Contrôle et planification de la production intégrant la reconfiguration dynamique des installations dans un contexte de logistique inverse

par

Morad ASSID

THÈSE PAR ARTICLES PRÉSENTÉE À L'ÉCOLE DE TECHNOLOGIE SUPÉRIEURE COMME EXIGENCE PARTIELLE À L'OBTENTION DU DOCTORAT EN GÉNIE
Ph. D.

MONTRÉAL, LE 06 JANVIER 2021

ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
UNIVERSITÉ DU QUÉBEC

PRÉSENTATION DU JURY

CETTE THÈSE A ÉTÉ ÉVALUÉE

PAR UN JURY COMPOSÉ DE :

M. Ali Gharbi, directeur de thèse
Département de génie des systèmes à l'École de technologie supérieure

M. Adnène Hajji, codirecteur de thèse
Département d'opérations et systèmes de décision à l'Université Laval

M. Jean-Pierre Kenné, président du jury
Département de génie mécanique à l'École de technologie supérieure

M. Mustapha Ouhimmou, membre du jury
Département de génie des systèmes à l'École de technologie supérieure

M. Claver Diallo, examinateur externe
Département de génie industriel à l'Université Dalhousie

ELLE A FAIT L'OBJET D'UNE SOUTENANCE DEVANT JURY ET PUBLIC

LE 17 DÉCEMBRE 2020

À L'ÉCOLE DE TECHNOLOGIE SUPÉRIEURE

REMERCIEMENTS

J’adresse tout d’abord mes plus vifs remerciements à mon directeur de recherche, Dr Ali Gharbi, pour sa disponibilité, sa confiance, son encadrement de haute qualité, et son soutien le long de ces années. J’ai beaucoup appris de lui.

Je désire également adresser ma profonde gratitude à mon codirecteur, Dr Adnène Hajji, pour son assistance continue aux idées discutées, ses précieux conseils, son encouragement et son support financier m’ont permis de mener à bien cette thèse.

Je tiens à remercier Dr Jean-Pierre Kenné qui m’a fait l’honneur de présider le jury. Je remercie également les professeurs Mustapha Ouhimmou et Claver Diallo d’avoir accepté d’examiner et de juger ma thèse de doctorat.

Mes remerciements vont aussi aux anciens et présents membres de l’équipe du Laboratoire de Conception et Contrôle des Systèmes de Production (LC2SP) de l’École de Technologie Supérieure pour leur gentillesse et la belle ambiance de travail.

Enfin, à ma famille, vont mes sincères remerciements pour leurs irremplaçables et inconditionnels soutiens et leurs supports moraux.

Contrôle et planification de la production intégrant la reconfiguration dynamique des installations dans un contexte de logistique inverse

Morad ASSID

RÉSUMÉ

Cette thèse traite de la planification et du contrôle de la production pour les systèmes hybrides de fabrication-refabrication utilisant à la fois de la matière première et des produits d'occasion récupérés dans un environnement dynamique et stochastique. Un tel système apporte une plus grande complexité managériale par rapport aux systèmes de fabrication traditionnels, en particulier avec la présence d'événements aléatoires, souvent négligés dans la littérature, tels que la panne des installations de production et les problèmes de de délai, de quantité et de qualité dans l'approvisionnement de matières premières et de retours. Ce projet de recherche est motivé par de multiples rapports soulignant la nécessité de développer des politiques de commande intégrées qui offrent un contrôle efficace de cette classe de systèmes. Les contributions de cette thèse sont présentées en quatre phases.

La première phase traite le problème de planification et de contrôle de la production pour les systèmes hybrides non fiables composés d'installations séparées qui consacrent chaque processus de production (fabrication ou refabrication) à une installation distincte. Des éléments clés de cette classe de système comme l'approvisionnement en matières premières et en retours, l'option de rejet des retours et la dynamique et le dimensionnement des stocks sont considérés. Une approche combinant une revue critique des travaux existants de la littérature et une technique d'optimisation basée sur la simulation est appliquée pour déterminer une structure efficiente des politiques de commande et optimiser leurs paramètres en matière de coûts.

La deuxième phase étend le travail précédent pour les systèmes hybrides non fiables constitués d'installations communes qui partagent les activités de fabrication et de refabrication. Dans ce contexte, le rôle des opérations de setup pour passer d'un mode de fabrication au mode de refabrication et vice versa devient crucial. La même approche que celle adoptée dans la première phase a été appliquée pour établir une meilleure structure des politiques de commande en matière de coûts comparativement à celles trouvées dans la littérature. Une analyse de notre système a été également effectuée pour fournir une meilleure compréhension de l'influence du setup sur sa performance.

La troisième phase s'inscrit dans la continuité des deux travaux précédents en considérant des systèmes hybrides non fiables avec une combinaison d'installations séparées et communes. Un modèle stochastique dynamique est proposé. Les conditions d'optimalité développées sont résolues numériquement pour déterminer la structure des politiques de commande optimisant conjointement les taux de production des installations de fabrication et de refabrication et le processus de prise de décision de setup en matière de coûts.

La quatrième phase intègre la variabilité de la qualité des retours dans le problème de planification et de contrôle de la production pour les systèmes hybrides de fabrication-refabrication non fiables. Le système considéré est composé d'installations de production séparées et communes. Les deux sont capables de produire une proportion de produits finis non conformes aux exigences des clients. Cette proportion dépend de la qualité de la matière première et de la catégorie de retours utilisés dans le processus de production. Deux catégories des retours sont considérées et sont classées selon leur temps de refabrication et la proportion des unités défectueuses. Un modèle d'optimisation stochastique a été développé en tenant compte des décisions de fabrication, de refabrication et de setup qui est nécessaire pour changer le mode de production et la catégorie de retours adoptés. Une approche de résolution combinant des méthodes numériques, la simulation et des analyses statistiques a été par la suite utilisée pour déterminer la structure optimale des politiques de commande intégrées et optimiser leurs paramètres en matière de coûts.

Les travaux de cette thèse apportent des solutions à une classe de problème de planification et de contrôle de la production des systèmes hybrides de fabrication-refabrication. Ils développent des structures efficientes des politiques de commande de production et offrent une meilleure compréhension du comportement des systèmes hybrides non fiables. Des exemples numériques et des analyses de sensibilité approfondies sont effectués à titre d'illustration afin de valider les structures des politiques de commandes obtenues. De plus, cette thèse emploie une approche de résolution qui répond mieux aux préoccupations des gestionnaires de production en permettant de contrôler efficacement de tels systèmes complexes.

Mots-clés : planification de la production, politique de commande, systèmes de production, refabrication, mise en course, simulation, optimisation.

Production planning and control integrating the dynamic reconfiguration of installations in a context of reverse logistics

Morad ASSID

ABSTRACT

The current thesis addresses the production planning and control problem within unreliable hybrid manufacturing-remanufacturing systems that use both raw materials and returned products in the production process. Such a system brings greater managerial complexity as compared to traditional manufacturing systems especially with the presence of random events, which are often neglected in literature. These include the breakdown of production facilities, the supply of both raw materials and returns in terms of time, quantity and quality. This research project is motivated by multiple related reports from real cases underscoring the need for efficient control policies that are practical for real-life unreliable hybrid systems. The contributions of this thesis are presented in four phases.

The first phase addresses the production planning and control problem for unreliable hybrid systems composed of dedicated facilities, which dedicate each production process (manufacturing or remanufacturing) to a separate facility. The important issue of integrating some key elements such as the supply of both raw materials and returns, the disposal option of returns and the stock dynamics is considered. A resolution approach combining a critical review of literature and a simulation-based optimization technique is applied in order to determine an efficient structure of control policies and to optimize their parameters in terms of costs.

