiple categories of end-of-life products under quality uncertainty considering cap-and-trade policy. Shekarian et al., (2021) focused on the impacts of remanufacturing and GHG emissions on dual-channel closed-loop supply chain, both forward logistics as well as reverse logistics considering a competition on collection. The impacts of various dual-collection settings are explored considering competition between collector parties under three possible options including manufacturer-retailer, manufacturer-third party, and retailer-third party. Liao and Li (2021) proposed an optimal sustainable ordering method for maximizing the environmental benefits for closed-loop supply chains under market uncertainty. They showed that the extended EOQ technique can significantly cut carbon equivalent emissions and enhance environmental efficiency. According to the literature, studies in Group 1 of Class 2 have only focused on the deterministic context of the manufacturing/remanufacturing systems where unreliability of machines is not considered.

Based on Group 2 of Class 2, there are only few studies on production planning of failure-prone manufacturing/remanufacturing systems considering environmental aspects. Accordingly, Salim et al., (2017) presented a mathematical model for a failure-prone manufacturing and remanufacturing production problem under environmental constraint. They obtained the production plans of manufacturing and remanufacturing machines as well as the quantity of emissions generated in each production period. Turki et al., (2018a) studied the production planning of the manufacturing/remanufacturing systems considering the difference between new products and remanufactured ones, random customer demand, random machine failures, and carbon emissions constraints. Turki et al., (2018b) presented a model for manufacturing/remanufacturing systems that differentiates between remanufactured and new products to obtain the optimal production rates and storage capacities maximizing the total profit. Hajej et al., (2019) provided a production and maintenance policy for failure-prone manufacturing/remanufacturing systems under carbon tax regulation. A subcontractor is used to help either manufacturing or remanufacturing to control total emissions during the production process. Ndhaief et al., (2020) presented an economic and environmental production and maintenance plan for unreliable manufacturing/remanufacturing systems under environmental constraints.

According to the literature, no new production control policy is developed by the existing studies which focused on production planning for failure-prone manufacturing/ remanufacturing systems considering environmental aspects. Turki et al., (2018a), Turki et al., (2018b), Hajej et al., (2019) and Ndhaief et al., (2020) used HPP and environmental hedging point policy (EHPP) that have been already developed by Ben-Salem et al., (2015a) under which there is a decrease in the machine usage by reducing the threshold level after exceeding the emission limit to reduce the generated emissions and minimize total costs. Hence, there is a lack of production control policies for failure-prone manufacturing/remanufacturing systems under carbon tax regulation aiming to address GHG emissions generated from production process. Also, one major weakness of existing studies is that the impact of quality of returns on emissions generated from unreliable manufacturing and remanufacturing systems is not considered.

To fill the gap in the literature, we develop new production control policies for failure-prone manufacturing/remanufacturing systems considering quality impact of returns under carbon tax regulation. In this study, the impact of quality of returns on the emission and production rates has been considered. Regarding quality-based class of returns, proposed production control policies are developed for manufacturing and remanufacturing using high- and low-quality returns considering their variant emitting levels. Our cost-effective environmentally friendly control policies help the companies in synchronizing manufacturing and remanufacturing together to minimize total costs while reducing GHG emissions.

4.3 Problem statement

4.3.1 Notations

In the rest of the paper, the following notations are considered. Here, i denotes the machines consisting of manufacturing machine ($i = 1$) and remanufacturing machine ($i = 2$). j defines the production modes including manufacturing ($j = 1$), remanufacturing using high-quality returns (j =2), and remanufacturing using low-quality returns ($j = 3$).

$x_{FP}(t)$	inventory/backlog level of finished products at time t
$E(t)$	emissions level of at time t
$\alpha_i(t)$	operational state of machine i, equals to 0 if it is under failure and equals to 1 if it is up
$\beta_j(t)$	state of production mode j, equals to 1 if it is off and equals 1 if it is on

$u_j(t)$	production rate of production mode j (product/time unit)
U_j^{max}	maximum production rate of mode j (product/time unit)
d_j	customer demand rate of products of mode j ($d_1 = d_2 = d_3 = d$)
L	emissions limit announced by the government
TTF_i	time to failure distribution function of machine i
TTR_i	time to repair distribution function of machine i
$MTTF_i$	mean time to failure of machine i
$MTTR_i$	mean time to repair of machine i
c^+	inventory cost (\$/product/time unit)
c^-	backlog cost (\$/product/time unit)
c^e	emission unit cost for each violation unit (\$/violation unit)
c_{P_j}	production cost in mode j (\$/product)
θ_j	emission index of producing using production mode j
Ava_i	availability of machine i
P_e	length of the monitoring period for emissions level

4.3.2 Problem description and formulation

As shown in Figure 4.1, we study a manufacturing/remanufacturing system composed of two failure-prone machines which simultaneously produce one product type with the same quality to satisfy the same customer demand. In the forward supply chain, Machine 1 manufactures using raw materials. In the reverse supply chain, Machine 2 remanufactures using returned products. In fact, manufacturing is more rapid than remanufacturing. Moreover, there is a market of used products with two sources for both high-quality and low-quality returns. According to the literature, there are various studies in which manufactured and remanufactured items are supposed to have the same quality and meet the same customer demand (for case studies like car parts, computers, and electronic devices) (Tang and Teunter 2006; Zanoni et al., 2012; Assid et al., 2021). Similarly, in our context, all finished products produced with manufacturing or remanufacturing machines are kept in the same storage area to be sold to the same customers. In this study, we make the following assumptions:

- ✓ the demand rate is considered to be constant.
- ✓ setup time or setup cost are negligible for switching between modes of remanufacturing.
- ✓ raw material and returns are always available.
- ✓ the quality of both manufactured and remanufactured products is the same.
- ✓ both remanufacturing and manufacturing machines are required to meet customer demand.

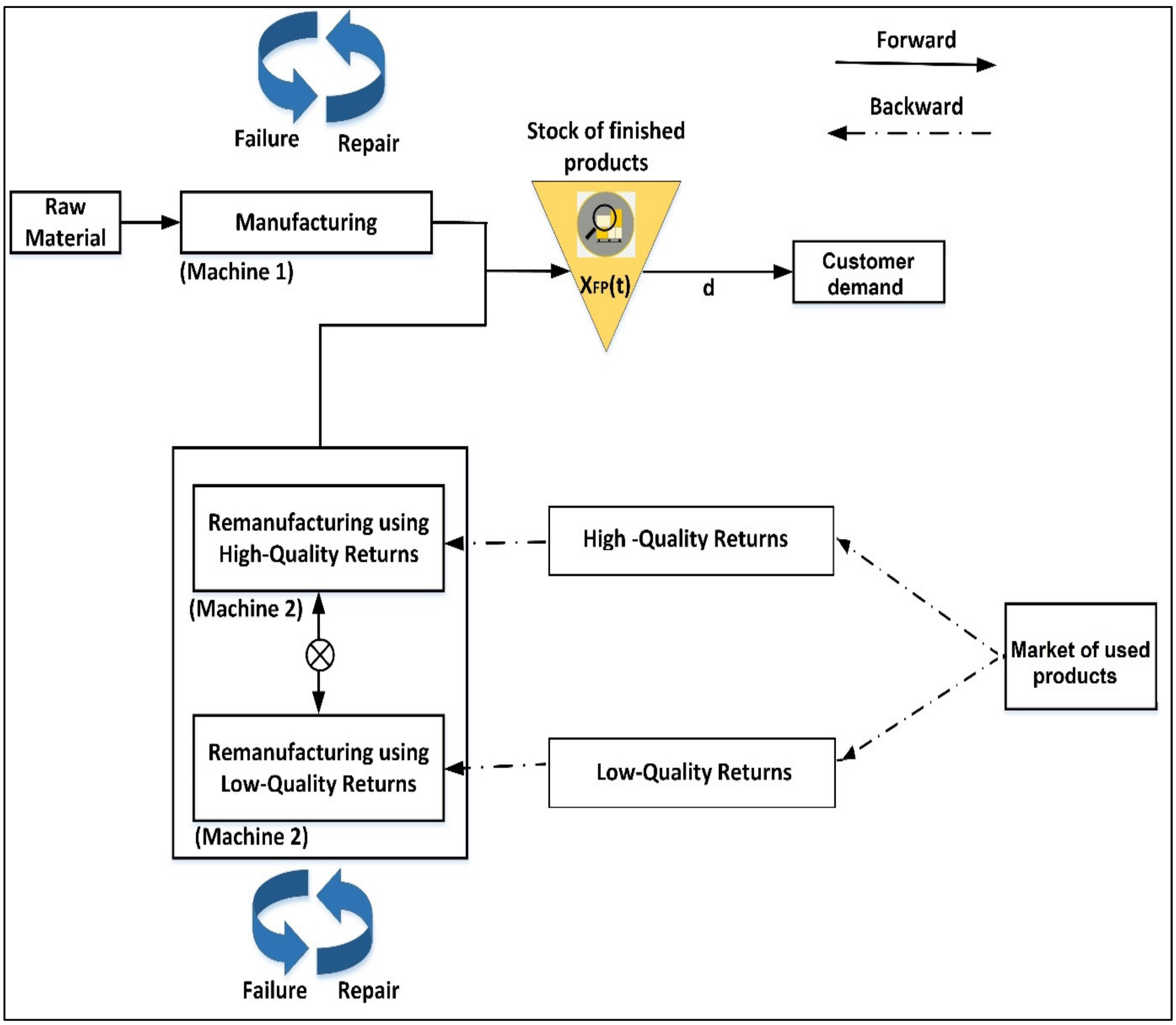

Figure 4.1 The considered failure-prone manufacturing/remanufacturing system

Moreover, the environmental impact of producing using manufacturing and remanufacturing facilities and the generated GHG emissions are taken into consideration. Here, we study the specific industries such as cartridges, retreated tires, as well as heavy-duty and off-road equipment where remanufacturing generates more emissions than manufacturing using raw material (Sundin and Lee 2012; Bazan 2015). Remanufacturing supplied by high-quality returns requiring less processing time than remanufacturing using low-quality returns and generates less emissions ($\theta_1 < \theta_2 < \theta_3$) (Zhou et al., 2018). To consider the stochastic aspect of emissions, we define θ_j as a random variable following a uniform distribution $[a_j, b_j]$ as in Chen and Monahan (2010). A carbon tax regulation is imposed on the system, under which if the emissions level, at the end of the emission control period, exceeds the emission limit L announced by the government, the violation is penalized. For the considered system, $u_1(t)$, $u_2(t)$, and $u_3(t)$ respectively show the production rates of the manufacturing, remanufacturing using high-quality returns and remanufacturing using low-quality returns. In fact, manufacturing has higher production rate compared with remanufacturing, and remanufacturing using high-quality returns is faster than remanufacturing using low-quality returns (Zhou et al., 2018) ($U_3^{max} < U_2^{max} < U_1^{max}$). The emission index defines the quantity of emissions generates by producing one product unit with each production mode.

Failure duration and repair duration for the manufacturing and remanufacturing machines evolve according to stochastic process. The availability of each machine can be defined as follows:

$$Ava_i = \frac{MTTF_i}{MTTF_i + MTTR_i} \qquad (\text{i} = 1, 2) \qquad (4.1)$$

$x_{FP}(t), E(t), \alpha_{\text{i}}(t), \beta_{\text{j}}(t)$ are defined as the state of the considered discrete/continuous manufacturing/remanufacturing system at any time t to describe its dynamic behavior. In the discrete part of the system state, $\{\alpha_i(t), t > 0\} \in \{0,1\}$ equals 0 when the machine is under failure and equals 1 when it is up. $\{\beta_{\text{j}}(t), t > 0\} \in \{0,1\}$ equals 0 when the machine is off and equals 1 if it is on according to the policy. Besides, in the continuous parts of the system state, the inventory level is shown as $x_{FP}(t) \in R$ and the emissions level is defined as $E(t) \in R$. The Equation (4.2) shows the inventory dynamics. x_0 is the initial surplus level ($x_{FP}(0) = x_0$). Also, the dynamic behavior of the quantity of emissions is given by Equation (4.3).

$$\frac{dx_{FP}(t)}{dt} = u_1(t).\alpha_1(t).\beta_1(t) + u_2(t).\alpha_2(t).\beta_2(t) + u_3(t).\alpha_2(t).\beta_3(t) - d \tag{4.2}$$

$$\frac{dE(t)}{dt} = u_1(t).\alpha_1(t).\beta_1(t).\theta_1 + u_2(t).\alpha_2(t).\beta_2(t).\theta_2 + u_3(t).\alpha_2(t).\beta_3(t).\theta_3 \tag{4.3}$$

Feedbacks will be sent to the system once the emissions level exceeds the voluntary limits or the level of inventory goes over threshold levels. Capacity constraint is given by Equations (4.4):

$$0 \le u_j(t) \le U_j^{max} \quad (j = 1, 2, 3) \tag{4.4}$$

Considering the random unavailability of the system, its capacity must fulfill, at the very least, the demand rate shown as follows:

$$U_1^{max}.\alpha_1(t).\beta_1(t).Ava_1 + U_2^{max}.\alpha_2(t).\beta_2(t).Ava_2 + U_3^{max}.\alpha_2(t).\beta_3(t).Ava_2 \ge d \tag{4.5}$$
$$\beta_2(t).\beta_3(t) = 0$$

The included costs of the system are the emission, production, inventory, and backlog costs. According to carbon tax regulation, for each unit of emission violation at the end of control period, the system should pay the penalty cost of c^e. The emission cost can be calculated as follows:

$$EC(t_k) = c^e.\max(0, E(t_k) - L) \quad k = 1, \dots, N;\ t_k = k \times P_e;\ E(t_k) = 0 \tag{4.6}$$

The emissions level is reset to zero, at the end of the emission control period (P_e). k represents emission control periods and N is the number of considered control periods.

The inventory and backlog costs are calculated based on inventory surplus level as shown in Equation (4.7) where $x_{FP}^{+} = \max(0, x_{FP})$, $x_{FP}^{-} = \max(-x_{FP}, 0)$. In fact, returns are less costly compared to raw material, however, high quality returns supplied from sorting centers are more costly than low-quality ones ($c_{P_3} < c_{P_2} < c_{P_1}$) (Masoudipour et al., 2017). The production cost can be calculated based on production rates as shown in Equation (4.8).

$$I(x_{FP}(t)) = c^{+}.x_{FP}^{+} + c^{-}.x_{FP}^{-} \tag{4.7}$$

$$PC\left(u_j(t)\right) = c_{P_1}.u_1(t).\alpha_1(t).\beta_1(t) + c_{P_2}.u_2(t).\alpha_2(t).\beta_2(t) + c_{P_3}.u_3(t).\alpha_2(t).\beta_3(t) \tag{4.8}$$

$$\mathrm{g}\big(x_{FP}(t), u_j(t)\big) = I(x_{FP}(t)) + PC(u_j(t)) \tag{4.9}$$

Using Equations (4.6) to (4.9), the average total cost is defined as shown below:

$$J\big(x_{FP}(t), E(t), \alpha_i(t), \beta_j(t)\big) = \int_0^{N \times P_e} \mathrm{g}\left(x_{FP}(t), u_j(t)\right)\, dt + \frac{1}{N \times P_e}\sum_{k=1}^{N} EC(t_k) \tag{4.10}$$

The optimal control policy aims to minimize the average total cost of the system, $j(.)$ Which is subject to constraints (4.1) to (4.5), and to specify the production rate of manufacturing and remanufacturing machines.

4.4 Resolution approach

Considering the stochastic and dynamic context of the system under study, it is difficult to find an analytical solution for such complex problems (Entezaminia et al., 2020). Hence, an experimental resolution approach combining the design of experiment (DOE), simulation and response surface methodology (RSM) is implemented to solve such complex problem. Thereby, the estimation of the optimal values for control parameters minimizing the total costs shown in Equation (4.10) are provided. This resolution approach is adapted to this paper as it has been used by Entezaminia et al., (2021). Our resolution approach consists of 7 steps as briefly provided in Figure 4.2:

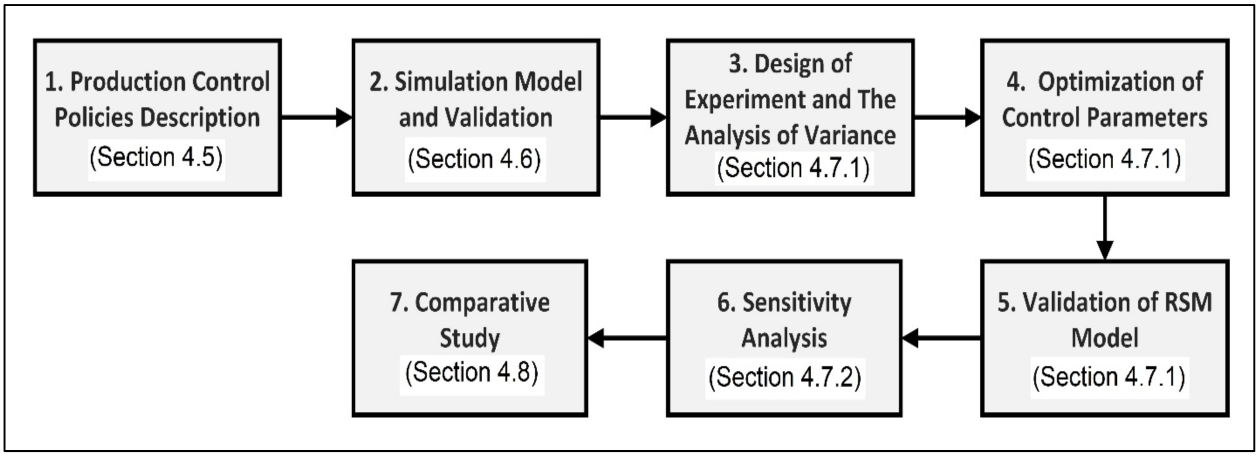

Figure 4.2 Methodology and resolution approach

✓ step 1: Production control policies description

The structure of the proposed production control policies is provided in Equations (4.12) to (4.17) (see Section 4.5).

✓ step 2: Simulation model and validation

To display the dynamic behavior of the system, the simulation model for proposed policy is provided, in which the control policy is considered as the input and total costs is taken into account as the output (see Section 4.6).

✓ step 3: Design of experiment and the analysis of variance

According to the experimental design approach, the number of experiments and the levels for each independent variable are determined to carry out several experiments. Analysis of variance (ANOVA) is implemented to indicate the effect of control parameters as well as their interactions on the response variable (total costs) in order to specify the main independent variables which have significant effect on total costs (see Section 4.7.1).

✓ step 4: Response surface methodology and optimization of control parameters

To identify the impact of significant main control parameters (A, B, C, D, E), their quadratic effects as well as their significant interactions on total costs, the response surface methodology

(RSM) is implemented. Using a combination of DOE, RSM and the regression analysis, the total costs approximation function can be provided as follows (Myers et al., 2016):

$$TC = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 D + \beta_5 E + \beta_{11} A^2 + \beta_{12} AB + \beta_{13} AC + \beta_{14} AD + \beta_{15} AE + \beta_{22} B^2 + \beta_{23} BC + \beta_{24} BD + \beta_{25} BE + \beta_{33} C^2 + \beta_{34} CD + \beta_{35} CE + \beta_{44} D^2 + \beta_{45} DE + \beta_{55} E^2 + \varepsilon \quad (4.11)$$

Data obtained from the simulation model are used to get the estimation of unknown coefficients including β_0, β_i and β_{ij} ($i, j \in \{1, 2, 3, 4, 5\}$). We define the random error by ε. We also obtain the optimal values of significant control parameters which minimizes the total costs (see Section 4.7.1).

✓ step 5: Validation of RSM model

To validate the RSM model (Equation (4.11)), according to Myers et al., (2016), three steps are followed.

- first, adjusted R-squared coefficient is considered to evaluate the overall performance of the RSM model. The adjusted R-squared coefficient measures the proportion of total variation in total costs which can be explained by independent variables of the RSM model. Indeed, the adjusted R-squared is better to be close to 1.

- secondly, to check the residual normality as well as homogeneity of variances, a residual analysis is carried out.

- thirdly, to crosscheck the validity of the model, after optimizing the RSM, we determine a confidence interval at 95% and carry out a Student's t-test. We run the simulation model for additional numbers of replications using as input of the optimal value of control parameters. The optimal total cost should fall within the confidence interval (see Section 4.7.1).

- ✓ step 6: Sensitivity analysis

To evaluate our proposed production control policies and robustness of considered resolution approach, sensitivity analyses are provided in this section (see Section 4.7.2).

- ✓ step 7: Comparative study

To identify the most cost-effective and environmentally friendly production control policy, a comparison is made among the proposed production control policies and an adaption of the most relevant production control policy from the literature, for a broad range of system and cost parameters (see Section 4.8).

4.5 Formulation of proposed production control policies

4.5.1 Proposed policy 1

In the current system under study, from an environmental point of view, manufacturing using raw material is considered as the low-emitting machine and remanufacturing is the high-emitting machine capable of producing using two categories of returns. We aim to find the best synchronization of manufacturing using raw materials and remanufacturing using high- and low-quality returns. According to the proposed policy 1, considering the available production capacity of machines, inventory threshold levels (Z_1, Z_2 and Z_3) are defined to help the system to face future unavailability caused by machine failures. For the same manufacturing system without consideration of environmental aspects, Assid et al., (2021) showed that the threshold level of manufacturing activity is less than those of remanufacturing. Because it is more profitable to produce better quality products at a faster rate in situation where there is a high risk of shortage. In this vein, Z_1 represents the threshold level for manufacturing using raw materials. Z_2 and Z_3 respectively stand for the threshold levels of remanufacturing using high-quality returns and remanufacturing using low-quality returns. As the available production capacity of manufacturing is more than remanufacturing, the system is less likely to experience a shortage when operating using manufacturing, so, less inventory in needed to deal with the shortage. Similarly, remanufacturing using high-quality returns which is faster needs lower threshold level than remanufacturing using low-quality returns to face the shortage, so that

$Z_1 \leq Z_2 \leq Z_3$. When the inventory level is less than Z_1, the manufacturing machine supports the remanufacturing to reduce the risk of backlog.