The second phase extends the previous work by considering unreliable hybrid systems where both manufacturing and remanufacturing operations are performed in a shared facility. In this context, the role of setup operations to switch from a manufacturing mode to a remanufacturing mode and vice versa becomes crucial. The same resolution approach is adopted to develop a better structure of control policies in terms of costs compared to those found in the literature and to provide a better understanding of the influence of setup on this class of systems.

The third phase is an extension of the two previous works considering unreliable hybrid manufacturing-remanufacturing systems composed of mixed dedicated and shared facilities. A dynamic stochastic model is proposed, and the optimality conditions developed are solved numerically to determine the structure of control policies, which jointly optimize the manufacturing and remanufacturing rates and the decision-making process of setup in terms of costs.

The fourth phase integrates the variability of returned products quality into production planning and control problem within unreliable hybrid manufacturing-remanufacturing systems. The considered system is composed of mixed dedicated and shared facilities, which are able to produce a proportion of non-conforming products. This proportion depends on the quality of both raw materials and returns used in the production process. Two categories of

returns are considered and are classified according to the time required to remanufacture them as well as the proportion of defective units. A stochastic optimization model is developed considering the manufacturing, remanufacturing and setup decisions that are necessary to change the production mode and the category of returns is use. A resolution approach combining numerical methods, simulation and statistical analysis are then adopted to determine the optimal structure of the integrated control policies and optimize their parameters in terms of costs.

This thesis provides solutions to a class of the production planning and control problem within hybrid manufacturing-remanufacturing systems. It develops efficient structures for production control policies and contributes to a better understanding of the behavior of hybrid systems evolving on a dynamic and stochastic environment. Numerical examples and in-depth sensitivity analysis are carried out as illustration in order to validate the structures obtained of integrated control policies. In addition, this thesis applies a global resolution approach, which is better aligned with the concerns of production managers and offers a powerful technique to effectively control such complex systems.

Keywords: production planning, control policy, production systems, remanufacturing, setup, simulation, optimization.

TABLE DES MATIÈRES

Page

LISTE DES TABLEAUX

Page

LISTE DES FIGURES

Page

INTRODUCTION

Les entreprises industrielles sont en quête continue d'efficience pour surmonter les difficultés liées à la dynamique des marchés et l'évolution de l'environnement socioéconomique. Sur la base de ces facteurs, tout comme le sentiment d'urgence environnementale par la société, la logistique inverse a fait l'objet de plusieurs contributions scientifiques et d'initiatives pratiques au cours des deux dernières décennies (Govindan, Soleimani, & Kannan, 2015). Du point de vue gouvernemental, les actions visent à résoudre les problèmes environnementaux (par exemple, réduire les déchets, réduire les émissions polluantes, utiliser des ressources environnementales renouvelables, substitution de ressources non renouvelables), mais touchent principalement la mise en place de nouvelles législations afin de dynamiser le secteur manufacturier et d'accroitre la productivité des entreprises. Ces législations comprennent, à titre d'exemple, la responsabilité élargie des producteurs quant aux produits à la fin de leur cycle de vie en incitant les entreprises à investir dans la logistique inverse. Parmi les solutions de traitement de ces produits récupérés, l'option de refabrication (en anglais, *Remanufacturing*) ne nécessite que 15 à 20% de l'énergie utilisée pour les ramener, ou leurs principaux composants, à un état tout aussi bons que les nouveaux produits (Lund & Hauser, 2003). Il s'agit d'un modèle économique de développement durable, car il génère des revenus de la vente des produits refabriqués et prolonge leur cycle de vie. Représentant une partie considérable de l'ensemble des activités de la logistique inverse dans la pratique, la refabrication est largement utilisée pour différents produits industriels tels que les appareils de reprographie, les ordinateurs, les moteurs de véhicules ou les équipements médicaux (Rogers & Tibben-lembke, 2001).

À mesure que la refabrication devient de plus en plus courante, les entreprises peuvent opérer simultanément deux processus de production pour la fabrication de produits nouveaux et refabrication des produits récupérés. De tels systèmes, appelés systèmes hybrides de fabrication-refabrication, sont devenus un sujet d'intérêt considérable dans l'industrie manufacturière avancée, en partie en raison des profits et des économies de coûts liés à la réutilisation d'unités récupérées dans les produits finaux. Toutefois, toutes les entreprises opérant dans un tel environnement sont confrontées à des problèmes uniques de planification et de contrôle de la production (PCP) qui est un important domaine de recherche, notamment liés à la productivité, à la gestion de stock et à l'utilisation des ressources. En fait, les activités de PCP sont assez différentes dans les systèmes hybrides de fabrication-refabrication que dans les systèmes où il n'y a que des opérations de fabrication. Cela est dû à la présence d'un flux de retour (flux inverse) des produits récupérés le long de certaines phases du processus de production, qui s'ajoute au flux conventionnel (flux direct).

De nombreuses questions se posent à propos de la complexité des problèmes de PCP au sein des systèmes hybrides de fabrication-refabrication où la matière première et les produits récupérés peuvent simultanément servir d'intrant dans les processus de fabrication et de refabrication, respectivement, pour satisfaire la demande du marché. Dans un monde de plus en plus compétitif, cette question est bien légitime puisque les entreprises doivent s'adapter aux multiples variations de leurs conditions d'exploitation et maîtriser leur système pour assurer leurs pérennités. Ces tâches passent en particulier, par la considération simultanée de tous les éléments du système, allant de l'approvisionnement en matières premières et produits récupérés jusqu'à la dynamique du stock des produits finis, en passant par les aléas de fonctionnement comme les pannes des installations de production. Or, cela a un prix, un niveau important d'accroissement de la complexité. En effet, en comparaison avec un système de production sans logistique inverse, le contrôle simultané de la fabrication et de la refabrication est rendu plus complexe par une incertitude plus large affectant le flux des retours (produits récupérés) en matière de quantité, de qualité et de temps d'acquisition. De plus, les processus de fabrication et de refabrication nécessitent une coordination continue en matière de quantités d'approvisionnement et de délais de traitement surtout si les ressources de production communes sont partagées (par exemple, un espace de stockage commun, une demande agrégée des produits nouveaux et refabriqués, une installation de production ou une main-d'œuvre commune). Malgré les travaux récents dans le domaine de PCP pour les systèmes hybrides de fabrication-refabrication non fiables, plusieurs questions de recherche restent ouvertes pour trouver des politiques et des stratégies de production efficaces et pourquoi pas optimales. De plus, le besoin d'une méthodologie efficace de résolution et d'optimisation dans ce contexte nous semble primordiale en vue d'une applicabilité industrielle.

Une autre question importante qui se pose est de savoir s’il faut conduire les opérations de fabrication et de refabrication dans des installations communes et partagées ou s’il faut consacrer chaque processus de production à une installation séparée et distincte. Les pratiques actuelles ont tendance à utiliser une configuration de système à deux installations séparées pour effectuer des opérations de fabrication et de refabrication lorsqu'un volume élevé de retours est assuré (R. Teunter, Kaparis, & Tang, 2008). Dans le même sens, un volume limité de retours peut conduire à une sous-utilisation majeure de l'installation de refabrication, impliquant une inefficacité considérable. D'un autre côté, l’utilisation d’une installation capable de soutenir à la fois les activités de fabrication et de refabrication en cas de besoin semble être la meilleure solution sur la base de nombreux travaux. Cependant, dans une telle situation, les opérations de setup (la mise en course) pour basculer entre les modes de fabrication et de refabrication pourraient être coûteuses et complexes à gérer, à cause notamment des activités de préparation et de planification des opérations des installations de production. En conséquence, une circonstance favorable pour notre recherche est d’examiner comment les entreprises pourraient bénéficier des avantages de chaque configuration de système en considérant des paramètres mixtes composés d'installations de production séparées avec des ressources (partiellement) communes.

En réponse à la nécessité de doter les gestionnaires de production de meilleurs outils pour contrôler efficacement les systèmes hybrides de fabrication-refabrication qui évoluent dans un contexte dynamique et stochastique, cette thèse vise à développer de nouvelles structures de politiques de commande intégrant simultanément la fabrication et la refabrication pour différentes configurations de système: des installations de production séparées, des installations communes ou une combinaison des deux. D’autres fonctions primordiales seront également intégrées dans de telles structures afin de mieux représenter la réalité industrielle. Parmi lesquelles figure la politique de rejet des retours qui est souvent appliquée lorsqu'ils ne satisfont pas les exigences de qualité pour la refabrication ou pour éviter des quantités de stock très élevées, donc très coûteuses. De même, la politique de setup sera considérée sous deux angles différents en déterminant la meilleure séquence pour basculer entre les modes de fabrication et de refabrication ainsi que pour définir quel type de retours devra être traité à quel moment, lorsque ces derniers sont classés selon leur niveau de qualité.

L'approche proposée vise non seulement à développer des processus décisionnels de gestion pour les systèmes hybrides de fabrication-refabrication, mais aussi à minimiser leurs coûts d'exploitation. Dans ce sens, cette thèse devra mettre en application une approche globale de modélisation et d'optimisation basée sur des méthodes numériques, de la simulation et des analyses statistiques. Cette approche, mieux adaptée aux préoccupations des gestionnaires de production, offre une technique puissante pour modéliser et prendre en considération la dynamique complexe de tels systèmes tout en surmontant les problèmes liés à la résolution des modèles analytiques. Des analyses de sensibilité seront également effectuées pour valider les résultats obtenus en montrant la robustesse des solutions proposées d'après plusieurs paramètres clés du système.

Le prochain chapitre présente la problématique de recherche de cette thèse, une revue critique de littérature relative à notre domaine d'étude, la méthodologie adoptée et les principales contributions de notre travail.

CHAPITRE 1

PROBLÉMATIQUE ET REVUE DE LITTÉRATURE

1.1 Introduction

Ce chapitre décrit, en premier lieu, la problématique de recherche de cette thèse. En deuxième lieu, nous présentons une revue critique de littérature qui porte sur le problème d'intégration du contrôle de la fabrication (en anglais, *Manufacturing*) et de la refabrication (en anglais, *Remanufacturing*) au sein des systèmes hybrides non fiables. En troisième lieu, nous résumons la méthodologie privilégiée pour réaliser notre travail. En dernier lieu, nous présentons les principales contributions ainsi que la structure de cette thèse.

1.2 Problématique de recherche

De nombreux chercheurs et praticiens ont et continuent d'aborder le sujet important de planification et de contrôle de production (PCP) pour les systèmes hybrides intégrant simultanément les processus de fabrication et de refabrication. Toutefois, les travaux existants dans la littérature continuent de négliger plusieurs éléments clés composant les systèmes hybrides de fabrication-refabrication. Par conséquent, les modèles résultants restent incomplets et traitent souvent les aspects de PCP séparément à cause de la complexité du processus de prise de décision au sein de ces systèmes. En fait, le développement d'un modèle qui considère conjointement ces aspects constitue un défi majeur pour les chercheurs afin de mieux répondre aux préoccupations des gestionnaires de production et à la réalité industrielle. Parmi ces aspects figurent ceux qui feront l'objet de notre travail :

- la dynamique des installations de production;
- la dynamique des stocks des matières premières, des retours (produits récupérés) et des produits finis;
- la dynamique des interactions entre les éléments du système (par exemple, fabrication, refabrication, setup, rejet des retours, l'approvisionnement des matières premières et des retours);

- l’incertitude caractérisant le délai, la quantité et la qualité des retours;
- la configuration du système (séparer les activités de fabrication et de refabrication sur des installations distinctes, les partager sur une installation commune ou combiner les deux options).

La contribution de cette thèse doit être considérée sous cet angle de vue. Toutefois, pour mieux expliquer notre problème de PCP des systèmes hybrides de fabrication-refabrication, nous nous attardons d’abord sur la signification de certains principes utilisés dans ce domaine.

1.2.1 Intégration de la refabrication dans le processus de production

En plus de l’aspect environnemental, l’attention croissante envers les activités de la logistique inverse, et plus particulièrement la refabrication est expliquée par les avantages économiques attendus de la réutilisation des produits d’occasion plutôt que de les éliminer. La refabrication peut apporter des gains directs aux entreprises par la réduction de la quantité utilisée des matières premières, la revalorisation des retours (produits récupérés ou ses composants) ainsi que la diminution des coûts d’élimination qui ont considérablement augmenté ces dernières années à cause de l'épuisement des capacités d'incinération et de l'enfouissement (Parsopoulos, Konstantaras, & Skouri, 2015). Selon (Lund & Hauser, 2003), il existe trois stratégies différentes qui caractérisent souvent le fonctionnement d’une entreprise industrielle œuvrant dans le domaine de la logistique inverse. La refabrication des retours peut être conduite par le fabricant d'équipement d'origine (FEO) (en anglais, *Original Equipment Manufacturer*) sur la même ligne hybride de fabrication-refabrication que les nouveaux produits. En général, le FEO mène aussi les opérations de distribution et vend ses produits finis aux détaillants ou aux consommateurs. La deuxième stratégie concerne les entreprises de refabrication indépendantes qui peuvent récupérer, refabriquer (en anglais, *Remanufacture*) et vendre les produits refabriqués directement aux clients finaux. Finalement, le FEO peut déléguer l’activité de refabrication à une entreprise contractuelle qui acheminera les produits refabriqués aux entrepôts du FEO ou les redistribuera directement.

Plusieurs travaux ont étudié les systèmes hybrides de fabrication-refabrication. Parmi les activités critiques liées au processus de refabrication, Fleischmann et al. (1997) ont identifié la gestion de stock et la planification de la production. Dans ce sens, Van der Laan & Teunter (2006) expliquent que pour un FEO ou une entreprise contractuelle, la coordination entre la refabrication et la fabrication est primordiale, que ce soit sur le niveau du processus de production ou celui d’assemblage. Cela engendre certes des complexités supplémentaires pour la planification et le contrôle de la production. Guide Jr. (2000) spécifie sept caractéristiques de complication qui ont été proposés dans diverses formes par des chercheurs. Ces caractéristiques sont:

- la nécessité d'équilibrer les retours avec la demande des clients;
- le désassemblage des produits retournés;
- la nature aléatoire du temps d’acquisition et de la quantité des retours;
- l'incertitude dans les matériaux récupérés à partir des produits retournés;
- les exigences d'un réseau de la logistique inverse (la manière dont les produits d’occasion sont collectés et acheminés à une installation de production);
- la complication des restrictions de la correspondance matérielle;
- les problèmes d’acheminements stochastiques des matériaux utilisés dans les opérations de refabrication qui sont très variables.

Dans le même contexte, Xie, Zhao, Kong, & Chen (2007) relient les caractéristiques de complication aux nombreux aspects stochastiques qui caractérisent le processus de production. Parmi lesquels ceux liés à:

- désassemblage des retours et de leurs composants, en rappelant que parfois cette opération ne peut être effectuée à cause de la qualité médiocre de certains produits récupérés;
- taux de refabrication qui dépend directement de l’état du produit récupéré (par exemple, possibles fissures internes, déformation de la surface, non-respect des tolérances);
- la qualité des produits finis;
- la demande des clients;
- la dynamique et la dégradation des installations de production;
- les interventions de maintenance, etc.