To control the emissions generated by the system, Y_1 and Y_2 ($Y_1 < Y_2$) are the defined as voluntary emission limits to switch from a higher emitting mode to a lower emitting production mode. In the beginning, the emissions level is low, the system operates the remanufacturing using low-quality returns which is the least expensive but highest emitting production mode. When emissions generated goes over a voluntary emission limit, Y_1 (and still $\leq Y_2$), the system remanufactures with high-quality returns which is not too costly and generates less emissions. When emissions generated is considerably high and exceeds the second voluntary limit, Y_2, the system stops remanufacturing and operates only with manufacturing which is the least emitting production mode. The proposed policy 1 is provided in Equations (4.12) to (4.14).

$$\text{If } E(t) < Y_1 \text{ then}$$
$$\begin{cases} u_1(t) = \begin{cases} U_1^{max}\ (\beta_1 = 1) & if\ x_{FP}(t) < Z_1\ and\ \alpha_1 = 1 \\ 0 & o.w \end{cases} \\ u_2(t) = 0\,; \quad (\beta_2 = 0) \\ u_3(t) = \begin{cases} U_3^{max}\ (\beta_3 = 1) & if\ x_{FP}(t) < Z_3\ and\ \alpha_3 = 1 \\ d_3\ (\beta_3 = 1) & if\ x_{FP}(t) = Z_3\ and\ \alpha_3 = 1 \\ 0 & o.w \end{cases} \end{cases} \tag{4.12}$$

$$\text{If } Y_1 \leq E(t) < Y_2 \text{ then}$$
$$\begin{cases} u_1(t) = \begin{cases} U_1^{max}\ (\beta_1 = 1) & if\ x_{FP}(t) < Z_1\ and\ \alpha_1 = 1 \\ 0 & o.w \end{cases} \\ u_2(t) = \begin{cases} U_2^{max}\ (\beta_2 = 1) & if\ x_{FP}(t) < Z_2\ and\ \alpha_2 = 1 \\ d_2\ (\beta_2 = 1) & if\ x_{FP}(t) = Z_2\ and\ \alpha_2 = 1 \\ 0 & o.w \end{cases} \\ u_3(t) = 0\,; \quad (\beta_3 = 0) \end{cases} \tag{4.13}$$

If $E(t) \geq Y_2$ then

$$\begin{cases} u_1(t) = \begin{cases} U_1^{max} & (\beta_1 = 1) & if\ x_{FP}(t) < Z_1\ and\ \alpha_1 = 1 \\ d_1 & (\beta_1 = 1) & if\ x_{FP}(t) = Z_1\ and\ \alpha_1 = 1 \\ 0 & & o.w \end{cases} \\ u_2(t) = 0\ ; \quad (\beta_2 = 0) \\ u_3(t) = 0\ ; \quad (\beta_3 = 0) \end{cases} \tag{4.14}$$

According to this policy, when the emissions level is less than Y_1, the system operates with the cheapest production mode which is remanufacturing using low-quality returns (j= 3). Remanufacturing using high-quality returns is stopped ($\beta_3 = 0$). If the inventory is less than the threshold level of Z_1 ($x_{FP}(t) < Z_1$), the manufacturing (j= 1) produces with maximum rate along with remanufacturing (j= 3) to reach required inventory threshold level. After reaching threshold level of Z_1 ($x_{FP}(t) = Z_1$), remanufacturing (j= 3) continues to produce with maximum production rate to build its threshold level of Z_3. After reaching Z_3 ($x_{FP}(t) = Z_3$), the system produces at demand rate. If the emissions level goes over Y_1 ($E(t) > Y_1$), the system switches to remanufacturing using high-quality returns (j= 2). If the inventory is less than Z_1 ($x_{FP}(t) < Z_1$), the manufacturing (j= 1) supports the remanufacturing to reduce the high risk of shortage. After reaching Z_1 ($x_{FP}(t) = Z_1$), the remanufacturing using high-quality returns continues to produce at maximum production rate until building its inventory threshold level, Z_2. When Z_2 is built, it produces at demand rate. If the emissions generated exceeds Y_2 ($E(t) > Y_2$), the system needs to control more the emissions by stopping the remanufacturing and producing only with manufacturing (j= 1). Remanufacturing using high- or low-quality returns are stopped ($\beta_2 = \beta_3 = 0$). If the inventory is less than Z_1 ($x_{FP}(t) < Z_1$), manufacturing produces with maximum rate. When the inventory reaches Z_1 ($x_{FP}(t) = Z_1$), the manufacturing produces with the rate of demand.

4.5.2 Proposed policy 2

Under our proposed policy 1, the system starts by operating the cheapest production mode (remanufacturing using low-quality returns) and gradually switches to the less emitting production mode if the emissions exceed its voluntary limits. In this way, remanufacturing using high-quality returns operates only if the emissions level is higher than (Y_1 and still $\leq Y_2$).

However, remanufacturing using high-quality returns is the least emitting and fastest remanufacturing which can help the system to reduce emissions and increase the system availability. The central question here is how can we improve the proposed policy 1 and make it more efficient in terms of emissions reduction? What if we use the fastest production modes, manufacturing using raw material and remanufacturing using high-quality returns, to reach the inventory threshold level of Z_1? In this way, could we improve the policy in terms of environmental matters? Could we generate less emissions and reduce the emission cost by more usage of remanufacturing using high-quality returns? Could we provide more available production capacity? Will that result in less inventory and backlog costs? Will that lead to more cost saving?

As an improvement of proposed policy 1, proposed policy 2 takes advantage of more usage of remanufacturing using high-quality returns (j = 2) which is the least emitting remanufacturing with higher production capacity. According to our proposed policy 2 which is expected to be more environmentally friendly and cost-effective, remanufacturing using high-quality returns (j = 2) operates along with manufacturing to provide more system availability for reaching the minimum inventory threshold level of Z_1 (emissions less than Y_2). Moreover, if the emissions level is considerably high and more than Y_2 ($E(t) > Y_2$), the remanufacturing using high-quality returns (j = 2) can operate when the manufacturing (j = 1) is down. Therefore, by providing more available production capacity under proposed policy 2, the system avoids future backlog and requires less inventory to keep. In this way, our proposed policy 2 is expected to reduce the inventory and backlog costs. On the other hand, more usage of remanufacturing using high-quality returns (j = 2) helps the system to generate less GHG emissions and reduces emissions cost. Proposed policy 2 is developed shown in the Equations (4.15) to (4.17) as follows:

If $E(t) < Y_1$ then

$$\begin{cases} u_1(t) = \begin{cases} U_1^{max} \ (\beta_1 = 1) & if\ x_{FP}(t) < Z_1\ and\ \alpha_1 = 1 \\ 0 & o.w \end{cases} \\ u_2(t) = \begin{cases} U_2^{max} \ (\beta_2 = 1) & if\ x_{FP}(t) < Z_1\ and\ \alpha_2 = 1 \\ 0 & o.w \end{cases} \\ u_3(t) = \begin{cases} U_3^{max} \ (\beta_3 = 1) & if\ Z_1 \leq x_{FP}(t) < Z_3\ and\ \alpha_3 = 1 \\ d_3 \ (\beta_3 = 1) & if\ x_{FP}(t) = Z_3\ and\ \alpha_3 = 1 \\ 0 & o.w \end{cases} \end{cases} \tag{4.15}$$

If $Y_1 \leq E(t) < Y_2$ then

$$\begin{cases} u_1(t) = \begin{cases} U_1^{max} \ (\beta_1 = 1) & if\ x_{FP}(t) < Z_1\ and\ \alpha_1 = 1 \\ 0 & o.w \end{cases} \\ u_2(t) = \begin{cases} U_2^{max} \ (\beta_2 = 1) & if\ x_{FP}(t) < Z_2\ and\ \alpha_2 = 1 \\ d_2 \ (\beta_2 = 1) & if\ x_{FP}(t) = Z_2\ and\ \alpha_2 = 1 \\ 0 & o.w \end{cases} \\ u_3(t) = 0\,; \quad (\beta_3 = 0) \end{cases} \tag{4.16}$$

If $E(t) \geq Y_2$ then

$$\begin{cases} u_1(t) = \begin{cases} U_1^{max} \ (\beta_1 = 1) & if\ x_{FP}(t) < Z_1\ and\ \alpha_1 = 1 \\ d_1 \ (\beta_1 = 1) & if\ x_{FP}(t) = Z_1\ and\ \alpha_1 = 1 \\ 0 & o.w \end{cases} \\ u_2(t) = \begin{cases} U_2^{max} \ (\beta_2 = 1) & if\ x_{FP}(t) < Z_1\ and\ \alpha_1 = 0\ and\ \alpha_2 = 1 \\ d_1 \ (\beta_2 = 1) & if\ x_{FP}(t) = Z_1\ and\ \alpha_1 = 0\ and\ \alpha_2 = 1 \\ 0 & o.w \end{cases} \\ u_3(t) = 0\,; \quad (\beta_3 = 0) \end{cases} \tag{4.17}$$

4.6 Simulation model

Arena software is used to develop a discrete-continuous simulation model for each production control policy as can be seen in Figure 4.3.

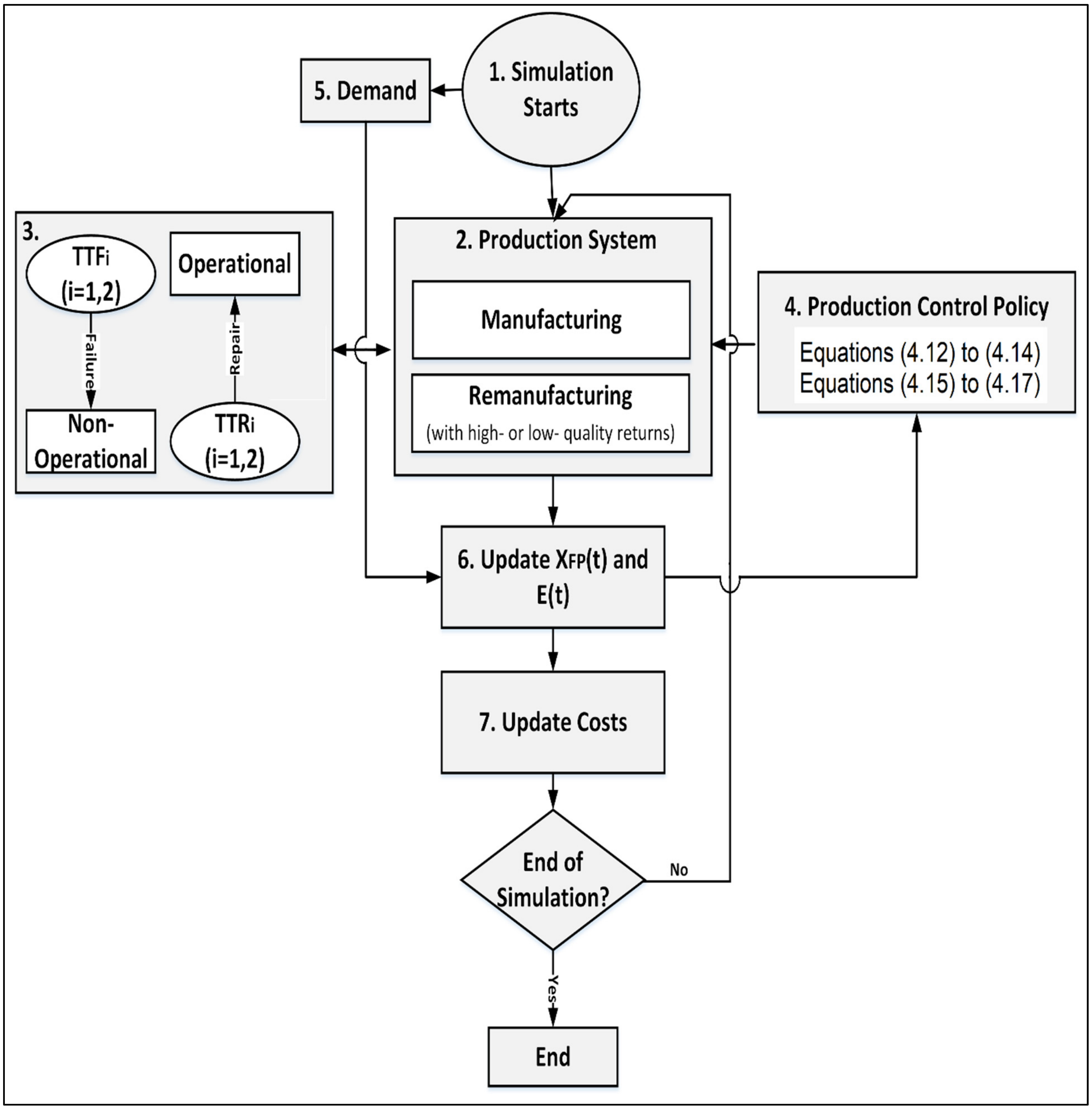

Figure 4.3 The diagram associated with the simulation model

As displayed in the figure, in Block 1, the simulation model starts to define the inputs and parameters ($Z_1, Z_2, Z_3, d,$ etc.). Blocks 2 and 3 represent the production system consisting of the manufacturing machine and remanufacturing using high- and low-quality returns which are prone to random failures and repairs. The system operates manufacturing and remanufacturing machines according to each proposed control policy indicated in Block 4 to satisfy the customer demand which is displayed in Block 5. As shown in Block 6, the model updates the surplus inventory level, $x_{FP}(t)$ and the emissions level, $E(t)$ based on Equations (4.2) and (4.3). Finally, the production, emissions, and inventory, backlog as well as total costs are calculated as can be seen in Block 7.

To validate our simulation model, the dynamic behavior of the considered manufacturing/remanufacturing system is tested under the proposed policy 2 (Equations (4.15) to (4.17)). As displayed in Figure 4.4, the simulation model accurately reproduces the behavior of the system when it is operating under proposed policy 2. To make it more reader-friendly, the symbol of "Y.©" is defined to show the phenomenon displayed in part © of Sub-Figure 4.4.Y. For example, a. ① in Figure 4.4 represents the phenomenon shown by part ① of Sub-Figure 4.4.a.

According to a.①, As the inventory level is less than threshold level of Z_1, the system operates both manufacturing machine and remanufacturing using high-quality returns at their maximum rate to build the inventory till Z_1. The inventory level rises at the rate of $U_1^{max} + U_2^{max} - d$, and the emissions level rises at the rate of $U_1^{max} \times \theta_1 + U_2^{max} \times \theta_2$. As can be seen in c.②, there is a failure in the remanufacturing machine and the system continues to produce with the manufacturing machine (a.③). Then, based on d.④, the manufacturing machine is also failed and there is a reduction in inventory level at the rate of -d as shown in a.⑤. Then after repairing, both machines are up and produce at their maximum rate. Once the inventory threshold of Z_1 is built (a.⑥), and the system is confident about the level of inventory to face future shortage, it stops the manufacturing machine (d.⑦) and operates with the least expensive mode which is remanufacturing using low-quality returns (*j* = 3).

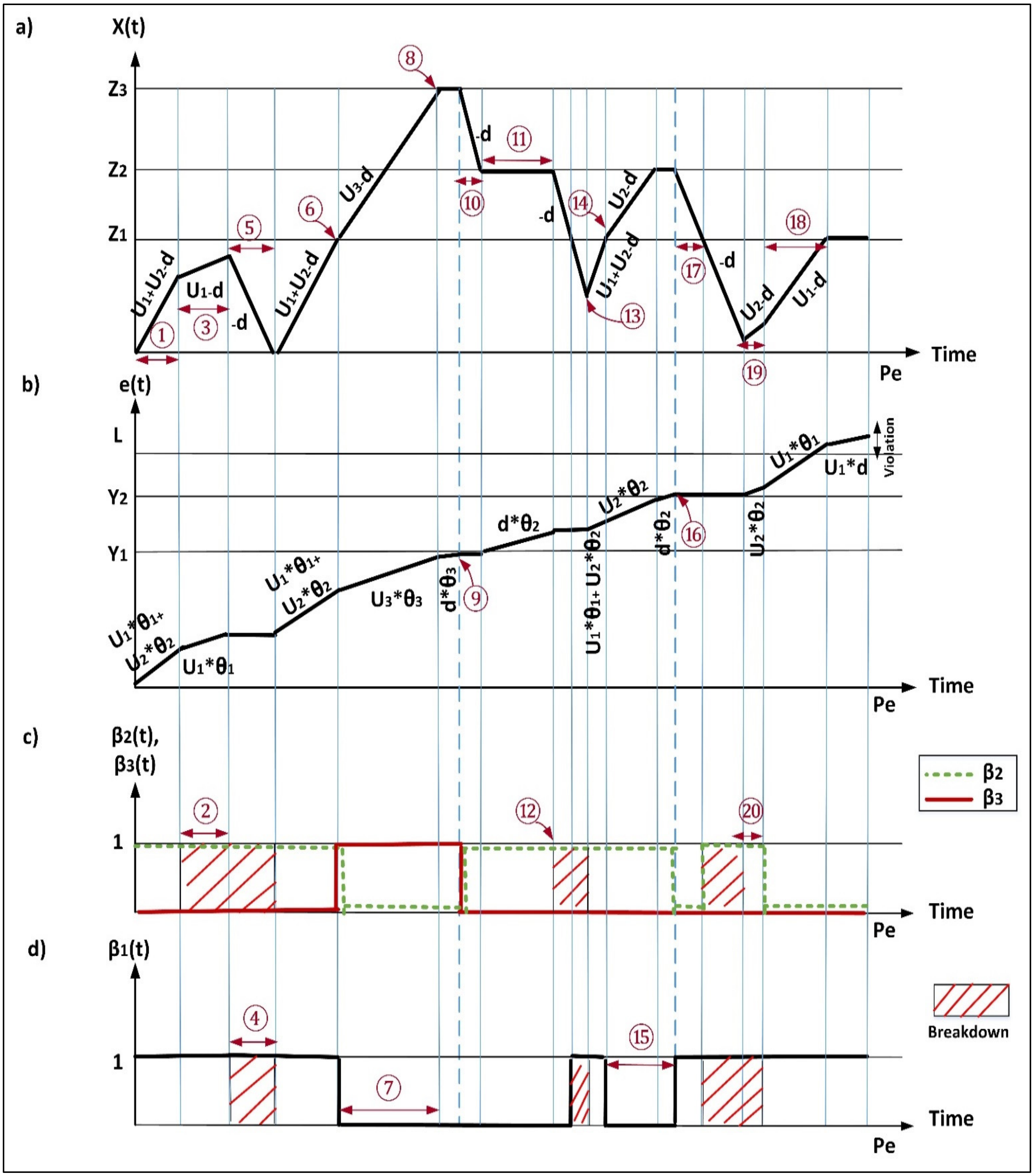

Figure 4.4 The system dynamic behavior by simulation run under proposed policy 2

When the inventory level reaches the threshold level of Z_3 (a.⑧), remanufacturing produces at the rate of demand. The emission increases with the rate of $d \times \theta_3$. When emissions go above the voluntary emission limit of Y_1(b.⑨), the system stops remanufacturing till reaching the inventory threshold of Z_2 (a.⑩), then remanufactures with high-quality returns (*j* = 2) at the demand rate (a.⑪) to control the emissions. Then, according to c.⑫, there is a failure in remanufacturing machine. There is a reduction in inventory level with the rate of -*d*. In a.⑬, when both machines are repaired, the manufacturing and remanufacturing using high-quality returns simultaneously produce to reach the inventory threshold of Z_1(a.⑭). When this inventory is reached the system stops the manufacturing (d.⑮) and operates only with remanufacturing till reaching the inventory level of Z_2 Once the emissions level is considerably high that reaches the voluntary emission limit of Y_2 (b.⑯), the system stops the production till reaching the inventory level of Z_1 (a.⑰). Then system produces only with the least-emitting production mode, which is manufacturing using raw material (*j* = 1) if it is up (a.⑱). Only if the manufacturing machine is down, remanufacturing using high-quality operates to help the system to face shortage (a.⑲ and c.⑳). The emissions are reset to zero, at the end of the emission control period (P_e).

4.7 The numerical example

In this section, using the design of experiment approach and response surface methodology, the optimization model is built to find the optimal value of control parameters as well as optimal total costs for our proposed production control policy 2. The values of cost and system parameters applied are summarized in Table 4.2.

Table 4.2 The cost and system parameters

Parameter	d	U_1^{max}	U_2^{max}	U_3^{max}	$TTF_1 = TTF_2$	$TTR_1 = TTR_2$	θ_1	θ_2	θ_3
Value	100	130	125	115	Exp (5)	Exp (0.4)	U [1,1.5]	U [4,4.5]	U [6,6.5]
Parameter	c^+	c^-	c_{P_1}	c_{P_2}	c_{P_2}	c^e	P_e	L	
Value	0.5	20	20	15	5	50	5,760	650,000	

4.7.1 Design of experiment (DOE), RSM model and optimization

For validation purpose and as a remarkable example, we applied a Box-Behnken design for our proposed production control policy 2 with control parameters of Z_1, Z_2, Z_3, Y_1 and Y_2 at three levels. By using five replications of combinations of control factors, for each design, 320 simulation runs are conducted. To ensure reaching the steady-state of the system, we run the simulation model for 500,000 time units (TU). Analysis of variance statistical processing of the data is provided by using “STATGRAPHICS” software. According to the ANOVA provided in Table 4.3, we obtained the effects of the considered control parameters (Z_1, Z_2, Z_3, Y_1 and Y_2), the interactions of parameters and their quadratic effects on the incurred total cost. The obtained adjusted R-square of 99.47% can sufficiently judge the quality of RSM model. Moreover, we conducted the residual normality analysis as well as the homogeneity of variance to examine the conformity of the model. To crosscheck the validity of the RSM model, we verified that the optimal total incurred cost, at a 95% level of confidence, falls within the confidence interval obtained from n= 40 extra replications of the simulation model.

Table 4.3 ANOVA for total costs

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
A:Z1	2.00139E6	1	2.00139E6	145.21	0.0005
B:Z2	2.61755E6	1	2.61755E6	155.36	0.0002
C:Z3	8.56776E6	1	8.56776E6	413.14	0.0000
D:Y1	9.01297E9	1	9.01297E9	8914.42	0.0000
E:Y2	2.56356E10	1	2.56356E10	15380.28	0.0000
AA	255762.	1	255762.	18.25	0.0015
AB	4545.92	1	4545.92	0.15	0.6815
AC	1.82545E6	1	1.82545E6	131.70	0.0009
AD	4876.72	1	4876.72	0.18	0.6465
AE	139674.0	1	139674.0	14.32	0.0026
BB	128255.0	1	128255.0	12.65	0.0029
BC	54546.1	1	54546.1	5.28	0.0087

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
BD	145452.6	1	145452.6	16.18	0.0024
BE	13588.	1	13588.	0.78	0.4920
CC	255234.	1	255234.	18.10	0.0015
CD	5.11025E6	1	5.11025E6	320.55	0.0001
CE	4940.25	1	4940.25	0.19	0.6425
DD	101559.0	1	101559.0	13.68	0.0035
DE	2.1621E9	1	2.1621E9	4551.87	0.0000
EE	5.4128E9	1	5.4128E9	6562.68	0.0000
blocks	195592.	4	26335.1	3.56	0.9699
Total error	6.91511E7	205	54684.2		
Total (corr.)	3.76552E10	229			

R-squared = 99.5034 percent
R-squared (adjusted for d.f.) = 99.47494 percent

The RSM model for our proposed production control policy 2, is determined as follows:

$$
\begin{aligned}
TC = {} & -6268.73 + 35.2923 \times Z_1 + 0.000426878 \times Z_2 - 0.0514795 \times Z_3 \\
& + 5.15796 \times Y_1 - 67.1258478 \times Y_2 + 19.46553 \times Z_1^2 \\
& + 6.85 \times 10^{-7} \times Z_1 \times Z_2 + 0.03498755 \times Z_1 \times Z_3 \\
& + 15.89566 \times Z_1 \times Y_1 - 1.48 \times 10^{-5} \times Z_1 \times Y_2 + 0.000375 \times Z_2^2 \\
& + 0.05228 \times Z_2 \times Z_3 - 9.5100867 \times Z_2 \times Y_1 + 0.0980012 \times Z_2 \times Y_2 \\
& - 76.159759 \times Z_3^2 + 2.097665 \times Z_3 \times Y_1 - 0.000647896 \times Z_3 \times Y_2 \\
& - 0.0050922 \times Y_1^2 + 2.1569884E8 \times Y_1 \times Y_2 + 6.794 \times 10^{-5} \times Y_2^2
\end{aligned}
\qquad (4.18)
$$

Then, the results of optimization consisting of optimal control parameters, Z_1^*= 231.45, Z_2^*= 305.71, Z_3^*= 418.78, Y_1^*= 316,452, Y_2^*= 504,769, as well as minimum total costs, TC^*= 6,453.54 are obtained. The optimal total incurred costs fall within the 95% confidence interval of [6,445.86, 6,461.25]. Figure 4.5 shows the contours of estimated total cots response surface as follows:

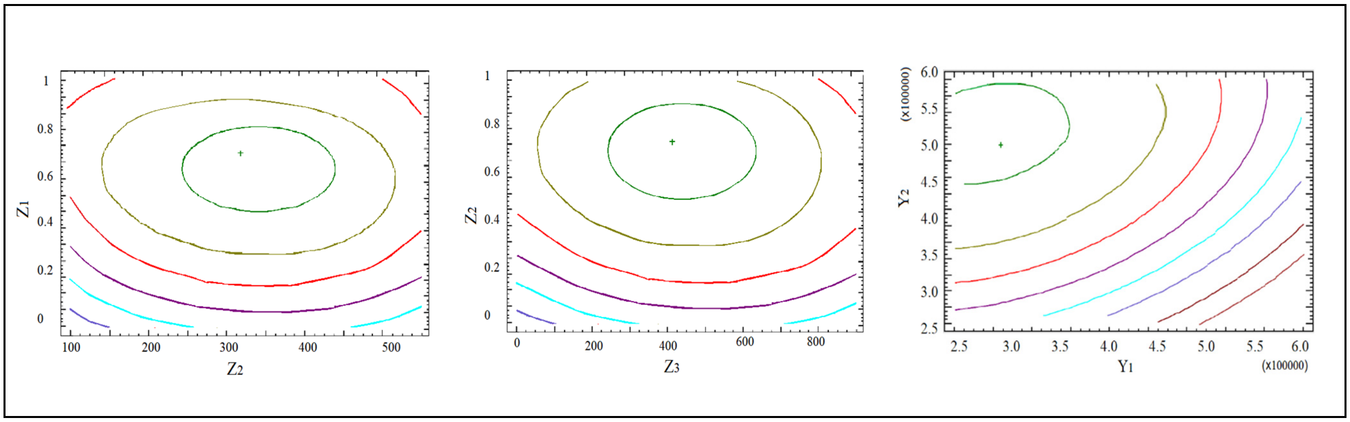

Figure 4.5 The contours of estimated cost response surface

4.7.2 Sensitivity analysis

In this section, a sensitivity analysis is conducted to confirm the robustness of our resolution approach and proposed policy 2. In the following subsections, the impact of cost and system parameters (c^+, c^-, c^e, c_{P_1}, c_{P_2} , c_{P_3}, $MTTR_1$, $MTTR_2$, θ_1, θ_2, θ_3) on the control parameters (Z_1^*, Z_2^*, Z_3^*, Y_1^*, and Y_2^*) of proposed policy 2, are examined.

4.7.2.1 Effect of varying cost parameters

According to Figure 4.6 (a), when there is an increase in the inventory cost (c^+), the system reduces the optimal inventory threshold levels to keep less inventory, so as can be seen there is a reduction in Z_1^*, Z_2^*, and Z_3^*. By reducing the inventory threshold levels, the system produces less at the maximum rate, so generates less emissions. In this way, the system works with the least costly production mode (higher emitting) for a longer time by increasing voluntary emission limits of Y_1^* and Y_2^*.

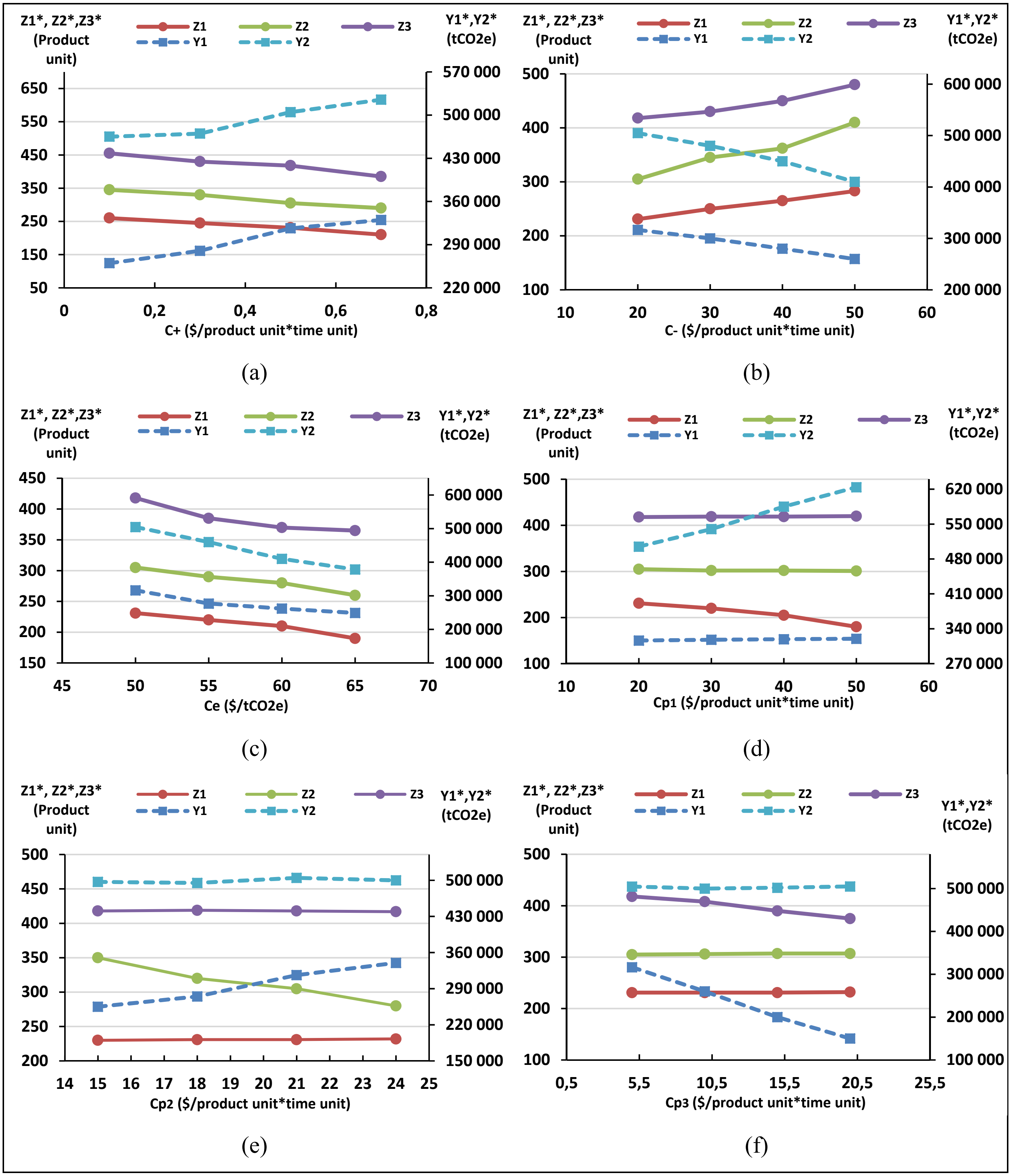

Figure 4.6 Variation of Z_1^*, Z_2^*, Z_3^*, Y_1^*, and Y_2^* when varying c^+, c^-, c^e, c_{P_1}, c_{P_2}, and c_{P_3}

As can be seen in Figure 4.6 (b), when the backlog cost (c^-) increases, the system reacts by rising the optimal inventory threshold levels of Z_1^*, Z_2^*, and Z_3^* to reduce the risk of shortage. Increasing the optimal threshold levels results in producing more at the maximum production rate and generating more GHG emissions. So, the system reacts by faster switching to low-emitting production modes by reducing voluntary emission limits of Y_1^* and Y_2^*.

Figure 4.6 (c) shows the impact of emission unit cost (c^e) on the control parameters. Accordingly, when there is a rise in the emissions cost, the system reacts by reducing inventory threshold levels to generate less emissions. Also, there is a decrease in the voluntary emission limits, Y_1^* and Y_2^*, to reduce the generated emissions by faster switching from high-emitting production modes to low-emitting ones.

As shown in Figure 4.6 (d), by increasing the production cost of manufacturing (c_{P_1}), there is a reduction in the inventory threshold level of manufacturing, Z_1^*. There is no change in the inventory threshold level of remanufacturing using high-quality and low-quality returns (respectively Z_2^* and Z_3^*). To reduce the usage of manufacturing, there is also an increase in Y_2^* where the system should switch from remanufacturing to manufacturing machine.

In Figure 4.6 (e), it is shown that increasing the production cost of remanufacturing using high-quality returns (c_{P_2}) leads to reduction in inventory threshold level of this production mode, Z_2^*. Moreover, the system has tendency to increase the voluntary emission limit of Y_1^*, to reduce the usage of remanufacturing using high-quality returns.

According to Figure 4.6 (f), when there is an increase in the production cost of remanufacturing using low-quality returns (c_{P_3}), the system has tendency to reduce the inventory threshold level of this production mode, Z_3^*. To reduce the usage of remanufacturing using low-quality returns, there is also a reduction in the voluntary emission limit of Y_1^* leading to faster switching from remanufacturing using low-quality returns to remanufacturing using high-quality returns.

4.7.2.2 Effect of varying system parameters

As can be seen in Figure 4.7 (a), when there is a reduction in $MTTR_1$, availability of manufacturing machine (Ava_1) increases. Therefore, the system can satisfy the customer demand with a lower inventory threshold level resulting in reduction in Z_1^*. By decreasing the threshold levels, the system produces less at maximum rate and generates less GHG emissions. Hence, the system can produce more with high-emitting production modes of remanufacturing using low- and high-quality returns by rising Y_1^* and Y_2^*.

According to Figure 4.7 (b), when there is a reduction $MTTR_2$, the availability of remanufacturing machine (Ava_2) rises and less inventory is needed to meet the demand. So, the system tends to reduce inventory levels of production modes 2 and 3, Z_2^* and Z_3^*. Reducing the emissions generated by the system leads to more usage of less expensive production modes and increase in Y_1^* and Y_2^*.

Figure 4.7 (c) shows the variation of control parameters when varying the emission index of manufacturing (θ_1) which defines the emissions generated by manufacturing each product using raw material. By increasing θ_1, there is a reduction in Z_1^* to reduce the emissions generated from manufacturing. The system also reacts by increasing Y_2^*, to delay switching to manufacturing.

As shown in Figure 4.7 (d), the emission index of remanufacturing using high-quality returns, θ_2 rises, the system tends to reduce the generated emissions by reducing its inventory threshold level, Z_2^*. Moreover, the system reacts by rising Y_1^*, to switch faster to less-emitting production modes. In Figure 4.7 (e), there is an increase in the emission index of remanufacturing using low-quality returns. when θ_3 rises, the system reacts by reducing its inventory threshold, Z_3^* to reduce emissions in this mode. Moreover, the system tends to switch faster to less-emitting production modes by reducing Y_1^*.

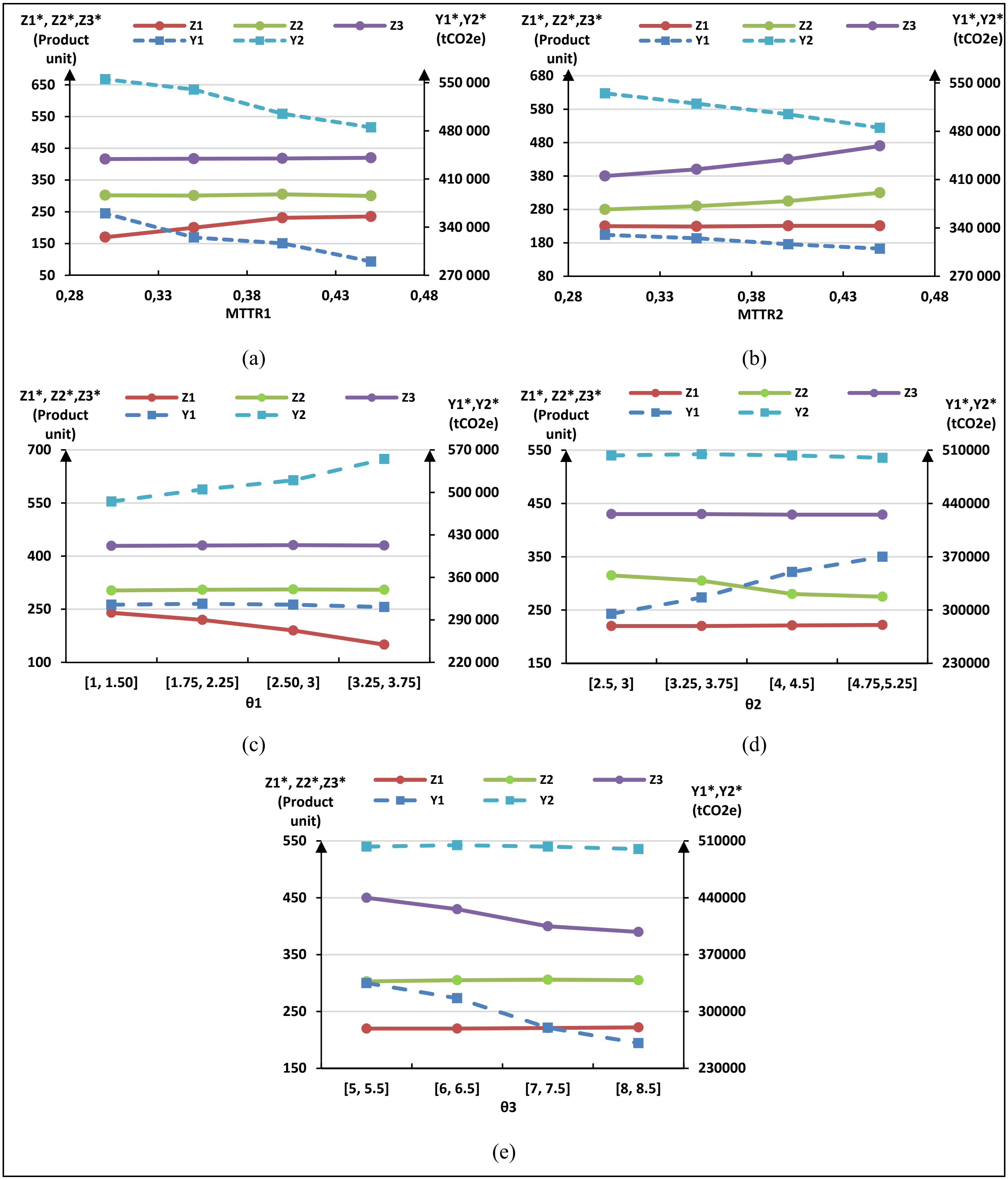

Figure 4.7 Variation of Z_1^*, Z_2^*, Z_3^*, Y_1^*, and Y_2^* when varying, $MTTR_1$, $MTTR_2$, θ_1, θ_2, and θ_3

4.8 Comparison between proposed and existing policies

In this section, we make a comparison between our proposed policies described in Section 4.5 and the most relevant production policies adapted from the literature. Considering different emission rates for manufacturing and remanufacturing using high- and low-quality returns, we also studied the policies developed for failure-prone manufacturing systems with variate emitting machines. In this regards, Afshar-Bakeshloo et al., (2018) proposed an EHPP under which high-emitting machine (HEM) and low-emitting machine (LEM) are not operating simultaneously. Accordingly, when total emissions exceed the voluntary limit, the production system stops HEM and continues to produce with LEM in order to control the generated emissions. Under the environmental hedging point policy developed by Entezaminia et al., (2020) which outperforms the previous policy, low-emitting machine (LEM) and high-emitting machine (HEM) are allowed to operate simultaneously. Accordingly, when the inventory level is less than a specific threshold level Z_1, the system simultaneously operates with both HEM and LEM to provide more production capacity. After reaching this inventory, the system decides whether to use LEM or HEM based on the emissions level. If the generated emissions are higher than a voluntary limit Y_1, the system operates with LEM, otherwise it produces with HEM. The threshold level of Z_2 is considered for both HEM and LEM to determine their production rates. To adapt the EHPP developed by Entezaminia et al., (2020) to our study, considering the manufacturing machine as LEM, the remanufacturing using high-quality returns is supposed to be HEM under EHPP1 and the remanufacturing using low-quality returns is HEM under EHPP2.

4.8.1 Comparison of policies for the base case

To make a comparison between our proposed production control policies (proposed policy 1 and 2) and policies adapted from the literature (EHPP1 and EHPP2), the optimal values of control parameters and total costs for each policy are obtained using Steps 2 to 5 of our resolution approach. The base case data provided in Table 4.2 is used to obtain the optimization results given in Tables 4.4 and 4.5.

Table 4.4 Optimal costs and machine usage under considered policies

Policy	Man usage %	Rem-HQ usage %	Rem-LQ usage%	Inventory Cost* ($/Time Unit)	Backlog Cost* ($/Time Unit)	Production Cost* ($/Time Unit)	Emission Cost* ($/Time Unit)	Optimal Total Cost* ($/Time Unit)	Confidence Interval ($/Time Unit)
EHPP1	33	67	-	525.6	463.6	5,352.12	2,464.84	8,806.19	[8,801.72; 8,814.72]
EHPP2	36	-	64	706.7	718.5	3,414.78	4,232.09	9,072.07	[9,064.07; 9,079.07]
Proposed policy 1	52	31	17	501.7	435.9	4,054.32	2,135.02	7,126.94	[7,121.09; 7,132.56]
Proposed policy 2	51	38	11	443.3	381.8	4,226.85	1,401.59	6,453.54	[6,445.86; 6,461.25]

Table 4.5 Optimal values of control factors under considered policies

Factor / Policy	Z^*_1 (Product Unit)	Z^*_2 (Product Unit)	Z^*_3 (Product Unit)	Y^*_1 (tCO2e)	Y^*_2 (tCO2e)	Weighted maximum production rate (product/time unit) $\sum_j(\%\, usage_j * U_j^{max})$	Emissions (tCO2e/ Time Unit)
EHPP1	152.86	289.40	-	517,219	-	126.65	335.28
EHPP2	284.59	342.5	-	486,725	-	120.40	445.32
Proposed policy 1	247.80	321.82	423.45	342,538	546,982	125.90	293.86
Proposed policy 2	231.45	305.71	418.78	316,452	504,769	126.45	281.65

Based on the results shown in Table 4.4 and 4.5, proposed policies outperform EHPP1 and EHPP2 in terms of cost and emissions reduction. Since remanufacturing using low-quality returns is the most emitting production mode in our system, the results indicate that EHPP2 results in larger amount of GHG emissions, so more emission cost compared with proposed policies 1 and 2. Also, the system under EHPP2 leads to less production cost. However, less available production capacity under EHPP2 is the reason for keeping more inventory (higher threshold levels Z_1 and Z_2 as shown in Table 4.5), consequently causing more inventory and backlog cost compared to proposed policy 1 and 2. EHPP1 which operates with more expensive production modes including manufacturing and remanufacturing using high-quality returns results in greater production cost compared with proposed policy 1 and 2. Under proposed policy 1 and 2, more usage of manufacturing leads to more available production capacity for the system, consequently less inventory and backlog cost as well as less emissions. To reach a minimum inventory threshold level of Z_1 under proposed policy 1, the manufacturing machine supports the remanufacturing machine by producing at its maximum rate. However, under proposed policy 2, the fastest production modes including manufacturing and remanufacturing using high-quality returns are used to reach threshold level of Z_1. Therefore, providing more available production capacity under proposed policy 2 results in less inventory and backlog costs. Indeed, under proposed policy 1, when there is a failure in manufacturing (if $E(t) \geq Y_2$) the system stops the production. However, under our proposed policy 2, in case of failure of manufacturing machine (if $E(t) \geq Y_2$), the system operates remanufacturing using high-quality returns. So, taking advantage of a higher available production capacity under proposed policy 2, the system can reduce inventory threshold level while reducing backlog cost. In Table 4.5, weighted maximum production rate ($\sum_j(\%\ usage_j * U_j^{max})$), stands for the available production capacity of the system under each policy considering the percentage of time that each production mode is used during the whole simulation time ($\%\ usage_j$). Furthermore, there is an increase in the percentage of operating remanufacturing using high-quality returns and reduction in remanufacturing using low-quality returns, which results in a reduction in generated emissions under proposed policy 2 compared with proposed policy 1. Moreover, less emission, inventory and backlog cost provide more advantageous for the system under proposed policy 2 compared to proposed policy 1.