En résumé, la refabrication peut impliquer différents niveaux de coordination par rapport aux activités de fabrication. Cela impose des contraintes supplémentaires sur les acteurs potentiels impliqués dans la planification et le contrôle de la production.

1.2.2 Structure du système étudié

Le système hybride de fabrication-refabrication auquel nous nous intéressons représente un problème commun dans de nombreuses industries (par exemple, l'automobile, l'aéronautique, l'électronique, le textile, etc.). Il représente le cas de FEOs qui acheminent les produits récupérés vers leurs installations de refabrication. Ces dernières sont intégrées au processus global de production, formant ainsi ce que l'on appelle un réseau de logistique inverse ou chaîne logistique en boucle fermée.

Le système étudié tel que décrit par la Figure 1.1 se compose de deux installations de production capables de produire un seul type de produits finis. L'installation de fabrication F_1 est alimentée uniquement par la matière première, tandis que l'installation F_2 peut fonctionner selon deux modes de production différents : le mode de fabrication qui utilise la matière première (comme F_1) et le mode refabrication qui est alimenté par les retours. Ce scénario est souvent rencontré chez de nombreux FEOs qui ne refabriquent que leurs propres marques parce que les retours sont limités par rapport à la quantité de produits finis vendus. En plus d'être sujettes à des pannes et des réparations aléatoires en temps continu, les activités de production des deux installations F_1 et F_2 dépendent de la disponibilité de la matière première et des retours en stocks. Au total, trois espaces de stockage sont considérés. Le premier est consacré à la matière première qui sera utilisée en mode de fabrication, tandis que le second est réservé aux retours afin d'alimenter le processus de refabrication en amont. La possibilité de rejeter certains produits récupérés est aussi envisagée afin de gérer le flux de retours. Cela signifie que ces unités éliminées ne seront plus acheminées vers F_2, mais des frais d'élimination sont ainsi engendrés. Finalement, le troisième espace de stockage est consacré aux produits finis qui seront accessibles pour être livrés aux clients. Cependant, il peut également contenir des produits finis non conformes aux normes de qualité exigées par les clients. Cette situation survient lorsque les processus de fabrication ou de refabrication utilisent des unités défectueuses de matières premières ou de retours respectivement.

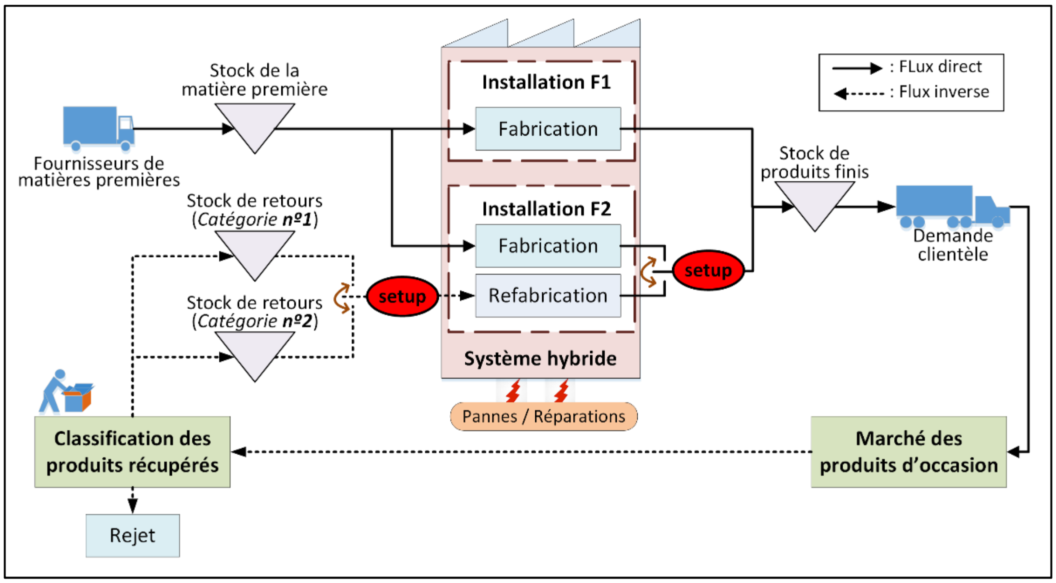

Figure 1.1 Structure du système hybride de fabrication-refabrication étudié

Les retours sont aussi définis par leur niveau de qualité puisqu'en pratique, ils sont collectés auprès de différentes sources d'approvisionnement (par exemple, retours de clients et de location, rejets par les clients en fin d'utilisation, produits endommagés). Pour gérer cette variabilité, une classification des retours est considérée afin de leur attribuer le niveau de qualité correspondant. Deux catégories ainsi adoptées pour classer les retours : la catégorie nº1 qui contient des retours de meilleure qualité avec une proportion d'unités défectueuses faible comparativement à la catégorie nº2 de moindre qualité ayant une proportion d'unités défectueuses plus élevée. Cette différence dans les conditions de qualité des retours, qui s'ajoute à la différence entre les processus de fabrication et de refabrication, implique des délais, et donc des coûts de production variables, car ils n'ont pas besoin des mêmes actions de traitement (Korugan, Dingeç, Önen, & Ateş, 2013). Cela signifie que l'installation F_2 peut fonctionner en mode de fabrication ou en mode de refabrication selon la catégorie de retours sélectionnés. Par conséquent, les opérations de setup deviennent incontournables pour passer d’un mode de production à un autre et lors du changement de la catégorie des retours utilisée. En même temps, elles représentent une préoccupation majeure en raison des coûts et des délais associés.

La prise en compte des différents composants du système étudié, en particulier pour la planification et le contrôle de la production, pourrait entraîner des économies importantes. Cependant, la solution doit répondre à plusieurs contraintes liées à la dynamique et à la faisabilité du système. Il s’agit d’un problème très complexe tant en ce qui touche la nature aléatoire des événements qui caractérisent les différents éléments du système que la dynamique des interactions de ces derniers. De toute évidence, des défis majeurs restent à relever pour savoir comment planifier conjointement les activités de fabrication, de refabrication, de setup, d’approvisionnement en matières premières et de rejet des retours dans un environnement dynamique et stochastique en vue de satisfaire le client tout en minimisant les coûts.

1.2.3 Hypothèses de travail

Certaines hypothèses de modélisation sont considérées, sans perdre de généralité, dans les chapitres suivants, à savoir :

- le système hybride de fabrication-refabrication est mono-produit;
- la demande des clients est connue;
- la demande des clients non satisfaite n’est pas perdue;
- les produits fabriqués et refabriqués sont identiques en matière de qualité;
- les fournisseurs de la matière première et des retours sont toujours disponibles;
- le taux maximal de production de chaque installation est connu et dépend du mode de production et de la catégorie (basée sur le niveau de qualité) des retours;
- la détection de panne des installations de production est instantanée et les interventions de réparations sont immédiatement lancées;
- les temps de panne et de réparations des installations sont aléatoires et suivent des distributions connues a priori;

- les temps de setup de l'installation F_2 pour changer le mode de production et la catégorie de retours utilisée dans la refabrication sont constants;
- le processus de production est parfait. Cela signifie que la production d’un produit fini défectueux est seulement due à la mauvaise qualité de la matière première ou le produit récupéré utilisé;
- les clients peuvent détecter les produits finis défectueux et imposent automatiquement des pénalités;
- le coût et le délai de la classification des retours basée sur la qualité sont négligeables;
- la politique de rejet des retours n'est pas liée à leur niveau de qualité et tous les produits récupérés peuvent être refabriqués;
- les coûts unitaires de fabrication, de refabrication, de stockage, de pénurie, de setup, de commande de la matière première, de rejet des retours, de vente de produits finis défectueux sont connus.