As can be seen in Table 4.4, both proposed policies result in significant cost saving and reduce generated emissions as compared to EHPP1 and EHPP2. However, proposed policy 2 outperforms proposed policy 1 and the existing policies adapted from the literature in terms of cost and emissions reduction. To conclude our proposed policy 2 is the most cost effective and environmentally friendly policy for the system under study. We should confirm it through comparisons for a wide range of cost and system parameters as provided in the following subsection.

4.8.2 Comparison of policies for a wide range of cost and system parameters

To confirm that our proposed policy 2 outperforms proposed policy 1 and other existing control policies adapted from the literature, in terms of total costs and emissions reduction, a comparative study is performed as shown in Figures 4.8 and 4.9 for a wide range of cost and system parameters. In this regard, the impact of cost parameters (production, emission, inventory, and backlog cost) and system parameters (MTTR of manufacturing machine, MTTR of remanufacturing machine and emission rate of manufacturing) on total costs and GHG emissions is determined under considered policies. In Figures 4.8 and 4.9, solid line is used to show the optimal total costs and dash line is used to represent emissions for each policy.

As can be seen from Figures 4.8 (a) and (b), when C^+ or C^- rises, there is an increasing difference between the optimal total cost and generated emissions under proposed and existing policies. This is because under our proposed policies, an effective synchronization of manufacturing and remanufacturing could decrease the inventory and backlog cost. By increasing the usage percentage of remanufacturing using high-quality returns and providing more available production capacity under proposed policy 2, when inventory cost (C^+) or backlog cost (C^-) rises, the difference between proposed policy 1 and 2 increases in terms of optimal total costs as well as emissions.

As the system under our proposed policies results in a significant emissions reduction, when there is an increase in emissions unit cost (C^e), the difference between the proposed and existing policies increases regarding optimal total costs and GHG emissions as shown in Figure 4.8 (c). based on the results, for a low emission unit cost, the system under EHPP2 becomes more advantageous than EHPP1 by considerably decreasing the emission cost. Because for a low value of C^e, the system is not penalized too much, and it costs less to produce with manufacturing and remanufacturing using low-quality returns under EHPP2.

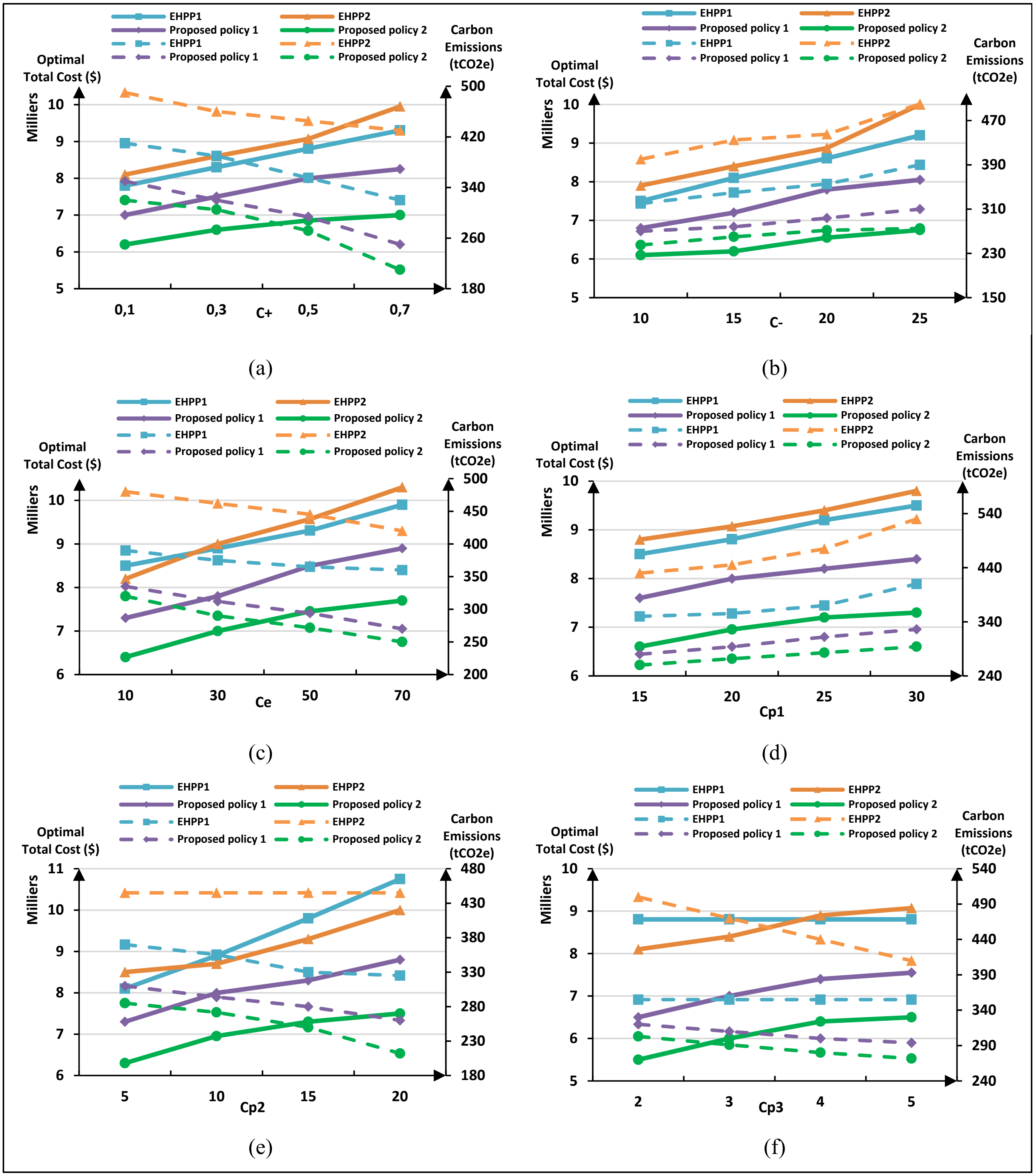

Figure 4.8 The impact of cost parameters on optimal total costs and emissions of considered policies

As can be seen in Figure 4.8 (d), when there is an increase in production cost of manufacturing (c_{P_1}), there is an increase in optimal total costs as well as emissions for each considered policy. By providing a more cost-effective and environmentally friendly synchronization of manufacturing and remanufacturing under our proposed policies, when c_{P_1} rises, there is an increasing difference between the proposed and existing polices in terms of optimal total costs and GHG emissions.

Remanufacturing using high-quality returns generates less emissions however, it costs more compared with remanufacturing using low-quality returns. Therefore, for a low value of the production cost of remanufacturing using high-quality returns (c_{P_2}), the system under EHPP1 brings great benefits regarding optimal total costs and emissions reduction compared to the system under EHPP2, as shown in Figure 4.8 (e).

In Figure 4.8 (f), our proposed policies result in a high cost saving and emissions reduction compared with EHPP1 and EHPP2 for a wide range of production cost of remanufacturing using low-quality returns (c_{P_3}). Indeed, the principal advantage of remanufacturing using low-quality returns is its lowest production cost among the production modes. So, after a high value of c_{P_3}, using low-quality returns is disadvantageous compared to high-quality ones. Consequently, the system under EHPP1 brings more advantage than EHPP2.

As depicted in Figure 4.9 (a), by increasing $MTTR_1$ (decreasing the availability of manufacturing machine (Ava_1)), there is a bigger difference between the proposed policies and existing policies regarding the optimal total costs and emissions. The proposed policy 2 provides more available production capacity by operating remanufacturing using high-quality returns when the manufacturing machine is down. Hence, as shown in the figure, when the availability of manufacturing machine decreases, the difference between total costs of proposed policy 1 and 2 increases. Moreover, Figure 4.9 (b) shows that reducing $MTTR_2$ provides more available production capacity. This leads to an increasing difference between the proposed policy 1 and 2 compared to the existing policies in terms of optimal costs and emissions, when Ava_2 increases.

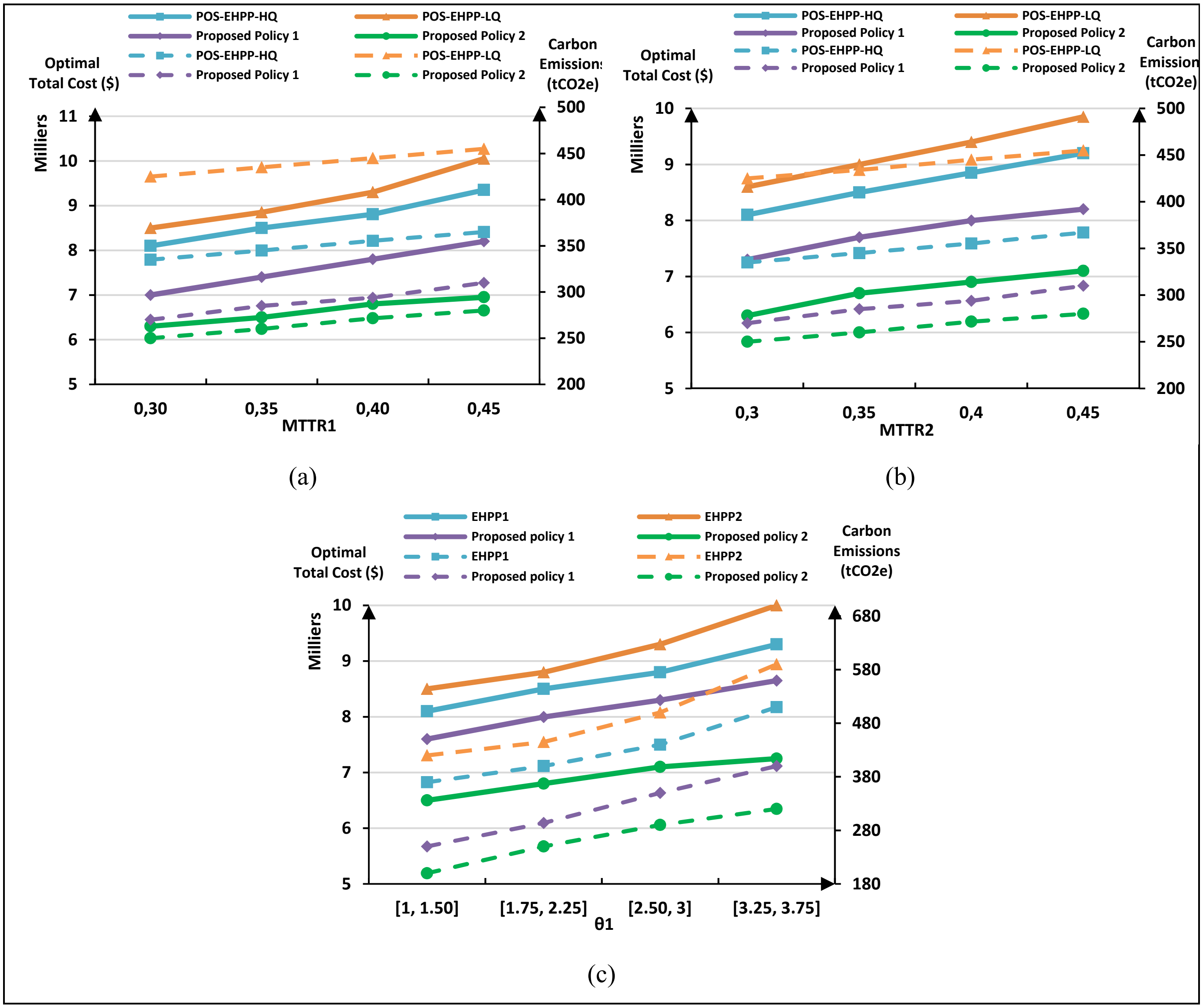

Figure 4.9 The impact of system parameters on optimal total costs and emissions of considered policies

As can be seen from Figure 4.9 (c), by increasing the emission rate of manufacturing machine (θ_1), there is a great difference between the proposed policies and EHPP1 and EHPP2 regarding the optimal total costs and emissions. Because the best synchronization of manufacturing and remanufacturing is provided under our proposed policies. By rising θ_1, higher utilization of manufacturing machine is disadvantageous. Therefore, proposed policy 2 by less utilization of manufacturing brings more advantage than proposed policy 1. Comparison between policies for θ_2 and θ_3 can be explained in the same way.

Figures 4.8 and 4.9 indicate that our proposed policy 2 outperforms the proposed policy 1 and the existing ones adapted from the literature regarding optimal total cost and carbon emission reduction for a wide range of system and cost parameters. This confirms that our proposed production control policy 2 is the best policy for the considered unreliable manufacturing/remanufacturing system under carbon tax regulation, in terms of reducing both optimal total cost and carbon emissions.

4.9 Managerial insights and practical implementation

The major challenge for manufacturing/remanufacturing systems with high variation of returns' quality is to find the best production policy to synchronize manufacturing and remanufacturing to reduce both total costs and emissions. Under our proposed policy 2 which is the most cost-effective and environmentally friendly policy for such systems, the manager can determine when and at which rate should produce with the manufacturing or remanufacturing (using high- or low- quality returns). To decide on the production plan, the manager should monitor the inventory level as well as emissions level. The best synchronization provided under our proposed policy 2 could reduce costs and emissions by starting to operate the production mode with lower cost and gradually switch to the lower emitting production mode when the emissions level exceeds its voluntary limits. Using the fastest production modes to build the minimum safety stock leaded to more available production capacity and reduced the inventory and backlog costs. The implementation chart of our proposed policy 2 for the base case data in Table 4.2 is represented in Figure 4.10.

Accordingly, first, the level of emissions and inventory should be monitored by the manager. If the emissions are less than the voluntary limit of 316,452 tCO2e and the inventory level is less than 231 units, the system should produce by the manufacturing and remanufacturing using high-quality returns at their maximum rates (respectively 130 and 125). After reaching this threshold, the system produces with the rate of demand (100). If the inventory exceeds the threshold, the manager should stop producing. After building this inventory, the system produces with the cheapest production mode that is remanufacturing using low-quality returns.

If the inventory is less than the threshold level of 418 units, the remanufacturing machine should produce at its maximum rate (115).

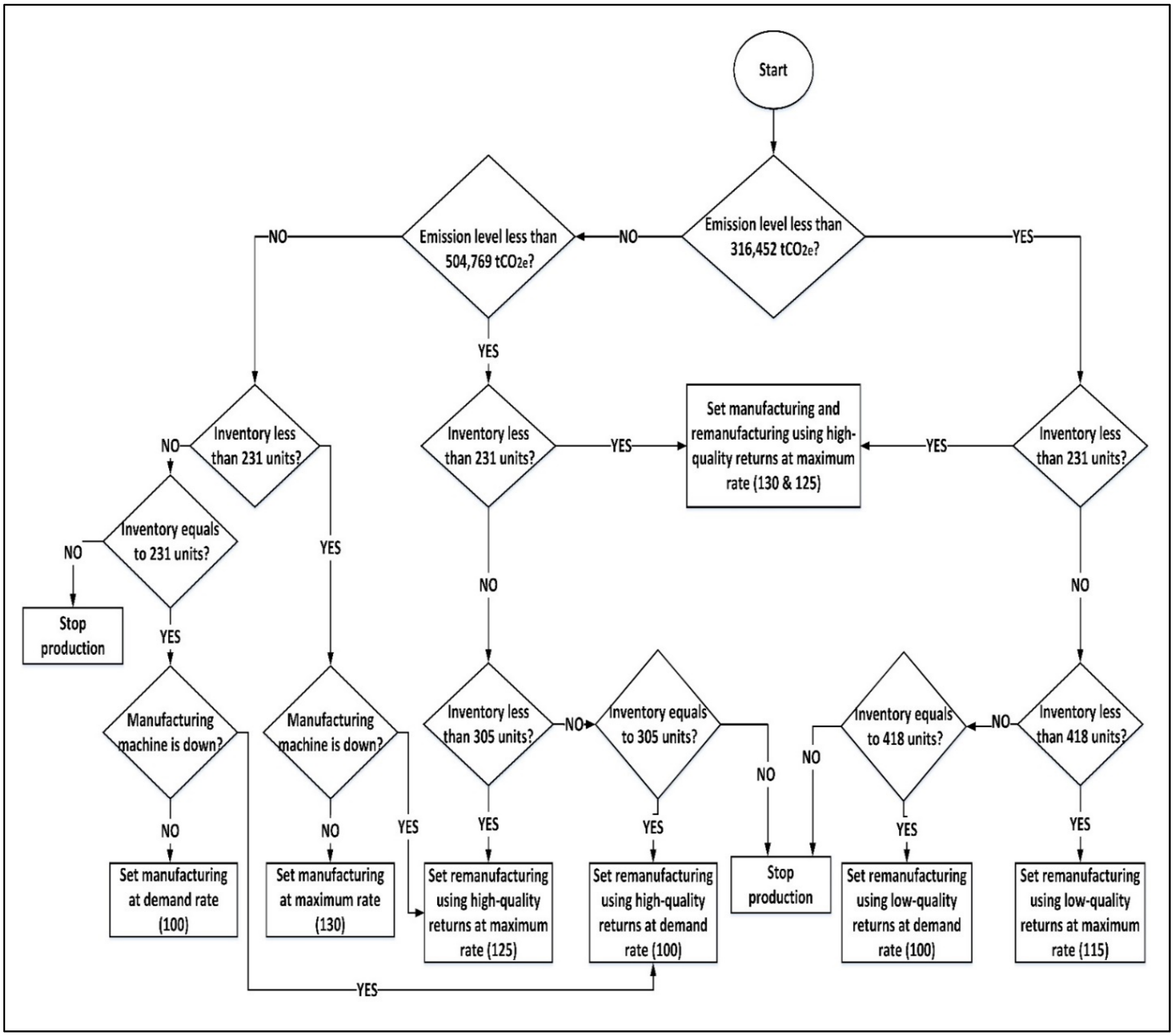

Figure 4.10 Implementation logic chart of proposed policy 2

If the emissions level is more than the voluntary limit of 316,452 tCO2e but less than 504,769 tCO2e, the level of inventory should be monitored. If the inventory level is less than 231 units, the system produces by the manufacturing and remanufacturing using high-quality returns at their maximum rates (respectively 130 and 125). After building this inventory, the system produces with remanufacturing using high-quality returns at maximum rate (125) if the inventory is less than its threshold level, 305 units. After reaching this threshold level, it produces at demand rate (100). When the inventory reaches the hedging level, the production needs to be stopped.

If the emissions level is more than 504,769 tCO2e, the emissions level is considerably high, and the system should stop the remanufacturing and produce only with manufacturing based on threshold level of 231 units. To avoid future backlog, only if the manufacturing machine is down, remanufacturing using high-quality can operate to provide more availability for the system.

4.10 Conclusion

For many industries, high variation of returns' quality is one of the challenges which makes production planning of remanufacturing activities complicated. In this paper, we deal with the production planning problem of failure-prone manufacturing/ remanufacturing systems using high- and low-quality returns under carbon tax regulation. The impact of returns quality on the GHG emissions generated by the manufacturing/remanufacturing systems is also taken into account. From an environmental point of view, our focus is on production planning for industries in which operating remanufacturing machine generates more GHG emissions compared with manufacturing machine. One of the biggest challenges for such systems is to decide on the condition and percentage of time the system should produce with manufacturing or remanufacturing to meet the customer demand. In this study, two new production control policies are developed to help the manager in synchronizing manufacturing using raw material and remanufacturing using high- and low-quality returns together to achieve both environmental and economic goals.

Under the proposed policy 1, the system starts by operating the least expensive production mode (remanufacturing using low-quality returns) and gradually switches to the less emitting production modes if the GHG emissions exceed its voluntary limits. To reach a minimum inventory threshold level, the manufacturing machine should support the remanufacturing to reduce the risk of backlog. To provide more environmentally responsible policy, proposed policy 2 has been developed under which the fastest production modes, manufacturing using raw material and remanufacturing using high-quality returns are used to reach the minimum inventory threshold level. In this way, less GHG emissions are generated, and more available production capacity is provided. To face future backlog, for a high level of GHG emissions, the remanufacturing using high-quality returns can operate if the manufacturing is down.

We obtained the optimal value of the costs and control parameters for the considered policies using an experimental resolution approach as well as response surface methodology. A comparison is made between our proposed policies and the existing production policies developed for the failure-prone manufacturing systems with variant emitting levels, for a wide range of cost and system parameters. Based on the results, proposed policy 2 brings high advantage of optimal costs and GHG emissions reduction as compared with proposed policy 1 and existing polices in the literature. In conclusion, our proposed policy 2 is the most cost effective and environmentally friendly policy that can help the managers to synchronize manufacturing and remanufacturing together and attain both economic and environmental goals.

In this paper two categorization of returns are assumed to be always available; however, in the future studies, the rate of return can be defined as a random variable since returned products in the market are not always available. Probability of returns remanufacturability and disposal options could be also taken into account in the future studies. The customer preference for manufacturing and remanufacturing products can be also considered in the future works. Moreover, further research may concentrate on the degradation phenomena and a non-linear emission rate as increasing the machine age results in decreasing the machine availability and increasing the emissions rate, not necessarily linearly. It would be interesting to prevent failure and maintain machines in service by preventive maintenance activities along with corrective maintenance. Future research will be required to find an optimal plan for preventive maintenance to minimize optimal total costs as well as generated GHG emissions.

4.11 Acknowledgements

This research has been supported by Natural Sciences and Engineering Research Council of Canada (NSERC) under grant number: RGPIN-2015-06026.