1.2.4 Objectifs de la recherche

En reconnaissance du rôle essentiel de la gestion intégrée des opérations dans l’amélioration des performances des entreprises industrielles, cette thèse a pour objectif principal de développer de nouvelles politiques de commande de production adaptatives pour les systèmes hybrides de fabrication-refabrication non fiables. Dans cette optique, plusieurs facteurs et phénomènes ont été identifiés comme pertinents et une attention particulière a été accordée à la minimisation du coût total. Ainsi, la considération simultanée de la fabrication, de la refabrication, du setup, de l’approvisionnement en matières premières et du rejet des retours permet de répondre à de multiples rapports soulignant la nécessité de politiques de commande intégrées qui offrent un contrôle efficace de cette classe de systèmes et une possibilité d’ajustement approprié pour faire face aux changements dans leur environnement. Plus précisément, cette thèse vise les sous-objectifs suivants :

- étendre les contributions précédentes dans le domaine de PCP des systèmes hybrides de fabrication-refabrication non fiables afin d’intégrer l’approvisionnement en matières premières et le flux des retours, tout en mettant l'accent sur l’amélioration de la performance économique de ces systèmes. Cela implique l'étude des interactions impliquant les activités de fabrication, de refabrication, d'approvisionnement et d'élimination. Le but est de montrer que les politiques de commande à développer peuvent être implantées dans la pratique.

- établir des politiques de commande de production dans le but de gérer efficacement les produits récupérés et les stocks pour différentes configurations de systèmes compte tenu de la combinaison de ses installations de production (installations communes partageant les activités de fabrication et de refabrication, installations séparées ou une combinaison des deux);
- montrer l'importance des informations issues de la classification des produits retournés en matière de qualité suivant des catégories ainsi que l'utilité de prendre en compte ces dernières dans l'élaboration de la structure des politiques de commande de production;
- appliquer des techniques basées sur la simulation afin de valider les résultats des modèles de PCP développés ainsi que de montrer l'efficacité et l'utilité des politiques de commande obtenues. Cet objectif comporte l'analyse de la performance économique des systèmes hybrides soumis aux différentes politiques de commande étudiées.

1.3 Revue critique de la littérature

Cette section présente une analyse critique de la littérature scientifique traitant les sujets relatifs à la problématique de recherche de cette thèse. Il s'agit des travaux qui portent sur :

- l'option de refabrication;
- les systèmes hybrides de fabrication et de refabrication;
- la planification et le contrôle de la fabrication et de la refabrication.

1.3.1 Option de refabrication

La refabrication est connue sous diverses appellations. La réfection, la remise à neuf, le retraitement, le reconditionnement et le réusinage sont également des termes fréquemment utilisés. Il est généralement admis que la refabrication est écologiquement efficace (V.D.R. Guide Jr., 2000). Elle représente une forme supérieure de réutilisation des produits d'occasion en mettant l'accent sur la récupération d'une partie de leur valeur. Cette valeur peut se composer de matière, d'énergie et de connaissances emmagasinées dans le produit durant son processus d'élaboration et de fabrication. De plus en plus, la refabrication devient le terme standard pour le processus de restauration des produits d'occasion à des conditions comme neuf (Lund, 1984 ; Naeem, Dias, Tibrewal, Chang, & Tiwari, 2013). Elle se distingue des autres processus de récupération (par exemple, la réutilisation directe, la réparation et le recyclage) par son intégralité: un produit refabriqué devrait correspondre aux mêmes attentes d'un client que pour un nouveau produit (King, Burgess, Ijomah, & Mcmahon, 2006 ; Thierry, Salomon, Nunen, & Wassenhove, 1995).

Les avantages de la refabrication vont dans le même sens que les intérêts de la société et les gouvernements au sujet de la disponibilité limitée des ressources naturelles, l'augmentation des niveaux de pollution, l'incinération des déchets, etc. Son importance est qu'elle permettrait aux fabricants de répondre à la pression environnementale en leur permettant de respecter la législation sur les déchets tout en maintenant une productivité élevée pour des produits de haute qualité et à moindre coût. Dans un contexte plus global, Ilgin et Gupta (2010) présentent une revue exhaustive sur la production écologique et la récupération des produits d'occasion (incluant la refabrication) ainsi qu'une discussion sur la conception des réseaux d'une chaîne logistique environnementale. Ils indiquent que le domaine de la production écologique permet de développer des méthodes pour la fabrication de nouveaux produits qui seraient faciles à refabriquer dans le futur d'une manière écologiquement appropriée. Les meilleures pratiques appellent à l'intégration de la gestion environnementale avec les opérations de production et de refabrication. Ce n'est pas seulement une question d'être respectueux de l'environnement; mais c'est aussi d'être raisonnable sur le plan des affaires et des profits les plus élevés (Srivastava, 2007). En effet, la refabrication fournit des incitations économiques aux entreprises en vendant les produits refabriqués et en prolongeant le cycle de vie des produits. En conséquence, elle est devenue une pratique répandue dans plusieurs industries comme l'automobile, l'électronique, l'informatique, etc. (Padmanabhan & Png, 1995)

1.3.1.1 Processus de refabrication

Lund (1984) définit la refabrication comme un processus industriel destiné à récupérer la valeur des produits d'occasion et à les restaurer dans un état comme neuf en remplaçant des composants ou en retraitant des composants d'occasion. Dans la pratique, Parkinson and Thompson (2003) expliquent que les opérations typiques d'un système de refabrication sont : le désassemblage, le tri, le nettoyage, l'inspection, le reconditionnement, le réassemblage et le test final. Ils rappellent également que les procédures d'inspection et de réassemblage ainsi que le contrôle final de la qualité des produits refabriqués sont aussi rigoureux que ceux employés dans la production des nouveaux produits. En effet, après l'opération de désassemblage du produit retourné, ses composantes sont largement inspectées et ceux qui ne sont pas conformes aux critères de qualité ou posent un certain problème sont réparés ou, si ce n'est pas possible, remplacés par de nouvelles composantes. Un exemple typique des unités refabriquées est les unités de rechange et les composants entrant dans l'assemblage des (E. A. Van der Laan & Teunter, 2006 ; E. Van Der Laan & Salomon, 1997). Plusieurs études de cas industriels traitant la refabrication comme celles des entreprises Fuji-Film, Kodack et Fuji-Xerox qui produisent des caméras et des photocopieurs, ont été décrites et comparées dans (Matsumoto & Umeda, 2011). La littérature inclut également des exemples de produits industriels où aucune distinction n'est faite entre les produits refabriqués et les nouveaux produits comme les appareils photo à usage unique (Toktay, Wein, & Zenios, 2000), les palettes et les conteneurs (Kelle & Silver, 1989), les moteurs de voiture (Driesch, van Oyen, & Flapper, 2005) et les ordinateurs (Fleischmann et al., 1997). D'autres exemples incluent les composants à haute valeur ajoutée tels que les moteurs et les équipements d'avions, les équipements médicaux, les mobiliers de bureau, les machines-outils, les photocopieurs, les équipements électroniques, les cartouches d'imprimantes et les téléphones cellulaires (Guide, Jayaraman, & Srivastava, 1999 ; Thierry et al., 1995). Dans ces secteurs, les unités refabriquées peuvent être de la même qualité et avoir la même garantie que les nouvelles, mais coûtent la moitié du coût de fabrication des nouvelles. Pourtant, les deux types sont vendus pour le même prix. En effet, le processus de refabrication des produits d'occasion est généralement moins coûteux que la fabrication d'une toute nouvelle unité, car leurs composants peuvent être réutilisés, évitant ainsi d'avoir à fabriquer ou à se procurer de nouveaux composants auprès de fournisseurs (Ferguson, 2010). Cependant, la grande variabilité des opérations de refabrication et l'incertitude relative aux produits d'occasion rendent le problème de planification et de contrôle des activités de la production plus complexe que dans l'industrie manufacturière traditionnelle (G. P. Kiesmüller, 2003b). Par conséquent, une meilleure compréhension du comportement de systèmes hybrides de fabrication-refabrication évoluant dans un environnent incertain est requise.