CHAPTER 5

PRODUCTION PLANNING OF FAILURE-PRONE MANUFACTURING SYSTEMS IN THE CONTEXT OF EMISSIONS REDUCTION BY FUEL SWITCHING

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Paper submitted in *The International Journal of Production Economics*, September 2022

Abstract

In this study, we focus on unreliable manufacturing systems under carbon tax regulation that committed themselves to reduce greenhouse gas (GHG) emissions. This targeted emissions reduction could occur with switching from high-emitting fuels (e.g., coal) to cleaner fuels (e.g., natural gas (NG)). However, production with a cleaner source of energy reduces carbon emissions but results in higher fuel cost. Our aim is to develop an environmental production control policy for failure-prone manufacturing systems with the possibility of fuel switching to minimize total costs while reducing GHG emissions. In this regard, we developed two production control policies to achieve both economic and environmental goals. According to our proposed policies, decisions on fuel switching depends on the market state including the random fluctuation of NG price, as well as the key elements of the system including its state, inventory, and emissions level. Our proposed policy 1 could reduce emissions while minimizing total cost of the system including inventory, backlog, fuel, and emission costs. Proposed policy 2 is also an extension of policy 1 under which a lower inventory threshold level is considered for production using coal when emissions level is high. Optimal value of control factors is determined using simulation, design of experiment, and response surface methodology. Our proposed control policy 2 surpasses the policies derived from the literature in terms of optimal total costs as well as emissions reduction.

Keywords: Unreliable manufacturing systems, fuel switching, greenhouse gas emissions, carbon tax, simulation optimization.

5.1 Introduction

Due to environmental regulations like carbon tax enacted by authorities, various industries are under pressure to reduce their harmful GHG emissions. The development of energy-efficient technologies to deal with environmental issues is a long-term vision for companies requiring major investment (Rustico and Dimitrov 2022). In turn, there is a growing preference towards switching to fossil fuel alternatives that generate less GHG emissions. For instance, switching from liquid and solid fuels to natural gas (NG) contributed to emission reductions, particularly in industries such as power plants as well as chemical process plants (Waltho et al., 2019).

Moreover, when it comes to energy intensive industries fuel switching is one of the most common strategies for decarbonization by reducing combustion emissions from energy sources. In cement industry, fuel switching from coal to natural gas can help reducing the carbon emissions and improving the environmental performance (Busch et al., 2022). The pulp and paper industry has responded to the need for energy transition by switching to bio-based fuels (Obrist et al., 2022). Replacing fossil fuels with hydrogen gaseous fuel and biofuels is a promising option to reduce GHG emissions from production process in global iron and steel industry (Fan and Friedmann 2021).

In industry, choice of fuel depends on some factors like economic assessment, availability, and legislative restrictions. Considering only fuel costs, it would be cheaper for companies to burn solid fuels instead of natural gas. However, considering carbon emissions penalty, using natural gas could be more preferred (Kermes et al., 2008). Therefore, to decide on consumption of multiple fuels in industry, there should be a trade-off between economic performance and reducing GHG emissions. Furthermore, varying fuel prices have put pressure on the total cost of manufacturing systems and emerged as one of the top challenges in industries. So, the impact of changes in fuel prices on production decisions can no longer be ignored in different industries like iron, glass, and chemical plants. In China, for example, chemical industry sector is strongly influenced by fluctuation of natural gas price (Wakiyama and Zusman 2016).

In this paper, we address the production planning of companies aiming to reduce GHG emissions by switching from high-emitting fuel to a cleaner fuel. In our study, coal stands for the high-emitting fuel and NG stands for the cleaner one. We also focus on deterministic and stochastic context of manufacturing systems by considering the unreliability of the machine. For these companies, one of the most difficult challenges is to decide when to switch between high-emitting and low-emitting fuels. In our study, fluctuation of NG price along with the key elements of the system is taken into consideration. So, when the emissions level is high, switching to NG seems to be an appropriate option, however, fluctuation of NG price and inventory level should simultaneously be taken into account. The primary research questions of our study are as follows: When and with what rate should the system produce using each fuel type? When and at which NG price should the system switch between high- and low-emitting fuels? What are the optimal safety stock levels for manufacturing? Our objective is to develop a new joint production and fuel switching policy to minimize total costs while reducing GHG emissions.

The following is how the rest of the paper is organised: Section 5.2 is a review of the literature. Sections 5.3 and 5.4 contain the problem statement and resolution approach, respectively. Section 5.5 presents the formulation of a proposed production control policies. The simulation model and its validation are discussed in Section 5.6. Section 5.7 presents the numerical results as well as the sensitivity analysis. Section 5.8 includes a comparison of proposed and current policies adapted from the literature. Finally, the management insights and conclusion are provided in Section 5.9 and Section 5.10, respectively.

5.2 Literature review

In this section, we look at the most relevant research studies to our topic. On the one hand, we focus on the publications on fuel switching models and potentials to reduce emissions from various industries. On the other hand, the publications on production planning of manufacturing systems with variant emitting levels without consideration of fuel switching are studied. A summary of the provided literature review can be seen in Table 5.1. A comparison is made among the publications in terms of specific criteria, such as inventory/ production policy, considering multi-fuels, fuel switching policy, varying fuel price, environmental regulations, and voluntary environmental approach.

In Class 1, we address the publications on fuel switching models and potentials for emission reduction in manufacturing systems. Group 1 in Class 1 is related to fuel switching models for manufacturing systems. In this context, Delarue et al., (2008) discussed the role of fuel switching in the European electricity generation sector under the European union's emissions trading system (EU ETS). An electrical generation simulation model is utilised to simulate potentials of switching from coal to gas in the EU ETS's first and second trading periods. Delarue and D'haeseleer (2008) explored the options for switching from coal-fired power to gas-fired power plants based on load levels. The cost of the allowance is assumed to be fixed, whereas the price of natural gas is supposed to be variable. GHG emission reduction potentials for several Western European countries are also compared with simulation results. Dunn and Du (2009) provided a second-order gradient search approach to optimally distribute a set of industrial steam boilers, each of which uses different fuel types at the same time. They determined the fuel mixture ratio and operating level that minimizes fuel costs. Xin-gang et al., (2021) examined the switching model from coal to gas in power generation enterprises to tackle air pollution considering incentives under China's emissions trading system.

Table 5.1 The literature on fuel switching policies and fuel alternatives analysis for emission reduction in manufacturing systems as well as models for reliable/unreliable systems with variant emitting levels without considering fuel switching

Publications	**Inventory/ production Policy**			**Multiple fuels**	**Fuel switching policy**	**Varying fuel price**	**Environmental regulations**	**Voluntary environmental approach**
	HPP*	**EPQ****	**EOQ*****					
Class 1: Fuel switching policies and fuel alternatives analysis for emission reduction in manufacturing systems								
Group 1: Fuel switching policies for emission reduction in manufacturing systems								
(Delarue et al., 2008)				✓	✓		✓	
(Delarue and D'haeseleer 2008)				✓	✓	✓	✓	
(Dunn and Du 2009)				✓	✓			
(Xin-gang et al., 2021)				✓	✓		✓	
Group 2: Fuel alternatives analysis for emission reduction in manufacturing systems								
(Smyth et al., 2012)				✓			✓	
(Fujishima et al., 2013)				✓			✓	
(Rahman et al., 2013)				✓				
(Büyüközkan and Güleryüz 2016)				✓			✓	
(Marchi et al., 2019)				✓				
(Rehfeldt et al., 2020a)				✓			✓	
(Rehfeldt et al., 2020b)				✓			✓	
(Yuan et al., 2022)				✓			✓	
Class 2: Models for manufacturing systems with variant emitting levels without considering fuel switching								
Group 1: Reliable manufacturing systems								
(Jauhari et al., 2021a)			✓				✓	
(Jauhari et al., 2021b)		✓					✓	
(Cheng et al., 2022)		✓					✓	
(Jauhari et al., 2022)		✓					✓	
Group 2: Unreliable manufacturing systems								
(Ben-Salem et al., 2015a)	✓						✓	✓
(Ben-Salem et al., 2016)	✓						✓	✓
(Hajej et al., 2017a)	✓						✓	
(Afshar-Bakeshloo et al., 2018)	✓						✓	✓
(Entezaminia et al., 2020)	✓						✓	✓
This paper	✓			✓	✓	✓	✓	✓

* Hedging point policy. ** Economic production quantity. *** Economic ordering quantity.

Group 2 in Class 1, studies the fuel switching potentials for emission reduction in manufacturing systems. In this regard, Smyth et al., (2012) investigated the possibility for inter-fuel substitution between coal, electricity, natural gas, and oil in the Chinese iron and steel sector and discover that these energy inputs are substitutes. They found that China has the capacity to switch from coal to cleaner energy sources, keeping the ability to feed its iron and steel sector while decreasing the negative environmental consequences. Fujishima et al., (2013) investigated the industrial applications of a super-clean boiler system containing a multi-fuel boiler. The goal of this study is to find the best way to cut emissions while also utilising waste bio-oil as a sustainable energy source. Rahman et al., (2013) examined the use of several types of alternative fuels and their effects on plant performance in the cement industry. They studied the quantification of the optimal mixing ratio of various alternative fuels in order to improve plant performance. Büyüközkan and Güleryüz (2016) analyzed renewable energy resources as an energy generation alternative to reduce negative environmental impacts of fossil fuels. A multi-criteria decision making approach is applied for selecting the most appropriate renewable energy resources in Turkey from technical, economic, political and social perspectives. Marchi et al., (2019) considered the environmental aspect of energy sources and presented supply chain models minimizing total costs total supply chain cost including the costs of holding inventory, GHG emissions and tax, energy usage, product and process quality, and transportation operations. Rehfeldt et al., (2020a) investigated fuel switching as a medium-term emission reduction strategy and offered a model-based analysis of price signal and regulatory action reactions in German industry. Rehfeldt et al., (2020b) examined the technical potential of fuel switching in the European basic materials sector with current or available technology. Yuan et al., (2022) explored the role of clean energy like wind, hydro, solar, etc., in reducing the greenhouse gas emissions as an alternative to the traditional energy sources in different industries. In Class 1, according to the literature review provided for publications on fuel switching potentials in manufacturing systems, most studies discussed the environmental impact of fuel switching in different industries like power plants, iron and steel, cement, and material sector (e.g., Smyth et al., 2012; Rahman et al., 2013; Rehfeldt et al., 2020b). Among them, there are only a few studies determined the switching point between coal and NG for power plants (e.g., Delarue et al., 2008; Delarue and D’haeseleer 2008; Xin-gang et al., 2021). Moreover, consideration of environmental impact of fuels at the operational level of decision-making is relatively new in the literature.

Class 2 consists of models and policies developed for manufacturing systems with variate emitting levels. Group 1 in Class 2 includes the reliable manufacturing systems ignoring the system failures. In this context, (Jauhari et al., 2021a) proposed a joint economic lot-sizing for a supply chain system consisting of a manufacturer and a retailer under carbon tax regulation. The manufacturer operates a hybrid system made of a green production and a regular production. The system production rate is assumed to be fixed. The optimal values of number of shipments, shipment lot, safety factor and production allocation are determined so that the total cost can be minimized. (Jauhari et al., 2021b) presented an inventory model for a closed-loop supply chain system containing a manufacturer and a retailer under the take-back incentive and carbon tax regulation. Manufacturing and remanufacturing are simultaneously performed in a manufacturer's hybrid system including both green production and regular production. They could minimize the total costs and emissions by controlling the collection rate and the production allocation. Cheng et al., (2022) focused on a closed-loop supply chain consisting of two types of manufacturers, high-emission and low-emission manufacturers, under the cap-and-trade and carbon tax regulations. All manufacturers are responsible in recycling as well as remanufacturing processes. Using game theory, they obtained the optimal pricing, optimal recycling, optimal carbon emission reduction and carbon trading decisions. (Jauhari et al., 2022) studied an integrated inventory model for a supply chain system consisting of a vendor (including a regular production and a green production) and a buyer considering stochastic demand. The objective of the model is to find the optimal shipment quantity, production allocation, number of shipments, and production rate so that the supply chain cost is minimized while reducing emissions. According to the literature in Group 1, most studies on production planning of manufacturing systems with variate emitting levels have disregarded the dynamic and stochastic aspect and machine failures.

Group 2 in Class 2 consists of models and policies developed for failure-prone manufacturing systems with variate emitting levels. To the best of our knowledge, there are a few studies focused on production planning of variate emitting unreliable manufacturing systems. In this regard, Ben-Salem et al., (2015a) developed an environmental hedging point policy (EHPP) under which there is a decrease in the machine usage by reducing the threshold level after exceeding the emission limit to reduce the generated emissions and minimize total costs. Ben-Salem et al. (2016) extended the EHPP to address the problem of GHG limit being exceeded by stopping the main manufacturing system after a specific emissions level and then outsourcing work to a green subcontractor. Hajej et al., (2017) developed an ecological joint production and maintenance policy for unreliable manufacturing systems subject to degradation. Under their proposed policy, when emissions exceed its limit, a subcontractor is called to control the generated GHG emissions. Afshar-Bakeshloo et al., (2018) extended the EHPP developed by Ben-Salem et al., (2015a) for high-emitting machine (HEM) and low-emitting machine (LEM) that are not operating simultaneously. Accordingly, when total emissions exceed the voluntary limit, the production system stops HEM and continues to produce with LEM in order to control the generated emissions. They also considered that the LEM threshold level is less than that for the HEM. Entezaminia et al., (2020) proposed an extension to the policy developed by Afshar-Bakeshloo et al., (2018) by relaxing the LEM threshold level constraint to present a more realistic policy. Then, they developed new environmentally friendly and cost-effective production control policies for the companies aiming to gradually invest in the LEM and synchronize HEM and LEM together. Based on the results, the new developed control policies bring significant cost and emissions reductions as compared with existing policies. According to Class 2, regarding the production control policies developed for manufacturing systems with variant emitting levels, there is no consideration of fuel switching as a mean to reduce emissions. In this vein, there is a lack of an environmental production control policy combined with fuel switching that simultaneously considers the fluctuation of NG price and the state of the system.

Our contribution is to propose a new environmental production control policy for failure-prone manufacturing systems considering fuel switching under carbon tax regulation. In the context of our study, the random variation of NG price as well as key elements of the system like its state, the change in the inventory and emissions are simultaneously taken into account to decide on fuel switching. Our proposed policy has a wide variety of implications for the high-emitting enterprises who tend to figure out how to make a dynamic plan for their production and conditions for switching to a cleaner fuel. Manufacturers can simultaneously minimize total costs while reducing GHG emissions by implementing our cost-effective and environmentally friendly proposed policy.

5.3 Problem Statement

5.3.1 Notations

The notations used in the remainder of this paper are as follows. Here, i denotes the fuel type, i=1 when the production is burning coal, and i=2 represents when the production is using NG.

$x(t)$	inventory/backlog level at time t
$e(t)$	emission level at time t
$u_i(t)$	production rate of the machine using fuel type i (product/time unit)
$\alpha(t)$	operational state of the machine, equals 0 if it is down and equals 1 if it is operational
U_i	maximum production rate of the machine when using ith fuel (product/time unit)
d	demand rate
TTF	distribution function of time to failure
TTR	distribution function of time to repair
$MTTF$	mean time to failure
$MTTR$	mean time to repair
c^+	inventory cost for each product time unit ($/product/time unit)
c^-	backlog cost for each product per unit of time ($/product/time unit)
c^e	penalty cost for each violation at the end of the emission control period ($/violation unit)
FP_1	fuel price of coal ($/gigajoule (Gj))
$FP_2(t)$	fuel price of NG ($/gigajoule (Gj))
θ_i	emission index when using ith fuel
Av	availability of the machine

L	emissions limit announced by the government
P_e	length of emission control period

5.3.2 Problem description

Our manufacturing system under study which consists of a failure-prone machine produces a single product type to meet the customer demand as depicted in Figure 5.1. In this study, the manufacturing system produces using a high-emitting fuel (i.e., coal), and benefits form the switching option to a cleaner fuel type (i.e., NG).

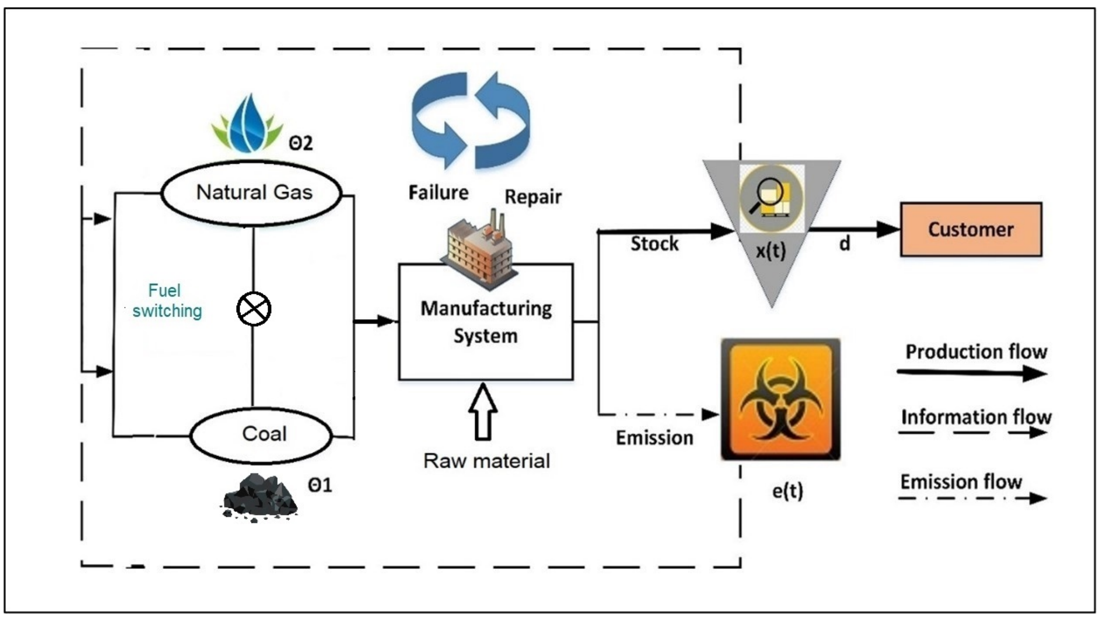

Figure 5.1 The manufacturing system under consideration

As natural gas has a lower carbon content than coal, production using NG generates less emissions than the production using coal ($\theta_1 > \theta_2$) (Chaaban et al., 2004). The operation of the manufacturing system using NG helps to reduce the total amount of GHGs generated. Here, a fixed coal price and a variable NG price (which follows a normal distribution) are assumed. However, the price of NG is generally higher than price of coal ($FP_2(t) > FP_1$). Moreover, the efficiency of production using NG is higher than that of using coal ($U_2 > U_1$) (Delarue et al., 2008). $u_1(t)$ and $u_2(t)$ respectively represent the production rates when consuming coal and NG.

Machine breakdown and repair duration is following a stochastic process. The emission index defines the amount of emissions generated by producing one product when consuming a specific fuel type. Emission indexes are following the uniform distributions of $\theta_1 \sim [a_1, b_1]$ and $\theta_2 \sim [a_2, b_2]$. When the inventory level surpasses the threshold level or the emissions level exceeds the voluntary limit, some feedbacks are given to the system. The machines' availability can be calculated as follows:

$$Av = (MTTF)/(MTTF + MTTR) \tag{5.1}$$

The dynamic behaviour of our investigated discrete/continuous system can be described by $x(t), e(t), \alpha(t)$ at every time (t). According to the discrete part, $\{\alpha(t), t > 0\} \in \{0,1\}$ equals 0 if the system is down and equals 1 when it is up. According to the continuous components, $x(t) \in R$ denotes the inventory level, and $e(t) \in R$ shows the emission level. Equations (5.2) and (5.3) can be used to respectively describe the dynamic of inventory and emissions. The initial surplus level is represented by x_0.

$$\frac{dx(t)}{dt} = u_1(t).\alpha(t) + u_2(t).\alpha(t) - d \qquad x(0) = x_0 \tag{5.2}$$

$$\frac{de(t)}{dt} = u_1(t).\alpha(t).\theta_1 + u_2(t).\alpha(t).\theta_2 \tag{5.3}$$

The capacity constraint of the systems under consideration is given by the equation:

$$0 \leq u_i(t) \leq U_i \quad (i = 1, 2) \tag{5.4}$$

To ensure the system's feasibility, the following restriction is imposed:

$$U_i \times Av \geq d \qquad (i = 1, 2) \tag{5.5}$$

The total cost of the system includes the inventory, backlog, fuel, and emission costs. The surplus level, $x(t)$, is used to determine inventory and backlog costs. The fuel cost is calculated by the machines' production rate using each fuel type. ω Gj energy is needed to produce each product. The followings are the inventory, backlog, and fuel costs. Here, $x^+ = max(0, x)$, $x^- = max(-x, 0)$.

$$h(x(t)) = c^+.x^+ + c^-.x^- \tag{5.6}$$

$$FC(u_i(t)) = \omega \times (FP_1.u_1(t).\alpha(t) + FP_2(t).u_2(t).\alpha(t)) \tag{5.7}$$

$$g(x(t), u_i(t)) = h(x(t)) + FC(u_i(t)) \tag{5.8}$$

The system is regulated by carbon tax under which if the emission level at the end of control period exceeds the level of L announced by the government, the violation will be penalized by the emission cost of c^e as shown in Equation (5.9). The emission level will be reset to zero, at the end of each control period. N represents the number of emission control periods.

$$EC(t_j) = c^e \times max(0, e(t_j) - L) \quad j = 1, \dots, N;\ t_j = j \times P_e;\ e(t_j) = 0; \tag{5.9}$$

Considering Equations (5.6) to (5.9), the average total incurred cost is determined as follows:

$$J(x(t), e(t), \alpha(t)) = \int_0^{N \times P_e} g(x(t), u_i(t))\, dt + \frac{1}{N \times P_e} \sum_{j=1}^{N} EC(t_j) \tag{5.10}$$

The optimal control policy aims to minimize $J(.)$ while taking constraints (5.1) to (5.5) into consideration to determine the machine production rate.

5.4 Resolution approach and research methodology

Considering the stochastic and dynamic context of the system under study, it is difficult to find an analytical solution for such complex problems (Afshar-Bakeshloo et al., 2018; Entezaminia et al., 2020). To handle such a difficult problem, an experimental resolution technique integrating design of experiment (DOE), simulation, and response surface methodology (RSM) is used. The steps of our resolution approach are shown in Figure 5.2.