1.3.1.2 Gestion des opérations de la refabrication

La refabrication est un processus industriel impliquant la gestion du flux inverse des produits d'occasion; provenant du consommateur en direction du fabricant, pour les remettre dans leur état fonctionnel initial (comme neuf) (Ilgin & Gupta, 2010). Les produits refabriqués ont généralement des délais plus courts que la production de nouveaux produits. Cependant, la grande variabilité des opérations de refabrication complique l'utilisation des techniques traditionnelles de planification et de contrôle de la production. C'est la raison pour laquelle les chercheurs ont développé de nouvelles approches pour faire face à diverses questions de gestion des opérations de refabrication. Parmi lesquelles :

- la prévision : la prévision exacte des retours des produits d'occasion est une contribution importante pour l'analyse des systèmes de refabrication. Cependant, l'incertitude concernant la quantité et le moment de livraison de ces retours rend l'utilisation de méthodes de prévision traditionnelles impossible (Marx-Gómez, Rautenstrauch, Nürnberger, & Kruse, 2002). Ainsi, un certain nombre de chercheurs se sont penchés sur le développement de méthodes de prévision plus efficace afin de prédire les retours de produits (Tsiliyannis, 2018).
- la planification de la production : les approches traitant la planification de la production pour les systèmes de fabrication et de refabrication ont pour but d'aider les gestionnaires à répondre aux besoins du genre : combien et quand désassembler, combien et quand refabriquer, combien produire ou commander de nouveaux matériaux, et coordonner le désassemblage et le réassemblage (Guide et al., 1999).

- l’ordonnancement de la production : la raison principale pour laquelle de nouvelles méthodologies d’ordonnancement orientées pour la refabrication sont développées est la grande incertitude et la complexité des systèmes de production (Ilgin & Gupta, 2010). Dans la plupart des travaux traitant les méthodologies d’ordonnancement de la production pour des systèmes incluant des activités de refabrication, la technique la plus couramment utilisée est la simulation à événements discrets. Cette technique vise à tester les performances des différentes méthodologies.
- la planification des capacités : la planification des capacités vise à projeter en avant les besoins en ressources comme la main-d’œuvre, la machinerie, l'espace de stockage et la capacité des fournisseurs. Par exemple, elle permet de comparer la capacité disponible dans les centres importants de travail ou les goulets d'étranglement critiques par rapport aux besoins requis (C. Fang et al., 2017 ; Lee, Doh, & Lee, 2015).
- la gestion de stock : la gestion de stock est l'un des domaines clés de prise de décisions pour les systèmes de production dont les retours des produits d’occasion sont considérés comme une source d'approvisionnement pour produire des produits finis et ainsi satisfaire les clients. Deux principales complexités sont rencontrées lors de la considération simultanée des retours des produits d’occasion et les options de refabrication dans les approches classiques de gestion de stock. La première est associée à l’incertitude relative aux retours, tandis que la deuxième représente la coordination entre la refabrication et leur mode d’acquisition (Inderfurth & Van Der Laan, 2001). Guide et al. (1999) expliquent qu’une grande partie des modèles de gestion de stock développés dans la littérature pour faire face à ces complexités est basée sur la modélisation de différentes approches pour la demande clientèle et les retours. D’autres modèles étudient l’effet de la variation du niveau des stocks et du délai de livraison des retours en se basant sur les coûts et la valorisation comme critères de comparaison. En général, une gestion efficace des stocks peut être un problème clé non seulement pour les producteurs industriels, mais également pour l'ensemble de la chaîne de distribution, y compris les distributeurs et les détaillants. En effet, la gestion de stock des retours dans les activités de refabrication nécessite une vue plus complète du comportement des stocks en matière de délai, de quantité, de qualité.

- l’effet des incertitudes : Le degré élevé d’incertitude dans le temps de traitement des opérations de production est l’un des problèmes associés à la refabrication. Dans la pratique vient s'ajouter l'effet dissuasif de l'incertitude par rapport à la quantité, la qualité et le moment de réception des retours. Plusieurs travaux présentant des modèles de prise de décision pour étudier l’impact de ce niveau élevé d'incertitude sur le comportement des systèmes hybrides de production et de refabrication peuvent être trouvés dans (Ilgin & Gupta, 2010 ; Mukhopadhyay & Ma, 2009 ; C.-H. Yang, Ma, & Talluri, 2019).

Dans les lignes qui suivent, nous nous intéressons aux systèmes hybrides de fabrication-refabrication qui sont devenus un sujet important dans l'industrie manufacturière, en bonne partie grâce aux profits et aux économies réalisées par l’intégration des opérations de refabrication le long de certaines phases du processus conventionnel de fabrication.

1.3.2 Systèmes hybrides de fabrication et de refabrication

Aujourd'hui, un nombre croissant d'entreprises de production dans presque tous les grands secteurs industriels perçoivent la valeur commerciale potentielle de la mise en œuvre du processus de refabrication dans leur système existant (Geyer, Van Wassenhove, & Atasu, 2007). Les systèmes de production qui en résultent sont connus sous le nom de systèmes hybrides de fabrication-refabrication (en anglais, *Hybrid Manufacturing-Remanufacturing Systems*) et sont devenus un sujet important dans l'industrie manufacturière (Esmaeilian, Behdad, & Wang, 2016). Ces systèmes hybrides se caractérisent par l’utilisation à la fois des matières premières et des retours (les produits d’occasion récupérés) qui servent d’intrant dans leurs processus de production pour générer simultanément des produits nouveaux et refabriqués. Ces produits finis sont généralement transportés vers un espace de stockage avant d’être livrés aux clients pour satisfaire leur demande. Quelques exemples industriels adoptant cette classe de système de production sont ceux qui produisent des produits de grande valeur tels que des ordinateurs, des pièces automobiles, des équipements aéronautiques et militaires, des instruments médicaux, des téléphones portables, des pneus et des cartouches d'encre (Ferguson & Toktay, 2006). Les systèmes hybrides de fabrication-refabrication ont reçu une attention considérable dans la littérature au cours des deux dernières décennies en raison de leur caractère important (voir par exemple (Souza, 2013 ; E. Van Der Laan, Salomon, Dekker, & Wassenhove, 1999)). L'étude de Tang et Teunter (2006) fournit un bon exemple d'application concrète de ces systèmes hybrides. Elle concerne une entreprise qui fabrique et refabrique des pièces automobiles et dont les travailleurs se heurtent à une grande variété de produits: moteurs diesel, moteurs à essence, pompes à eau, culasses, etc. Un autre exemple sur l'application d'un système hybride se trouve dans (S. X. Zhou, Tao, & Chao, 2011) qui considérait une entreprise qui fournit des services sur les compteurs et les transformateurs pour les maisons privées et les bâtiments commerciaux.