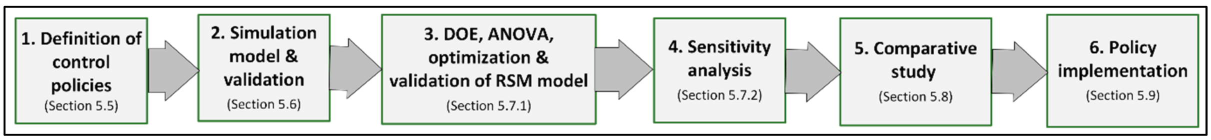

Figure 5.2 Resolution approach and methodology

- step 1: Definition of control policies

In this step, we present the structure of our proposed production policies provided in Equations (5.12) to (5.17) (see Section 5.5).

- step 2: Simulation model and its validation

Simulation model is used to demonstrate the dynamic behaviour of the system, in which the control policy is the input and total cost is the output (see Section 5.6).

- step 3: DOE, the analysis of variance (ANOVA), optimization and validation of RSM

Following DOE approach, the number of experiments and levels for each policy parameter are set. ANOVA is used to describe the main independent variables that have a significant impact on response variable. RSM is also implemented to determine the impact of main policy parameters (A, B, C, D, E), their quadratic impacts, and their interactions on total costs. The total costs approximation function is given in Equation (5.11) (Myers et al., 2016). The data obtained from the simulation model is employed to estimate unknown coefficients such as β_0, β_i and β_{ij} ($i, j \in \{1, 2, 3, 4, 5\}$). The random error is denoted by ε. We find the optimal values for significant control parameters, minimizing total costs.

$$Total\_Cost = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 D + \beta_5 E + \beta_{11} A^2 + \beta_{12} AB + \beta_{13} AC + \beta_{14} AD + \beta_{15} AE + \beta_{22} B^2 + \beta_{23} BC + \beta_{24} BD + \beta_{25} BE + \beta_{33} C^2 + \beta_{34} CD + \beta_{35} CE + \beta_{44} D^2 + \beta_{45} DE + \beta_{55} E^2 + \varepsilon \qquad (5.11)$$

To validate the RSM model, three stages are taken according to Myers et al., (2016). First, the modified R-squared coefficient is used to assess the RSM model's overall performance. It indicates how much of the total variation in total costs can be explained by the RSM model's independent variables. An adjusted R-squared close to 1 is preferable. Second, a residual analysis is performed to ensure residual normality and homogeneity of variances. Third, a confidence interval of 95% is calculated and a Student's t-test is performed to double-check the model's validity (see Section 5.7.1).

- step 4: Sensitivity analyses

They are performed to evaluate our proposed control policies and robustness of our resolution approach (see Section 5.7.2).

- step 5: Comparative study

A comparison among our proposed control policies and an adaptation of the most relevant control policies from the literature is made, for a wide range of system and cost parameters, to identify the most cost-effective and environmentally friendly control policy (see Section 5.8).

- step 6: Implementation of the best control policy

It highlights the actions that should be taken by decision makers to effectively control the production processes. In this way, complete information on the current NG price, state of production system, emissions and inventory levels is required (see Section 5.9).

5.5 Structure of our proposed joint production and fuel switching policies

5.5.1 Proposed control policy 1

In this study, we focus on high-emitting failure-prone manufacturing systems which tend to benefit from switching to a cleaner fuel in order to reduce emissions generated by the system. As production using coal and NG is different in terms of generated emissions, fuel cost, and production capacity, it is important to make a trade-off between using these fuel sources to achieve both environmental and economic goals. We aim to develop a new production control policy combined with fuel switching under carbon tax regulation to minimize total costs while reducing emissions.

When it comes to failure-prone manufacturing systems, hedging point policy (HPP) is one of the approaches that have been developed to provide better control and management of such systems. HPP is an efficient in managing random events in a stochastic and dynamic manufacturing environment. In this vein, Gharbi and Kenné, (2000) developed HPP for a manufacturing system composed of a single machine subject to failures and repairs. Under this policy, the production rate is considered as a control variable, while the system state and the inventory level are considered as state variables. This involves building the inventory level at a specific threshold when the production system is available, to avoid backlogs during failure periods. Recently, considerable attempts have been made to extend this control policy to address the management of production planning from different perspectives like quality control (Rivera-Gomez et al., 2013), remanufacturing (Assid et al., 2020), subcontracting (Rivera-Gomez et al., 2016), transshipment (Dhahri et al., 2022a), environmental aspects (Ben-Salem et al., 2015), etc.

Inspired from HPP, under our proposed control policy 1, we define inventory threshold levels (Z_c and Z_{NG}) to assist the system in dealing with future backlog due to machine failure. As the maximum production rate of the machine when using coal is different from that of when using NG, two threshold levels Z_c and Z_{NG} are defined. Z_c denotes the safety stock (threshold level) that should be maintained when coal is consumed for production. Z_{NG} defines the safety stock (threshold level) that is needed to be kept, when the system is using NG. As the system's maximum production rate when using NG is greater than when using coal, it is less likely to experience a shortage when NG is consumed. Therefore, less inventory is required to deal with the shortage when the system consumes NG for production ($Z_{NG} < Z_c$).

In order to develop an environmentally friendly production control policy, we integrate HPP with environmental aspects of unreliable manufacturing systems under carbon tax regulation. In this vein, Y is defined as a voluntary emission limit to control the emissions generated by the system. When the emission level reaches Y, it is necessary to think of reducing emissions by switching to NG as a cleaner fuel type.

Moreover, in the context of our study, the fluctuation of NG price in the market is taken into account. In order to design our proposed policy, the NG price (varying over time) along with the key elements of the system including its state, level of inventory and emissions are simultaneously under consideration. As the NG price fluctuates over time, the manager should also take the NG price into account when deciding on fuel switching in order to emission reduction. Considering the random variation of NG price, the manager is able to take advantage of lower NG prices for fuel switching to cleaner energy. Consequently, when the system starts operating using coal (cheaper fuel type), if the NG price is low enough, switching to cleaner energy is advantageous. Also, when the emission is high, only if the NG price is considerably high, the system should operate using coal. Then, when the emissions level is extremely high, the system should operate using NG at any price. In this regard, the control factor of σ is set as the NG price fluctuation (μ±σ) defining the low, medium, and high price. Therefore, FP_L = μ-σ, and FP_U = μ+σ. Any price of NG which is less than FP_L, is considered as a low price. Any NG price higher than FP_U is considered as a high NG price. Proposed policy 1 is formulated as follows:

If $e(t) < Y$ then

$$\begin{cases} u_1(t) = \begin{cases} U_1 & if\ FP_2(t) > FP_L\ and\ x(t) < Z_c \\ d & if\ FP_2(t) > FP_L\ and\ x(t) = Z_c \\ 0 & o.w \end{cases} \\ u_2(t) = \begin{cases} U_2 & if\ FP_2(t) \leq FP_L\ and\ x(t) < Z_{NG} \\ d & if\ FP_2(t) \leq FP_L\ and\ x(t) = Z_{NG} \\ 0 & o.w \end{cases} \end{cases} \tag{5.12}$$

If $Y \leq e(t) < L$ then

$$\begin{cases} u_1(t) = \begin{cases} U_1 & if\ FP_2(t) \geq FP_U\ and\ x(t) < Z_c \\ d & if\ FP_2(t) \geq FP_U\ and\ x(t) = Z_c \\ 0 & o.w \end{cases} \\ u_2(t) = \begin{cases} U_2 & if\ FP_2(t) < FP_U\ and\ x(t) < Z_{NG} \\ d & if\ FP_2(t) < FP_U\ and\ x(t) = Z_{NG} \\ 0 & o.w \end{cases} \end{cases} \tag{5.13}$$

If $e(t) \geq L$ then for any $FP_2(t)$

$$\begin{cases} u_1(t) = 0 \\ u_2(t) = \begin{cases} U_2 & if\ x(t) < Z_{NG} \\ d & if\ x(t) = Z_{NG} \\ 0 & if\ x(t) > Z_{NG} \end{cases} \end{cases} \tag{5.14}$$

According to Equation (5.12), when the level of emissions is lower than Y $(e(t) < Y)$, the system operates using the less expensive (but higher emitting) fuel type which is coal. However, NG price should simultaneously be taken into consideration. If the NG price is considerably low $(FP_2(t) < FP_L)$, the system can benefit from switching to NG which generates less emissions. When consuming coal, if the inventory is less than threshold level of coal, Z_c, the manufacturing system produces at maximum rate of U_1. If the inventory level of Z_c is built, the system produces at customer demand rate. When the inventory level is higher than Z_c, the system stops producing. In case of consuming NG for production, if the inventory level is less than the threshold level defined for NG, $Z_{NG}(< Z_c)$, the system produces at maximum rate of U_2. When the inventory level reaches Z_{NG}, the system produces at demand rate. If the inventory level is higher than Z_{NG}, the production will be stopped.

Based on Equation (5.13), when the emission level goes over the voluntary emission limit of Y $(Y < e(t) < L)$, an immediate action should be taken to reduce GHG emissions. Switching to NG as a cleaner fuel source is an option, however, the NG price needs to be monitored as well. In this situation, if the NG price is not high (is low or medium, $FP_2(t) < FP_U$), the system switches to production using natural gas. If the NG price is considerably high $(FP_2(t) > FP_U)$, the system continues production using coal.

According to Equation (5.14), if the level of generated emissions exceeds the emission limit announced by the government, L, ($e(t) > L$) the manager stops consuming coal and continues production using natural gas at any NG price to avoid considerable emission penalty cost.

5.5.2 Proposed control policy 2 (An extension of policy 1)

According to our proposed control policy 1, the manufacturing system operates using coal if the emission level is lower than $Y$and the NG price is not low enough to switch (Equation (5.12)). Also, coal is used if the emission level exceeds Y ($Y < e(t) < L$) but the NG price is considerably high for switching (Equation (5.13)). In both cases, the production rate will be determined based on the threshold level of Z_c^1 that needs to be maintained when coal is consumed for production. However, in the latter case ($Y < e(t) < L$), the high emission level caused by consuming coal may result in huge emission penalty cost increasing total costs of the system. On one hand, it is not quite environmentally friendly to continue consuming coal when emissions level goes over Y (and NG price is high for switching). On the other hand, stopping the machine may lead to a major backlog cost for the system.

Here, the primary question is how we can improve the proposed policy 1 in terms of environmental aspects as well as optimal total costs? How can we reduce generated GHG emissions without stopping the machine for a long time? What if we stop the machine until reaching a specific threshold level to avoid a huge backlog cost? As a result, will there be a reduction in GHG emissions and the emission penalty cost? Will there be a reduction in fuel as well as inventory costs? Will this result in even more cost savings?

As an improvement, under our proposed policy 2, when the emissions level is lower than $Y$and the NG price is not low enough to switch, the system operates using coal to reach the inventory threshold level of Z_c^1 (Equation (5.15)). If the GHG emissions exceed Y ($Y < e(t) < L$) and switching to NG is costly ($FP_2(t) > FP_U$), a lower threshold level is defined for production using coal, Z_c^2 (Equation (5.16)). In this way, the system reduces emissions by stopping production until reaching a lower safety stock level, Z_c^2 (Z_{NG}< $Z_c^2 < Z_c^1$). Our proposed policy

2 is expected to be more cost-effective and environmentally friendly. Accordingly, less consumption of coal helps the system to generate less GHG emissions and decreases fuel and emissions cost. Furthermore, as less inventory is kept by the system, inventory cost is expected to be reduced under proposed policy 2. Equations (5.15) to (5.17) provide the formulation of our proposed control policy 2.

If $e(t) < Y$ then

$$\begin{cases} u_1(t) = \begin{cases} U_1 & if\ FP_2(t) > FP_L\ and\ x(t) < Z_c^1 \\ d & if\ FP_2(t) > FP_L\ and\ x(t) = Z_c^1 \\ 0 & o.w \end{cases} \\ u_2(t) = \begin{cases} U_2 & if\ FP_2(t) \leq FP_L\ and\ x(t) < Z_{NG} \\ d & if\ FP_2(t) \leq FP_L\ and\ x(t) = Z_{NG} \\ 0 & o.w \end{cases} \end{cases} \tag{5.15}$$

If $Y \leq e(t) < L$ then

$$\begin{cases} u_1(t) = \begin{cases} U_1 & if\ FP_2(t) \geq FP_U\ and\ x(t) < Z_c^2 \\ d & if\ FP_2(t) \geq FP_U\ and\ x(t) = Z_c^2 \\ 0 & o.w \end{cases} \\ u_2(t) = \begin{cases} U_2 & if\ FP_2(t) < FP_U\ and\ x(t) < Z_{NG} \\ d & if\ FP_2(t) < FP_U\ and\ x(t) = Z_{NG} \\ 0 & o.w \end{cases} \end{cases} \tag{5.16}$$

If $e(t) \geq L$ then for any $FP_2(t)$

$$\begin{cases} u_1(t) = 0 \\ u_2(t) = \begin{cases} U_2 & if\ x(t) < Z_{NG} \\ d & if\ x(t) = Z_{NG} \\ 0 & if\ x(t) > Z_{NG} \end{cases} \end{cases} \tag{5.17}$$

5.6 Simulation model and its validation

Figure 5.3 shows how Arena software is used to create a discrete-continuous simulation model for each control policy. The level of inventory and GHG emissions are regarded as continuous events, while the system state is regarded as the discrete part.

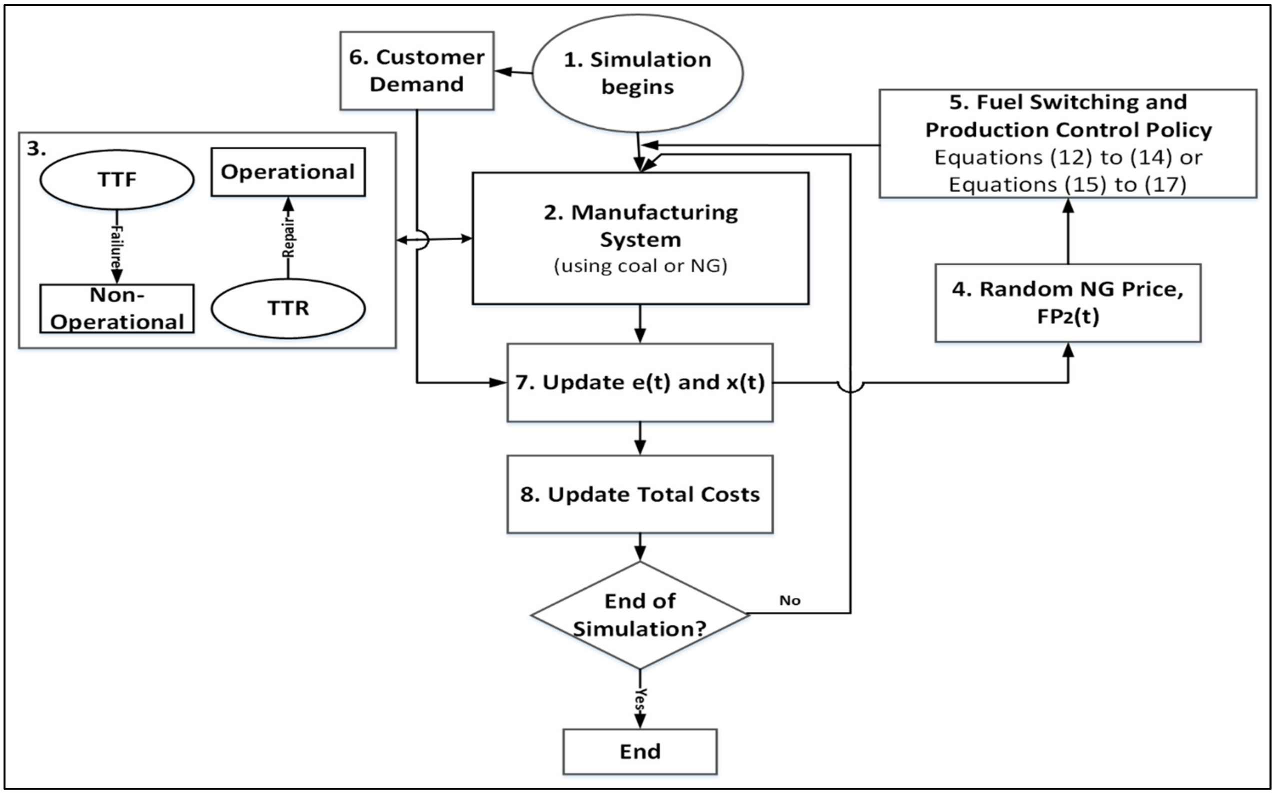

Figure 5.3 The simulation model's diagram

As can be seen in the figure, the simulation model begins to specify the inputs and parameters in Block 1. Blocks 2 depicts the manufacturing system under study which consumes either coal or NG. Block 3 shows that the system is prone to random failures and repairs. Block 4 depicts the NG price which randomly changes. The considered manufacturing system operates in accordance with each proposed control policy shown in Block 5 to meet the customer demand depicted in Block 6. As shown in Block 7, the model updates the surplus inventory level, $x(t)$, emission level, $e(t)$, using Equations (5.2) and (5.3). Finally, total cost including emissions, fuel, inventory, and backlog cost is computed in Block 8.

to validate our simulation model, the dynamic behaviour of the studied manufacturing system is evaluated under the proposed control policy 2 (Equations (5.15) to (5.17)) in Figure 5.4.

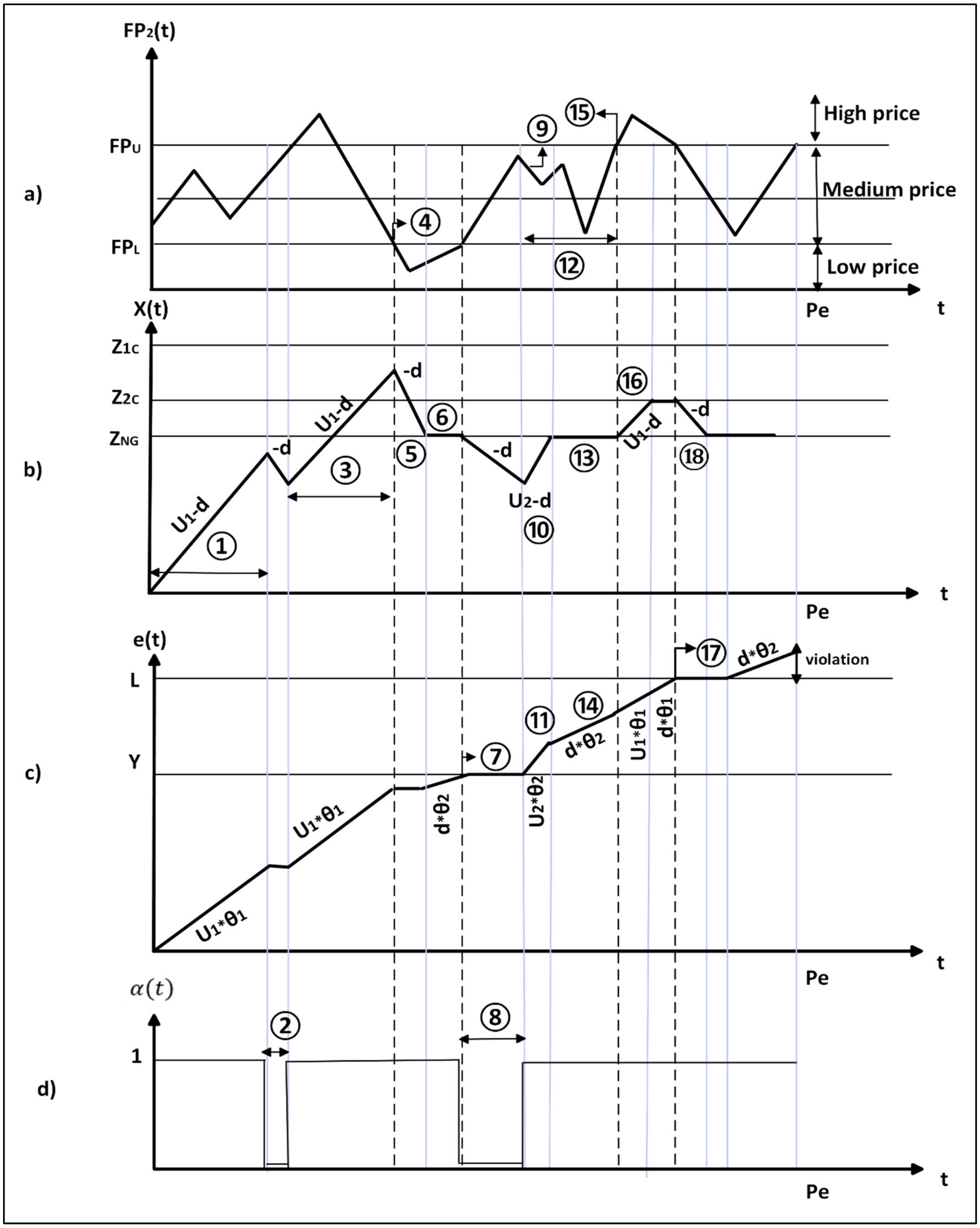

Figure 5.4 Simulation of system's dynamic behavior of under proposed policy 2

As can be seen from the figure, the simulation model accurately reproduces the system's behaviour when operating under proposed control policy 2. To make it more readable, the symbol "Y.©" is used to represent the event depicted in part © in Sub-Figure 4.Y. For instance, b.① in Figure 5.4 shows the event depicted in part ① of Sub-Figure 4.b.