Les systèmes hybrides de fabrication-refabrication sont plus difficiles à contrôler que les systèmes de fabrication traditionnels en raison de nombreux facteurs (Ahiska, Gocer, & King, 2017). Premièrement, le flux de retour des produits récupérés en matière de délai, de quantité et de qualité est incertain. Deuxièmement, les processus de fabrication et de refabrication peuvent être interdépendants surtout s’ils partagent des ressources de production communes (par exemple, des espaces de stockage, des installations de production ou d’une main-d’œuvre commune). Cela engendre des complexités supplémentaires pour la gestion de stock ainsi que la planification et le contrôle de la production pour l'ensemble du système hybride. De plus, pour un contrôle efficace du système hybride, la coordination entre les processus de fabrication et de refabrication est essentielle de telle manière que les décisions de fabrication et de refabrication doivent être prises ensemble afin de répondre à la demande des clients et de maximiser le profit total.

Une autre question importante est celle de la configuration des systèmes hybrides de fabrication-refabrication. Debo, Toktay, et Van Wassenhove (2006) expliquent que lors de la conception de ces systèmes, différents choix qui dépendent de contraintes de personnel et de technologie peuvent être disponibles concernant l'intégration des activités de fabrication et de refabrication. Il s’agit de savoir s'il faut effectuer les opérations de fabrication et de refabrication dans des installations de production communes ou consacrer chaque processus de production à une installation (moins coûteuse) distincte et séparée (Aras, Verter, & Boyaci, 2006).

1.3.2.1 Installations de production séparées

Les pratiques actuelles ont tendance à utiliser deux installations séparées pour effectuer des opérations de fabrication et de refabrication. Utiliser des installations de fabrication et de refabrication séparées capables de soutenir respectivement les activités de fabrication et refabrication semble être la solution la plus logique. En effet, la refabrication implique de nombreux processus tels que le désassemblage, l'inspection, le nettoyage et de nombreux autres processus mécaniques et métallurgiques qui ne font pas partie du processus de fabrication normal. Par conséquent, il n'est pas possible d'intégrer les opérations de fabrication et de refabrication tant qu'il n'y a pas de standardisation des processus. Cela est confirmé par l'entreprise Caterpillar qui est un fabricant mondial de matériel de construction et d'exploitation minière (Mitra, 2016). Dans la pratique, l'utilisation d'installations de production séparées est également fréquente lorsqu'un volume élevé des produits récupérés est assuré (R. Teunter et al., 2008). C'est le cas de l'entreprise Michelin qui refabrique les pneus d'occasion sur un système de production différent des pneus neufs (Debo et al., 2006). Cette situation est due principalement au fait qu'un flux de produits retournés incertain et limité peut engendrer une sous-utilisation majeure de l'installation de refabrication séparée, conduisant à une inefficacité marquante.

Une grande attention a été concentrée dans la littérature pour cette classe des systèmes hybrides où les opérations de fabrication et de refabrication sont consacrées à des installations distinctes. Parmi les auteurs qui ont traité cette catégorie, Van Der Laan et Salomon (1997) ont étendu les politiques bien connues de commande de la production « Push » et « Pull » pour une meilleure coordination des opérations de fabrication, de refabrication et de rejet. Ils ont montré que des réductions de coûts peuvent être obtenues au moyen de rejet, qui se produisent lorsque les stocks de systèmes deviennent trop élevés. Dobos (2003) a développé une politique optimale de production et de gestion de stock qui minimise le coût total pour les systèmes hybrides avec rejets. Teunter et al. (2008) se sont basés sur étude de cas portant sur une entreprise qui refabrique des pièces automobiles pour le marché des services et envisage de mettre en place une ligne de refabrication distincte. Ils ont montré que l'adoption de lignes de production séparées peut conduire à des réductions significatives des coûts de stockage et à une meilleure flexibilité de planification des activités de production. Feng, Zhang et Tang (2013) ont considéré un système de récupération des produits périssables avec des contraintes de capacité pour les processus de fabrication et de refabrication. Kenné, Dejax et Gharbi (2012) ont utilisé la méthodologie de la programmation dynamique stochastique pour développer une politique de commande optimale de la fabrication et de la refabrication, qui minimise la somme des coûts d'inventaire et pénurie. Kouedeu, Kenné, Dejax, Victor et Polotski (2015) ont utilisé une approche similaire pour développer un modèle d'optimisation stochastique qui est appliqué dans une étude de cas réel d'une entreprise européenne produisant des cartouches d'encre pour les imprimantes. Liao, Deng et Wang (2017) ont calculé l'effet des incertitudes dans l'approvisionnement et la demande sur le profit net d'une usine de refabrication de moteurs automobiles et ont fourni des lignes directrices utiles pour une coordination efficace des activités de fabrication et de refabrication. Fang, Lai et Huang (2017) ont utilisé cinq scénarios basés sur la demande du marché et la capacité de production pour trouver la stratégie d'exploitation optimale maximisant le profit total pour un système hybride avec une relation de substitution entre les produits nouveaux et refabriqués. Ouaret, Kenné et Gharbi (2018) ont développé un modèle d'optimisation stochastique de planification de la production et du remplacement un système hybride non fiable qui se détériore avec le temps. Ils ont montré que la politique de commande optimale de la production et du remplacement est de type seuil critique. Ainsi, les décisions de production et de remplacement des installations de production sont essentiellement influencées par la dynamique des stocks et l'âge de ces installations.

1.3.2.2 Installations de production communes

De l'autre côté, l'utilisation d'une installation commune capable de soutenir à la fois les activités de fabrication et de refabrication en cas de besoin semble être la meilleure solution sur la base de nombreuses études. Ainsi, il est préférable de mener ces opérations sur des installations communes dans des situations de faible taux des retours comme ils le sont généralement au début de leur cycle de vie (R. Teunter et al., 2008). Thierry et al. (1995) ont montré que cette configuration permet de réduire significativement les coûts de démarrage pour la refabrication pour un système de refabrication dans l'industrie de l’impression. L'utilisation de la même installation pour les deux processus de production pourrait être également plus avantageuse pour la configuration, surtout si tous les produits sont vendus sur le même marché (Francas & Minner, 2009) ou lorsque les processus de production sont similaires, sauf pour la source des matériaux (Bulmuş, Zhu, & Teunter, 2013). C’est le cas de Hewlett Packard qui refabrique des serveurs haut de gamme sur la même ligne de production que les nouveaux serveurs. Cependant, même en cas de standardisation (partielle ou totale) des processus de fabrication et de refabrication, la décision de conduire les opérations de fabrication / refabrication dans les mêmes installations dépendrait de nombreux facteurs tels que les coûts d'exploitation fixes, les économies d'échelle, les emplacements et les demandes du marché, la disponibilité des produits récupérés, les coûts de livraison, les politiques et réglementations gouvernementales en matière de refabrication et de vente de produits refabriqués, etc. (Mitra, 2016). Ainsi, il peut ne pas être toujours avantageux d’utiliser des installations communes chaque fois qu'il y a une standardisation des processus de fabrication et de refabrication. Parmi les principales difficultés rencontrées pour contrôler les systèmes hybrides composés d’installations communes figurent les opérations de setup qui sont nécessaires pour basculer entre le mode de fabrication (produire en utilisant la matière première) et celui de refabrication (produire en utilisant les retours). Ces opérations pourraient être coûteuses et complexes à gérer, ce qui exige un degré élevé de coordination. De plus, même si les coûts de refabrication sont faibles, le système peut avoir besoin d’un volume relativement élevé de produits d’occasion, ce qui implique des coûts de stockage élevés.