As can be seen in b.①, when the system starts operating, coal is consumed as the cheaper fuel type. Because the inventory level is less than Z_c^1, the system produces at maximum rate of U_1. The emission rises at the rate of $U_1 \times \theta_1$. According to d.②, there is a failure in the system. The inventory level decreases with the rate of -d. As shown in b.③, when the system is repaired, it continues to produce at maximum rate of U_1 to reach the threshold level of Z_c^1. As can be seen in a.④, the NG price is low enough $(FP_2(t) < FP_L)$ to switch to NG. The system stops production using coal and can start consuming NG. However, as the inventory level is higher than threshold level of Z_{NG}, the system stops production, and the inventory reduces at the rate of -d (b.⑤). After reaching Z_{NG}, it operates using NG at the demand rate (b.⑥). According to c.⑦, the emissions level goes over Y, so the NG price should be taken into account to decide on switching. If the NG price is not high, it is beneficial to switch to NG. According to d.⑧, the system is failed. After repairing, as shown in a.⑨ the NG price is medium and suitable for switching. The system produces using NG at the maximum rate of U_2 because the inventory level is lower than Z_{NG} (b.⑩). According to c.⑪, the emission increases at the rate of $U_2 \times \theta_2$. During the time shown in a.⑫, the NG price is still low enough to continue production using NG. In b.⑬, as the inventory reaches Z_{NG}, the production is set at the demand rate (c.⑭). In a.⑮, the NG price is high, and the system must switch to coal. Because the inventory is less than Z_c^2, the system produces at the maximum rate of U_1 (b.⑯). After maintaining Z_c^2, it operates at the demand rate. In c.⑰, the emissions level goes above L which is the emission limit announced by the government. So, the system stops production using coal and switches to NG in order to avoid huge emissions penalty cost. The system stops production till reaching the threshold level of Z_{NG}. After reaching Z_{NG}, it produces at the rate of demand (b.⑱). The emissions level will be reset to zero, at the end of the emission control period (P_e).

5.7 Numerical example

The optimization model is built in this section utilising the design of experiment strategy and response surface methodology to identify the optimal value of control parameters as well as the optimal total costs for our proposed production control policy 2. Table 5.2 summarises the cost and system parameter values used.

Table 5.2 The cost and system parameters

Parameter	d	U_1	U_2	TTF	TTR	θ_1	θ_2
Value	100	120	130	Exp (7)	Exp (0.4)	U [0.5,1.5]	U [4.5,5.5]
Parameter	c^+	c^-	c^e	FP_1	$FP_2(t)$	P_c	L
Value	1	50	30	1.5	NORM (5,1.5)	5760	650,000

5.7.1 DOE, ANOVA, and optimization using RSM

For the sake of validation, here we explain how we used a Box-Behnken design for our proposed policy 2 as a remarkable example, with three levels of control factors Z_{NG}, Z_c^1, Z_c^2 , Y and σ. For each design, 320 simulation runs are undertaken using five replications of combinations of control factors. We run the simulation model for 500,000 time units to guarantee that the system reaches its steady-state (TU). The data is statistically processed using "STATGRAPHICS" software for analysis of variance (ANOVA). We found the effects of the examined control factors (Z_{NG}, Z_c^1, Z_c^2, Y, σ), their interactions, and their quadratic impacts on total cost using the ANOVA shown in Table 5.3. The adjusted R-square of 98.85% achieved can adequately measure the quality of the RSM model. Furthermore, we examined the model's conformance using residual normality analysis and variance homogeneity. To validate the RSM model, we validated that the optimal total incurred cost falls within the confidence range generated from n=40 extra replications of the simulation model at a 95% level of confidence.

The RSM model for proposed production control policy 2, is determined in Equation (5.18). Optimization results include optimal control factors, Z_c^{1*}= 294.50, Z_c^{2*}= 274.12, Z_{NG}^*= 257.86, Y^*= 319,448, σ^*= 0.79, as well as minimum total costs, TC^*= 3,688.33. Running the simulation model for 50 additional number of replications, the optimal total cost is between [3,682.15, 3,695.36] at a 95% confidence level. Figure 5.5 shows the contour plot of RSM model.

Table 5.3 ANOVA associated with total cost

Source	***Sum of Squares***	***Df***	***Mean Square***	***F-Ratio***	***P-Value***
A: Z_c^1	2.93064E6	1	2.93064E6	157.62	0.0000
B: Z_c^2	2.88665E6	1	2.88665E6	155.14	0.0000
C: Z_{NG}	1.50639E8	1	1.50639E8	8102.04	0.0000
D: Y	1.87532E6	1	1.87532E6	100.86	0.0000
E: σ	395655.	1	395655.	21.28	0.0000
AA	569008.	1	569008.	30.60	0.0000
AB	74921.0	1	74921.0	4.03	0.0470
AC	89133.0	1	89133.0	4.79	0.0306
AD	2248.26	1	2248.26	0.12	0.7287
AE	67555.0	1	67555.	3.86	0.0410
BB	4.85951E7	1	4.85951E7	2613.66	0.0000
BC	1.56092E6	1	1.56092E6	83.95	0.0000
BD	171073.	1	171073.	9.20	0.0024
BE	99248.0	1	99248.0	5.54	0.0204
CC	29768.2	1	29768.2	1.60	0.2083
CD	321488.	1	321488.	17.29	0.0001
CE	92789.0	1	92789.0	5.18	0.0208
DD	14887.7	1	14887.7	0.80	0.3727
DE	12571.5	1	12571.5	0.76	0.3915
EE	88452.0	1	88452.0	4.54	0.0307
blocks	3193.07	4	798.267	0.04	0.9965
Total error	6.91511E7	205	54684.2		
Total (corr.)	3.76552E10	229			

R-squared = 99.0105 percent
R-squared (adjusted for d.f.) = 98.8569 percent

$$TC = 148.9751 + 3.25653 \times Z_c^1 + 0.1692 \times Z_c^2 - 0.012856 \times Z_{NG} + 2.58454 \times Y - 18.54654 \times \sigma + 0.006566 \times (Z_c^1)^2 + 10.5468 \times Z_c^1 \times Z_c^2 + 0.0551328 \times Z_c^1 \times Z_{NG} - 11.9468 \times Z_c^1 \times \sigma + 0.000375 \times (Z_c^2)^2 + 0.05228 \times Z_c^2 \times Z_{NG} - 7.8 \times 10^{-11} \times Z_c^2 \times Y + 11.05018 \times Z_c^2 \times \sigma + 0.0059965 \times Z_{NG} \times Y - 0.001254 \times Z_{NG} \times \sigma + 3.181028 \times \sigma^2 \quad (5.18)$$

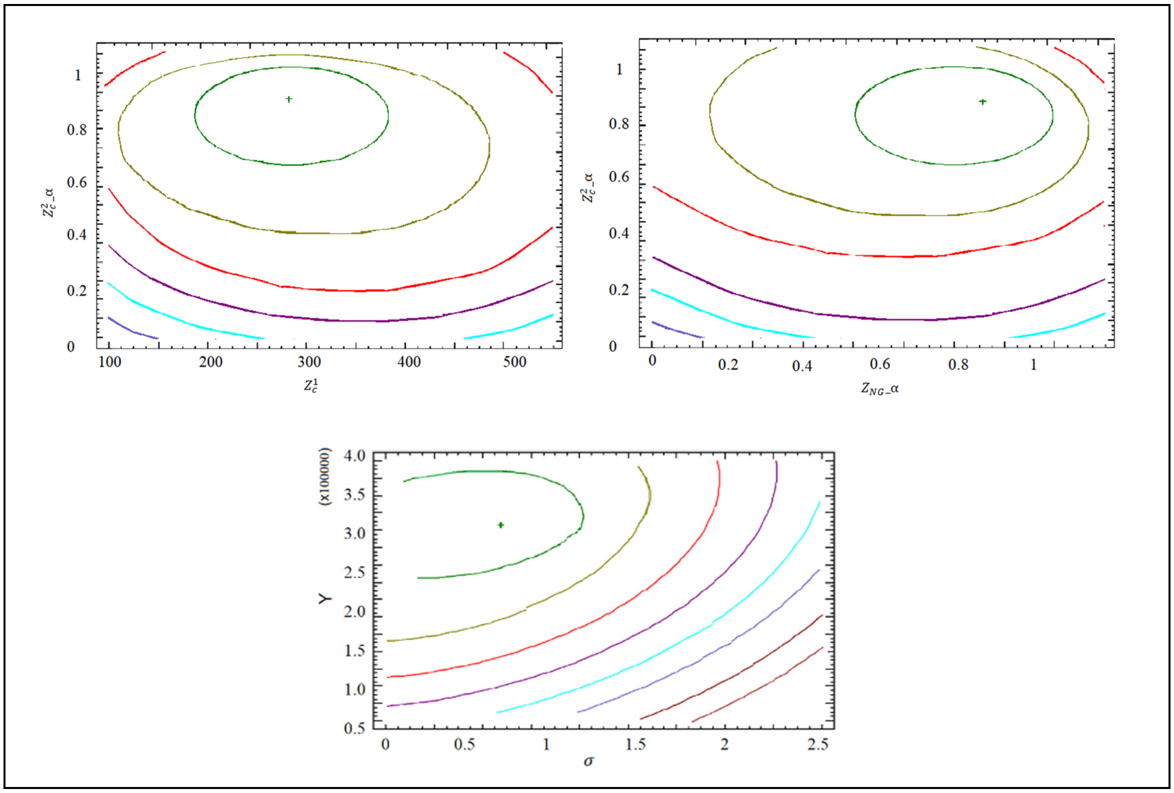

Figure 5.5 Contour plot for RSM model

5.7.2 Sensitivity analyses

A sensitivity analysis is performed in this section in order to confirm the robustness of our resolution approach and proposed control policy 2. The impact of cost and system parameters (c^+, c^-, c^e, FP_1, $FP_2(t)$, Av, θ_1 and θ_2) on the control factors defined for our proposed control policy 2 (Z_{NG}, Z_c^1, Z_c^2, Y and σ) is briefly explored in Table 5.4.

Table 5.4 Sensitivity analysis of proposed policy 2 for different variations of cost and system parameters

Case	Parameters								Proposed policy 2					Remark
	C+	C-	Ce	FP1	FP2(t)	Av	θ1	θ2	Zc1*	Zc2*	ZNG*	Y*	σ*	
-	1	50	30	1.5	N (5, 1.5)	0.94	U (0.5, 1.5)	U (4.5, 5.5)	294.50	274.12	257.81	319,448.26	0.79	Basic case
1	0.8	50	30	1.5	N (5, 1.5)	0.94	U (0.5, 1.5)	U (4.5, 5.5)	308.73	281.69	264.72	302,589.42	0.81	Zc1* ↑, Zc2* ↑, ZNG* ↑, Y* ↓, σ ↑
2	1.2	50	30	1.5	N (5, 1.5)	0.94	U (0.5, 1.5)	U (4.5, 5.5)	287.55	269.17	246.40	325,245.81	0.78	Zc1* ↓, Zc2* ↓, ZNG* ↓, Y* ↑, σ ↓
3	1	30	30	1.5	N (5, 1.5)	0.94	U (0.5, 1.5)	U (4.5, 5.5)	281.57	262.63	245.35	332,558.65	0.77	Zc1* ↓, Zc2* ↓, ZNG* ↓, Y* ↑, σ ↓
4	1	70	30	1.5	N (5, 1.5)	0.94	U (0.5, 1.5)	U (4.5, 5.5)	321.66	285.45	269.98	298,549.25	0.80	Zc1* ↑, Zc2* ↑, ZNG* ↑, Y* ↓, σ ↑
5	1	50	20	1.5	N (5, 1.5)	0.94	U (0.5, 1.5)	U (4.5, 5.5)	312.89	288.56	273.81	357,159.36	0.75	Zc1* ↑, Zc2* ↑, ZNG* ↑, Y* ↑, σ ↓
6	1	50	40	1.5	N (5, 1.5)	0.94	U (0.5, 1.5)	U (4.5, 5.5)	275.18	267.45	237.76	283,564.50	0.82	Zc1* ↓, Zc2* ↓, ZNG* ↓, Y* ↓, σ ↑
7	1	50	30	1	N (5, 1.5)	0.94	U (0.5, 1.5)	U (4.5, 5.5)	321.98	295.32	257.81	330,569.68	0.76	Zc1* ↑, Zc2* ↑, ZNG* ↔, Y*↑, σ ↓
8	1	50	30	2	N (5, 1.5)	0.94	U (0.5, 1.5)	U (4.5, 5.5)	270.59	257.67	257.81	288,275.27	0.82	Zc1* ↓, Zc2* ↓, ZNG* ↔, Y* ↓, σ ↑
9	1	50	30	1.5	N (4,1.5)	0.94	U (0.5, 1.5)	U (4.5, 5.5)	294.50	274.12	268.46	276,268.20	0.80	Zc1* ↔, Zc2* ↔, ZNG* ↑, Y* ↓, σ ↑
10	1	50	30	1.5	N (6,1.5)	0.94	U (0.5, 1.5)	U (4.5, 5.5)	294.50	274.12	243.19	328,166.58	0.77	Zc1* ↔, Zc2* ↔, ZNG* ↓, Y* ↑, σ ↓
11	1	50	30	1.5	N (5, 1.5)	0.93	U (0.5, 1.5)	U (4.5, 5.5)	313.58	290.66	269.45	286,153.49	0.82	Zc1* ↑, Zc2* ↑, ZNG* ↑, Y* ↓, σ ↑
12	1	50	30	1.5	N (5, 1.5)	0.95	U (0.5, 1.5)	U (4.5, 5.5)	283.55	264.03	239.18	329,258.37	0.78	Zc1* ↓, Zc2* ↓, ZNG* ↓, Y* ↑, σ ↓
13	1	50	30	1.5	N (5, 1.5)	0.94	U (0.25,1.25)	U (4.5, 5.5)	319.28	289.43	257.81	331,545.20	0.77	Zc1* ↑, Zc2* ↑, ZNG* ↔, Y* ↑, σ ↓
14	1	50	30	1.5	N (5, 1.5)	0.94	U (0.75,1.75)	U (4.5, 5.5)	278.92	259.87	257.81	295,265.38	0.80	Zc1* ↓, Zc2* ↓, ZNG* ↔, Y* ↓, σ ↑
15	1	50	30	1.5	N (5, 1.5)	0.94	U (0.5, 1.5)	U (4.25,5.25)	294.50	274.12	264.98	285,364.09	0.81	Zc1* ↔, Zc2* ↔, ZNG* ↑, Y* ↓, σ ↑
16	1	50	30	1.5	N (5, 1.5)	0.94	U (0.5, 1.5)	U (4.75,5.75)	294.50	274.12	241.69	338,489.22	0.77	Zc1* ↔, Zc2* ↔, ZNG* ↓, Y* ↑, σ ↓

The variation of c^{+} and c^{-} has an opposite effect on the policies parameters. Indeed, when there is an increase in c^{+}(case 2), (respectively decrease in c^{-} (case 3)), the system needs less inventory to face the future shortages. So, there is a decrease in Z_{NG}^{*}, Z_{c}^{1*}, and Z_{c}^{2*}. By lowering the inventory threshold levels, the system produces less at its maximum production rate, resulting in less emissions. So, there is an increase in the voluntary emission limit of Y* which allows the system to operate using the less expensive fuel (coal) for a longer period of time. As less emission is generated by the system, there is a decrease in $\sigma*$ to reduce the pressure of switching to NG when emissions level reaches Y. Moreover, according to the results, when there is an increase in emission cost c^{e}, the system responses by lowering inventory threshold levels (Z_{NG}^{*}, Z_{c}^{1*}, and Z_{c}^{2*}) to produce less at the maximum production rates. This results in generating less emissions. Also, there is a reduction in the voluntary emission limit, Y* to reduce the generated emissions by faster switching from coal to NG. There is also an increase in $\sigma*$ to give more chance to the system for switching to NG, when emissions level goes over Y.

By increasing the price of coal, FP_{1}, there is a decrease in the inventory threshold levels of coal (Z_{c}^{1*} and Z_{c}^{2*}). There is no change in the inventory threshold level the system when using NG (Z_{NG}^{*}). To reduce the usage of coal, there is also a decrease in Y* where the system should switch from coal to NG. Also, $\sigma*$ increases to provide the system a better chance of switching to NG, when emissions exceed Y. On the contrary, when $FP_{2}(t)$ rises, there is no change in threshold level of (Z_{c}^{1*} and Z_{c}^{2*}). To reduce the usage of NG, there is an increase in Z_{NG}^{*} and Y* and a reduction in $\sigma*$.

When availability of the system rises, the system requires to keep less inventory to face future backlogs. Therefore, as can be seen from the results, there is a reduction in inventory threshold levels (Z_{NG}^{*}, Z_{c}^{1*}, and Z_{c}^{2*}). Reducing the GHG emissions generated by the system leads to more usage of coal which is less expensive by increasing Y*. As the system generates less emissions, there is a reduction in $\sigma*$ to lessen the pressure of switching to NG whenever emissions level reaches Y. When there is an increase in θ_{1}, production using coal generates more emissions. So, the system reduces the inventory threshold levels of coal (Z_c^{1*} and Z_c^{2*}). There is no change in the threshold level of NG (Z_{NG}^{*}). To decrease the usage of coal, the system provides a better chance of switching to NG by reducing Y* and increasing σ*. On the contrary, when θ_2 increases, there is a reduction in the threshold level of NG (Z_{NG}^{*}) and no change in threshold levels of coal (Z_c^{1*} and Z_c^{2*}). To reduce production using NG, there is an increase in Y* and a reduction in σ*.

5.8 Comparison between proposed and existing policies adapted from the literature for a wide range of cost and system parameters

In this section, we compare our proposed control policies with the most relevant policies adapted from the literature. Considering production using coal and NG as variate emitting production modes, we addressed the control policies proposed for unreliable manufacturing systems with variate emitting levels. In this vein, Ben-Salem et al., (2015a) developed an environmental hedging point policy (EHPP) under which there is a reduction in the inventory threshold level after exceeding a voluntary emission limit to reduce the generated emissions while minimize total costs. Afshar-Bakeshloo et al., (2018) extended the EHPP model developed by Ben-Salem et al., (2015a) for high and low-emitting production modes. Accordingly, when total emissions level goes over the voluntary emissions limit, the production system stops the high-emitting machine (HEM) and continues to produce with low-emitting machine (LEM) to reduce the generated GHG emissions. In their policy, it is considered that the LEM's threshold level is less than that for the HEM. As an extension of the policy developed by Afshar-Bakeshloo et al., (2018), Entezaminia et al., (2020) proposed a policy for the systems in which LEM and HEM are not operating simultaneously (PNOS). According to their policy, the LEM's threshold level constraint has been relaxed in order to present a more realistic policy. Indeed, the PNOS policy already outperforms the previous policy in terms of optimal cost and emissions reduction.

To make a comparative study, we adapted the EHPP presented by Ben-Salem et al., (2015a) to our system under study. EHPP-coal stands for the EHPP under which the system consumes only coal, and EHPP-NG stands for the EHPP under which the system uses only NG. Moreover, the PNOS policy developed by Entezaminia et al., (2020) is adapted to our system with multiple fuels (PNOS-MF). MF stands for multiple fuels. Under PNOS-MF, if the machine operates using coal, it is considered as HEM and when the machine operates using NG, it is considered as LEM. In the next subsection, a comparison is made between our proposed control policies and adaption of policies from the literature (EHPP-coal, EHPP-NG, PNOS-MF).

5.8.1 Comparison of policies for the base case

To compare our proposed production control policies (policy 1 and 2) with policies adapted from the literature (EHPP-coal and EHPP-NG, PNOS-MF), the optimal values of control factors and total costs are obtained utilising Steps 3 and 4 of our resolution approach. The base case data in Table 5.2 is utilised to get the optimization solutions shown in Tables 5.5 and 5.6.

Table 5.5 Optimal costs for the considered control policies

Factor / Policy	Z_C^{1*} (Product Unit)	Z_C^{2*} (Product Unit)	${Z_{NG}}^*$ (Product Unit)	${Z_1}^*$ (Product Unit)	${Z_2}^*$ (Product Unit)	Y^* (tCO2e)	σ^*
Policy-1	321.28	-	253.63	-	-	285,373	0.82
Policy-2	294.50	274.12	257.81	-	-	319,448	0.79
EHPP-NG	-	-	-	172.64	155.49	482,624	-
EHPP-coal	-	-	-	349.23	288.73	225.073	-
PNOS-MF	-	-	-	285.45	240.98	345.279	-

Table 5.6 Optimal values of control factors for the considered control policies

Policy	Inventory Cost* ($/Time Unit)	Backlog Cost* ($/Time Unit)	Fuel Cost* ($/Time Unit)	Emission Cost* ($/Time Unit)	Optimal Total Cost* ($/Time Unit)	Carbon Emissions* (tCO2e/Time Unit)
Policy-1	594.76	812.28	732.64	1,892.40	4,032.08	189.29
Policy-2	513.25	975.59	678.41	1,521.08	3,688.33	175.40
EHPP-NG	465.68	778.35	3,590.43	1,176.14	6,010.60	121.68
EHPP-coal	1,047.33	2,576.41	460.22	3,525.66	7,609.62	285.15
PNOS-MF	615.12	1,046.62	1,650.65	2,045.68	5,358.07	246.07

Under EHPP-NG and EHPP-coal, it is considered that the system produces using only one fuel type, either NG or coal (under Ben-Salem's EHPP policy). Based on the results, under EHPP-NG where only NG (cleaner fuel type) is consumed, the system generates less emissions than the system under EHPP-coal. This resulted in lower GHG emissions cost under EHPP-NG compared with EHPP-coal. Also, higher available production capacity under EHPP-NG leads to less inventory and backlog costs compared to EHPP-coal. However, when it comes to fuel cost, EHPP-NG brings a considerable expense to the system than EHPP-coal because the higher NG price.

Based on the results, our proposed policies outperform PNOS-MF which is the policy adapted from the literature for systems with variant emitting levels, in respect of emissions and optimal total cost. Under PNOS-MF the system is able to consume either NG or coal. Emissions and inventory level are taken into consideration to decide on the system's production plan. When the emission reaches the voluntary emission limit, the system stops using coal and produces using NG. There is no consideration of fluctuating NG price. Under our proposed policies, NG price, emissions, and inventory level should be jointly considered to decide on production plan and fuel switching. So, considering the fluctuation of NG price under our proposed policies, NG would not be consumed at any price. This leads to considerable reduction in fuel cost.

Better synchronization of fuel types, results in lower generated GHG emissions under our proposed policies. Providing more available production capacity under our proposed policies resulted in lower inventory and backlog costs.

Compared with proposed control policy 1, proposed policy 2 is more cost effective and environmentally friendly by setting a lower inventory threshold level for coal, when emissions exceed its voluntary limit. This results in less usage of coal at its maximum rate leading to less emissions and fuel costs of the system. Reduction in safety stock brings less inventory cost and more backlog cost. However, the excess backlog cost is offset by reductions in inventory, emission, and fuel costs, leading to a total cost reduction.

All in all, according to the results, proposed policy 2 resulted in significant cost saving and emissions reduction as compared to proposed policy 1 and existing policies adapted from the literature. To summarise, we believe that proposed control policy 2 is the best cost-effective and environmentally beneficial policy for the system under consideration. To confirm this, comparisons for a wide variety of cost and system parameters are made, as shown in the following subsection.

5.8.2 Comparison between control policies for a wide range of cost and system parameters

A comparative study is undertaken as indicated in Figure 5.6 for a wide range of cost and system parameters to confirm the superiority of our proposed control policy 2 in terms of optimal total costs and emissions reduction. Under the policies, the influence of cost parameters (inventory cost, emission cost, coal price and standard deviation (SD) of NG price) and system parameters (system availability, and emission index) on total costs and GHG emissions is determined. Figure 5.6 shows the optimal total cost as a solid line and the emissions as a dashed line, for each policy. Obviously, the system under EHPP-NG results in the lowest emission as only the cleaner fuel type is used. So, when our proposed policies are compared with existing policies in terms of emissions, EHPP-NG is excluded.

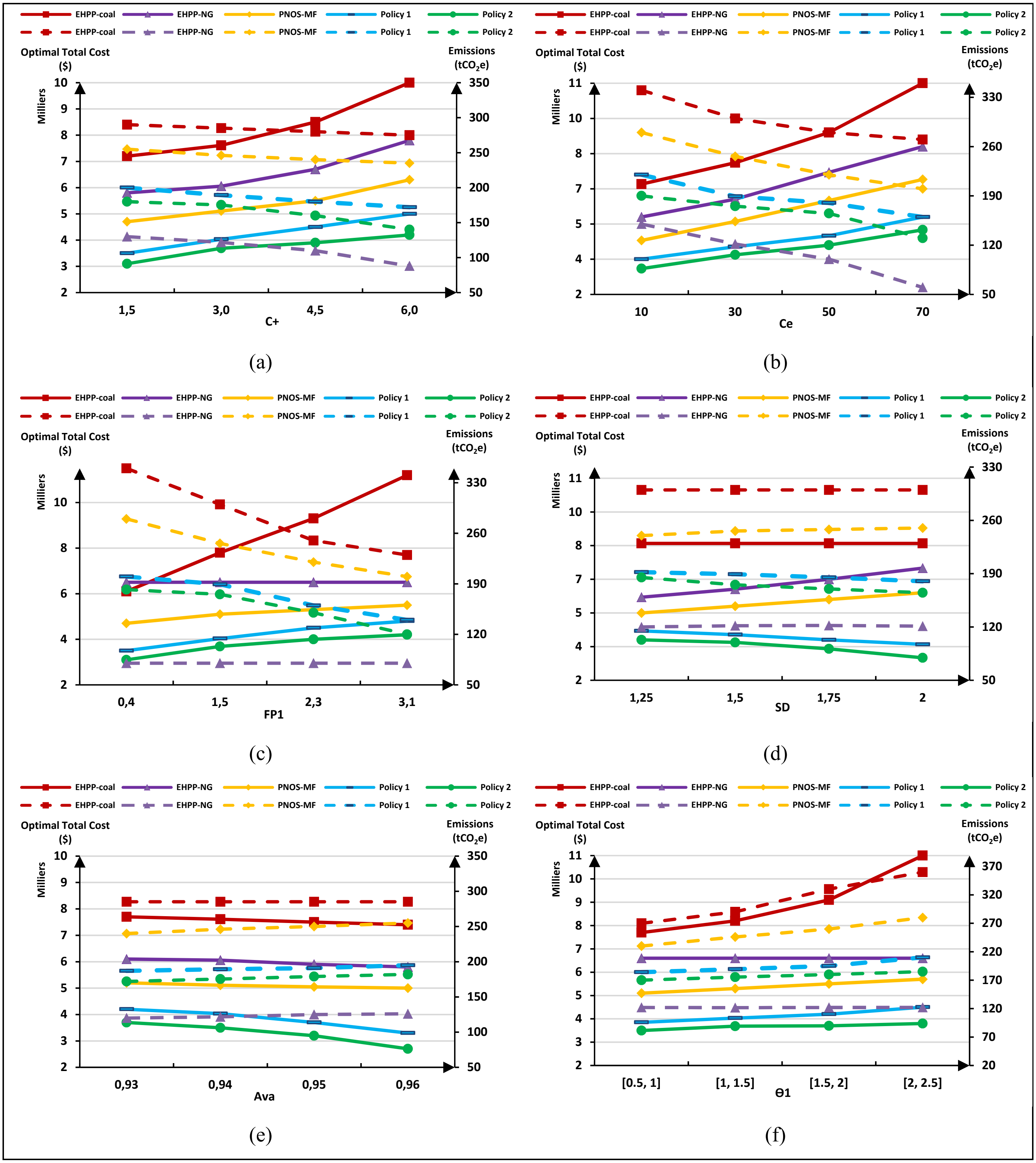

Figure 5.6 The impact of parameters on optimal total costs and emissions of studied policies

In Figure 5.6 (a), when C^+ increases, the gap between the optimal total cost and generated emissions under proposed policies and existing policies grows. This is because under our proposed policies, an effective switching between fuel types leads to more available production capacity (lower inventory cost) compared with existing policies. By reducing the inventory threshold level of coal under our proposed policy 2, when inventory cost (C^+) rises, the gap between proposed policy 1 and 2 grows in respect of optimal total costs as well as emissions. Because the system under our proposed policies leads to a considerable emissions reduction, when emissions cost (C^e) rises, there is an increasing gap between the proposed and existing policies regarding emissions and optimal total costs. As can be seen in Figure 5.6 (b), for a wide range of emission cost, proposed policy 2 becomes more advantageous than existing policies from the literature as well as proposed policy 1. Because under proposed policy 2, less usage of coal at maximum production rate considerably decreases the generated GHG emissions.

As shown in Figure 5.6 (c), our proposed policies lead to a high emission reduction and cost saving compared to existing policies for a wide range of coal price. Indeed, the principal advantage of manufacturing using coal is its lowest production cost than NG. So, by increasing the coal price, using coal is disadvantageous compared to NG. Consequently, by rising the coal price, EHPP-NG brings more advantage of cost and emissions reduction for the system than EHPP-coal. However, as depicted in Figure 5.6 (c), for a very low price of coal, the total cost of the system when using only coal would be less than that of when using only NG.

As the system under existing policies decides on production and fuel switching based on emissions and inventory level regardless of the NG price, increasing the fluctuation of NG price results in more production using NG at inappropriate prices. Our proposed policies bring advantage of considering NG price jointly with emissions and inventory level. This results in a bigger difference between proposed and existing policies in terms of optimal total costs and carbon emissions, when standard deviation (SD) rises in Figure 5.6 (d).

As depicted in Figure 5.6 (e), by providing more available production capacity under our proposed policies, the gap between the proposed and existing policies grows regarding optimal total costs and emissions, for a wide range of system availability. Moreover, when there is an increase in emission index of coal (θ_1), higher utilization of coal is disadvantageous. So, when θ_1 increases, there is a great difference between EHPP-coal and EHPP-NG regarding the optimal total costs and emissions. In this regard, our proposed policies are more advantageous than existing ones by providing the best synchronization of fuel types. Less usage of coal at its maximum rate under proposed policy 2 brings more benefits in terms of emissions and cost savings than proposed policy 1, when θ_1 rises (Figure 5.6 (f)).

5.9 Managerial insight and practical implementation

In this study, we focus on the challenges of high-emitting companies that take advantage of switching to a cleaner fuel (but more expensive) to reduce their GHG emissions. Indeed, the manager needs to make a trade-off between environmental and economic objectives to decide when the system should switch between high-emitting and low-emitting fuels, and at which rate it should produce using each fuel type. In this vein, simultaneous consideration of varying NG price and key elements of the system including its state, inventory, and emissions level under our control policy 2 could reduce optimal total costs as well as GHG emissions generated by the system.

Figure 5.7 represents the implementation chart of our proposed control policy 2 for the base case data. Accordingly, first, the level of GHG emissions, NG fuel price and inventory need to be monitored by the manager. When the emission level is lower than 319,448 tCO2e, and NG price is not low enough (not less than 6.21 $/Gj) to switch, the system produces using coal. If the inventory is less than the threshold level of coal (294 units), the system should produce at the maximum rate of 120. When the inventory reaches 294 units, the system produces at the rate of demand (100). If the inventory goes above 294 units, the system stops the production. If the NG price is low enough, the manager decides to switch from coal to NG. If the inventory is less than threshold level associated to NG (257 units), the system should produce at the maximum rate of 130. After reaching its threshold level (130), the system produces at the demand rate. If the inventory goes over 275 units, the system stops producing.

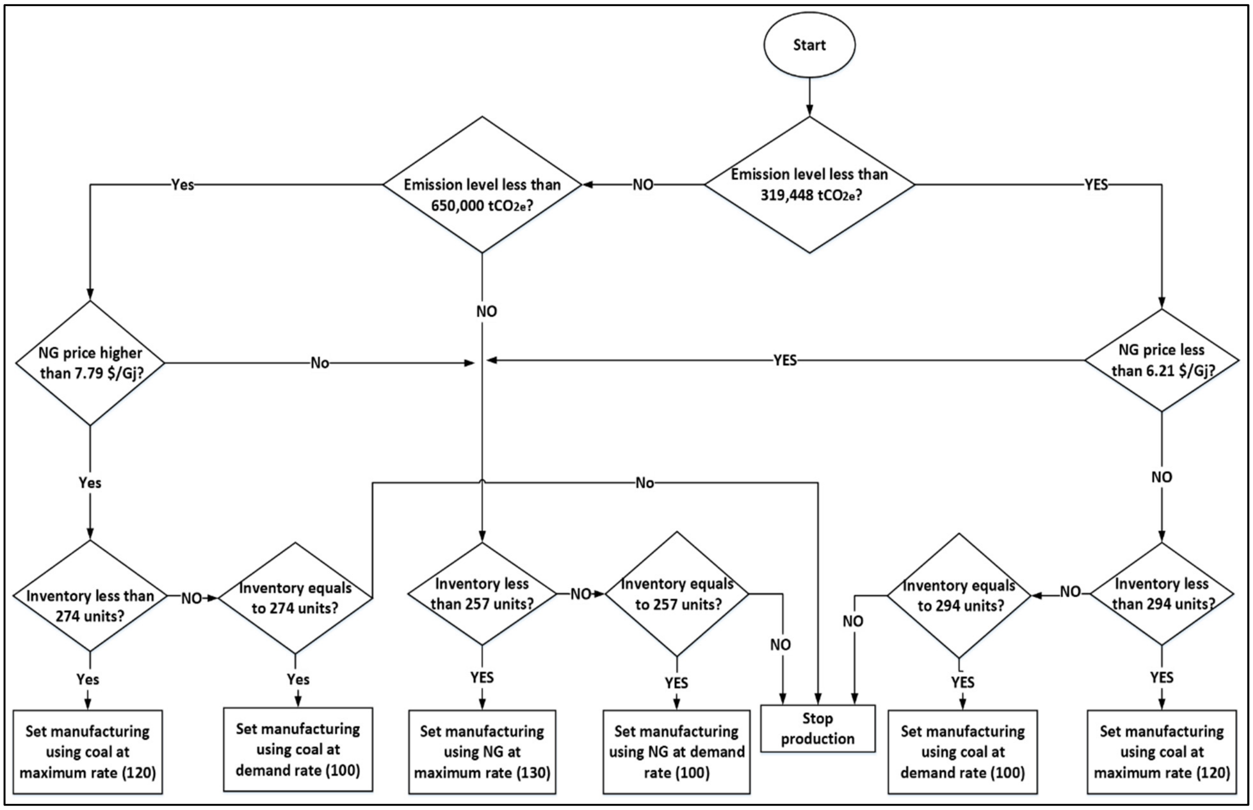

Figure 5.7 Implementation logic chart for our proposed control policy 2

When the emission is more than 319,448 tCO2e but still less than the emissions limit announced by the government (650,000 tCO2e), the system should produce using NG. If the price of NG is considerably high (higher than 7.79 \$/Gj), the system should produce using coal but with a lower inventory threshold level (274 units). If the inventory level is lower than 274 units, the system should produce at the maximum rate of 120. When the safety stock is built, the system produces at the demand rate (100). If the inventory is more than 247 units, the production is stopped.

If the GHG emissions exceed the limit announced by the government (650,000 tCO_2e), the manager stops consumption of coal and continues to produce using cleaner fuel type, NG to reduce emissions.

5.10 Conclusion

Currently various businesses are under pressure to minimise their hazardous GHG emissions because of government-enacted environmental laws and regulations. Switching to cleaner energy sources is an effective emission reduction approach for high-emitting companies. In this research, we address the production planning of high-emitting unreliable manufacturing systems that tend to reduce their emissions by switching to cleaner fuels (e.g., natural gas (NG)). Although producing with a cleaner source of energy reduces carbon footprints, it does so at the expense of increased fuel costs. In the context of our research, the random fluctuation of NG price along with the key element of the system (its state, inventory, and emissions level) is taken into account. We aim to develop production control policies integrated with fuel switching for manufacturing systems under carbon tax regulation to minimize total costs while reducing GHG emissions.

By simultaneous consideration of system state, emissions, and inventory level as well as varying NG price, our proposed policies assist the manager to decide when to switch between fuel types and determine the production rate. Our proposed control policy 1 cut emissions while minimizing the system's total cost, which includes inventory, backlog, fuel, and emissions costs. We also developed proposed control policy 2 as an extension of policy 1, under which a lower threshold level for coal production is considered when emissions level exceeds a voluntary limit. This results in a greater reduction in emissions. Simulation, design of experiment, and response surface methodology are used to determine the optimal value of control factors for each policy. For a wide variety of cost and system parameters, we compared our proposed policies to existing policies presented for unreliable manufacturing systems with varying emissions levels. According to the results, in respect of optimal total costs and GHG emissions reduction, our proposed policy 2 excels the policies derived from the literature.

Finally, our proposed policy 2 is the most cost-effective and environmentally friendly policy for failure-prone manufacturing systems which consume both high- and low- emitting fuels subject to carbon tax regulation.

One of our study's limitations is that it only looked at one machine one product systems. Future research on our findings should focus on more complicated production systems with several products and machines. Another drawback is that the machine's emission rate is assumed to be linear regardless of degradation. According to degradation phenomena, as a machine's age increases, its availability reduces and its emission rate rises, though not necessarily in a linear way. To create more realistic emission models, future research should consider degradation processes and non-linearity of emission rate. Future research can cover both preventive and corrective maintenance in industrial systems, as a progressive degradation occurs owing to a lack of preventive maintenance efforts. Moreover, the energy sources like NG are not always available in the market. Further research into inventory control of the energy sources in the context of production planning combined with fuel switching would be of interest.

CONCLUSION

Over the past century, greenhouse gas (GHG) emissions have increased dramatically, resulting in catastrophic effects such as global warming and climate change. In order to control the carbon footprints, authorities imposed several environmental rules and regulations on industrial sectors such as carbon tax and cap-and-trade. As a result, firms are willing to find strategies to reduce GHG emissions while achieving economic goals. In this context, the integration of the environmental aspect into the control and management of unreliable manufacturing systems has attracted our attention. Indeed, a detailed review of the relevant literature has showed that most of the studies dealt with this kind of problems ignored the stochastic and dynamic context of manufacturing systems. However, due to unpredictable events in manufacturing systems such as random failure and repair times, they have a dynamic behaviour in practice. In this thesis, our objective is to develop production control policies for failure-prone manufacturing systems looking at environmental aspects from multiple perspectives (low-emitting technologies, carbon trading, reverse logistics).

In the first article presented in Chapter 2, we addressed the problem of production planning for unreliable manufacturing companies that employ high-emitting machines (HEM) and decide to gradually invest in low-emitting machines (LEM) rather than replacing all equipment at once in order to reduce GHG emissions. An environmental hedging point policy was recently proposed, in which the system stops using the HEM once the emission limit is surpassed and solely uses the LEM after that. First, we proposed a control policy that relaxes the unrealistic constrict on LEM threshold level which considered in the previous work. We also developed two new control policies which allow the system to produce with both HEM and LEM at the same time. We aimed to increase the LEM utilisation and system's availability while lowering inventory, emission, and backlog costs. Using simulation, experimental technique and response surface methodology, we obtained the optimal values of control parameters. Based on the results, our new proposed policies provided considerable cost savings and GHG emission reduction, for a variety of cost and system parameters. The outcomes of this study support the companies that are ready to invest in innovative low-emitting technologies and gradually replace HEMs with LEMs.

In the second article presented in Chapter 3, we investigated the production and trading problem of unreliable manufacturing systems regulated by cap-and-trade. As carbon prices fluctuate randomly in the market, determining the production rate and trading amount to take full advantage of the carbon market is difficult for such companies. Our goal was to propose a new joint production and trading policy for failure-prone manufacturing systems under cap-and-trade to reduce total costs such as emissions, backlog, inventory, trading, and transaction costs. Under our proposed policy, the decision-maker can jointly decide on the production rate and trading carbon allowances based on the inventory level, allowance level, and carbon price. This policy assists the manager in determining when production rate should be increased or lowered, as well as when allowances should be sold or purchased in the carbon market. To ensure that our proposed policy outperforms existing policies, we run a sensitivity analysis that shows how control parameters change as a function of cost and system parameters. When compared to previous policies, designing our policy to buy at low prices and sell at high prices resulted in a significant reduction in transaction costs, an increase in trading profit, and, as a result, a reduction in the optimal overall cost and carbon emissions. More allowance selling under our proposed policies reduced the system's allowances and puts more pressure on manufacturers to produce less at maximum rate, resulting in fewer inventories and emissions. Overall, our developed policy is the most environmentally friendly and cost-effective control policy for cap-and-trade regulation, lowering the optimal overall cost and resulting in fewer carbon emissions than existing policies.

In third article in chapter 4, high diversity in return quality is considered as a serious issue for many businesses, making remanufacturing production planning complicated and difficult. We focused on the production planning problem of failure-prone manufacturing/remanufacturing systems using high- and low-quality returns under carbon tax. The impact of return quality on GHG emissions produced by manufacturing/remanufacturing processes is also considered. One of the most difficult decisions for such systems is determining the condition and percentage of time the system should produce with manufacture or remanufacturing in order to fulfill customer demand. Two new production control policies are developed in this study to assist managers in synchronising manufacturing using raw material and remanufacturing using high- and low-quality returns to achieve both environmental and economic goals. We obtained the optimal value of control parameters using an experimental resolution approach. A comparison is made between our proposed policies and the existing production policies developed for the failure-prone manufacturing/remanufacturing systems, for a wide range of cost and system parameters. Based on the results, our proposed policies bring high advantage of optimal costs and GHG emissions reduction as compared with existing polices in the literature.

In fourth paper in Chapter 5, we dealt with unreliable manufacturing systems which consume high-emitting fuels (e.g., coal) and tend to reduce their generated emissions by switching to low-emitting fuels (e.g., natural gas (NG)). Although production using a cleaner fuel reduces GHG emissions, it does so at the expense of more fuel cost. The random fluctuation of NG price is also considered in our research. We aimed to develop joint production control and fuel switching policies for such systems under carbon tax regulation to minimize total costs while reducing emissions. In this regard, we developed two production control policies under which decisions on fuel switching depends on the random fluctuation of NG price, as well as the key elements of the system including its state, inventory, and emissions level. Our proposed control policy 1 reduces emissions while minimizing the system's total cost including inventory, backlog, fuel, and emission costs. We also developed our proposed control policy 2 under which a lower threshold level for coal production is set when emissions exceed a voluntary limit. This leads to a greater reduction in emissions. Simulation, design of experiment, and response surface methodology are used to determine the optimal value of control factors for each policy. According to the results, in respect of optimal total costs and GHG emissions reduction, our proposed policy 2 excels the proposed policy 1 and the policies derived from the literature, for a wide variety of cost and system parameters.

All in all, the research carried out in this thesis allowed us to achieve our objectives and make original scientific contributions to studies on the production control planning of unreliable systems considering environmental aspects. Our developed control policies better respond to the concerns of production managers by considering certain key elements that reflect the manufacturing reality (for example, random failure and repair times, and the variability in the quality of returns) and environmental aspects (like low-emitting technologies, carbon trading, and quality impact of returns on generated emissions). Finally, within the framework of this thesis, we were able to write four journal articles as presented in Chapter 2, Chapter 3, Chapter 4 and Chapter 5.

FUTURE WORKS

Our policy has some limitations that, in turn, provide directions for future research. One of the limitations is that the machine's emission rate is assumed to be linear regardless of degradation. According to degradation phenomena, as a machine's age increases, its availability reduces and its emission rate rises, though not necessarily in a linear fashion.

Future research may cover both preventive and corrective maintenance in industrial systems, as a gradual degradation occurs owing to a lack of preventive maintenance efforts. To reduce total costs and emissions, an appropriate preventive maintenance plan can be developed.

Moreover, the other limitation of our study on production and trading problem of unreliable manufacturing systems is to consider one machine and one product type system. Future studies on our research should deal with more complex manufacturing systems consisting of multi-products and multi-machines. On the other hand, the impact of environmental regulations (carbon tax and cap-and-trade) and their flexibility on capital decisions like purchasing low-emitting machines can be taken into account in future studies.

Furthermore, when it comes to closed-loop supply chains, in this research, two types of returns are assumed to be always available; however, because returned products are not always available in the market, the rate of return can be described as a random variable in future studies. Future research could take into account the probability of returns, remanufacturability, and disposal choices. Moreover, in this study a market of used products is considered with two sources for both high-quality and low-quality returns. But the future study could address systems with quality-based categorization of returns in which the quality grades can be considered as decision variables.

Moreover, owing to the fact that the energy sources like NG are not always available in the market, further research into inventory control of the energy sources in the context of production planning combined with fuel switching would be of interest.

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