Dans la littérature, les systèmes hybrides de fabrication-refabrication composés d'installations communes qui utilisent des stratégies de setup demeurent faiblement explorés. Parmi les travaux de cette catégorie, Teunter, Bayindir et Van Den Heuvel (2006) ont abordé le problème de dimensionnement des lots intégrant les coûts de setup qui est fonction à la fois de l’utilisation de nouveaux matériaux et de changement du plan de travail. Tang et Teunter

(2006) ont traité le problème de l'ordonnancement économique en se basant sur une étude de cas concernant une entreprise qui fabrique et refabrique plusieurs types de pièces automobiles. Teunter, Tang et Kaparis (2009) ont étendu les résultats du dernier en proposant des heuristiques simples qui sont très rapides et peuvent être appliquées dans un tableur informatique. Francas et Minner (2009) ont étudié le problème de conception de réseaux impliquant les systèmes hybrides de fabrication-refabrication produisant plusieurs types de produits finis. Ils ont examiné la planification des capacités des installations et les avantages de plusieurs configurations de réseau pour la refabrication. Les auteurs ont conclu qu'il est plus avantageux en matière de profits de configurer un seul site de production flexible si tous les produits finis sont destinés au même marché. Flapper, Gayon et Lim (2014) ont étudié le problème d’ordonnancement optimal de la production pour les systèmes hybrides de fabrication-refabrication en utilisant une approche basée sur la théorie des files d'attente. Polotski, Kenné et Gharbi (2017) ont développé un modèle de commande optimale pour les systèmes hybrides à faible taux de retour en intégrant la dynamique du système. Ils ont ainsi proposé une structure générale de politique de commande optimale qui combine les activités de production et de setup. Turki, Sauvey et Rezg (2018) ont étudié le problème de planification conjointe de la fabrication, de la refabrication et du stockage conformément aux contraintes industrielles relatives aux réglementations sur les émissions de carbone.

Cette section a été organisée en fonction de la configuration du système hybride étudié de fabrication-refabrication. Au total, deux configurations ont été observées dans la littérature en se basant sur le type des installations utilisées dans les activités de production : (1) des installations totalement distinctes (où chaque installation sera uniquement séparée à la fabrication ou à la refabrication) ou (2) des installations communes (capables de soutenir à la fois les activités de fabrication et de refabrication). Un environnement mixte où les systèmes hybrides combinent des installations de production séparées et communes peut saisir les avantages de chaque configuration en vue d’atteindre une meilleure planification et contrôle de la production.

1.3.3 Planification et contrôle de la fabrication et de la refabrication

Compte tenu de la mondialisation des marchés, le nombre grandissant de législations environnementales et la sensibilisation croissante des consommateurs à l'importance des facteurs environnementaux, sociaux et économiques, les entreprises industrielles sont continuellement confrontées à des problèmes de planification et de contrôle de la production (PCP). Ce dernier est un domaine de recherche important notamment lié à la productivité, à la gestion de stock et à l'utilisation des ressources.

Le problème de base de la planification et du contrôle de la production est de déterminer combien et quand (par exemple, fabriquer et refariquer) et ce, pour un certain nombre de variables de décision interdépendantes (Guide et al., 1999). Pour les systèmes hybrides de fabrication-refabrication, la planification et le contrôle de la production doivent aider le gestionnaire à planifier la quantité et le moment du désassemblage, la quantité et le moment de la refabrication des retours, la quantité à fabriquer en utilisant la matière première et la coordination des activités d’assemblage des produits finis. Le système devrait également être capable de coordonner une combinaison de fabrication et de refabrication. Ainsi, les activités de PCP sont assez différentes que dans les systèmes où il n'y a que des opérations de fabrication. Cela est dû à la présence d'un flux de retour (flux inverse) des produits récupérés le long de certaines phases du processus de production qui s’ajoute au flux conventionnel (flux direct). Ce flux présente certaines caractéristiques qui rendent la planification et le contrôle de production très complexes (V.D.R. Guide Jr., 2000). Il s’agit principalement de l'incertitude sur la qualité, la quantité et le temps d'acquisition des retours qui alimenteront le processus de refabrication. En effet, cette instabilité accroit la complexité du problème de PCP qui est déjà confronté à des défis comme les événements stochastiques caractérisant la demande clientèle, les pannes des installations de production et leurs durées de réparation. En conséquence, la structure optimale de politiques de commande de production n’est pas encore connue pour une telle situation générale et il est prévu qu’elle soit assez complexe.

Le problème de PCP au sein des systèmes hybrides de fabrication-refabrication a fait l'objet de plusieurs contributions scientifiques et initiatives pratiques au cours des deux dernières décennies (Govindan et al., 2015). Des revues de littérature détaillées peuvent être trouvées dans (Ilgin & Gupta, 2010 ; Lage & Godinho Filho, 2016). Bien que notre travail de recherche aborde ce problème dans une perspective intégrée, il existe des études qui se sont concentrées sur des aspects bien particuliers comme les systèmes hybrides, les délais de traitement de la production, la demande des clients, la gestion de stock, la modélisation mathématique et la solution optimale (Ozcan & Corum, 2019).

1.3.3.1 Planification de production et gestion de stock

L'un des principaux problèmes de gestion dans l'industrie de la refabrication est de simultanément contrôler le niveau des stocks et planifier les activités de production, et ce de façon efficace. Ces problèmes de PCP deviennent essentiels pour gérer efficacement les activités de production et pour ajuster de manière optimale les niveaux des stocks tout en adaptant de manière flexible l'ensemble du système aux variations de son environnement (par exemple, la demande des clients et le marché des produits d'occasion). Un survol de l'état d'art porté sur la planification de la production et la gestion de stock pour les systèmes incluant la refabrication a été présenté dans (Fleischmann et al., 1997 ; Guide et al., 1999). Muckstadt et Isaac (1981) sont parmi les premiers auteurs à traiter la planification de production et le contrôle des stocks pour les systèmes de production intégrant les activités de refabrication. Leur effort a permis de développer un modèle d'optimisation des coûts dans le cadre d'une politique d'approvisionnement en temps continu pour un système produisant un seul type de produits finis. Ils ont considéré les contraintes de capacité de refabrication, l'incertitude par rapport au délai de refabrication, ainsi que le temps et les coûts impliqués dans l'approvisionnement externe. Cependant, ils n'ont pas pris en compte le coût fixe de la refabrication ni l'option de rejet des retours non utilisés. Les travaux ultérieurs dans ce domaine de planification de la production de gestion de stock se sont concentrés principalement sur le développement et l'étude des modèles basés sur la notion de la quantité économique de commande (en anglais, *Economic Order Quantity* ou *EOQ*). Ainsi, des politiques de production et d’approvisionnement par lots (par exemple, la politique bien connue (s, Q) qui consiste à passer une commande de lot de taille Q pour alimenter le stock en question lorsque celui-ci atteint le niveau s) sont majoritairement considérées pour contrôler les systèmes hybrides.

Dans la pratique, les entreprises ayant une gamme limitée de produits ou qui ont besoin d'un temps de réponse rapide utilisent traditionnellement des systèmes de production sur stock (configuration en flux poussé) (Talay & Özdemir-Akyıldırım, 2019). En revanche, les systèmes de production à la demande (configuration en flux tiré) sont couramment utilisés lorsque le début de la production est uniquement déterminé par la demande (Kaminsky & Kaya, 2009). Van Der Laan, Dekker, Salomon et Ridder (1996) ont étendu les travaux de Muckstadt et Isaac (1981) pour inclure l’option de rejet de certains retours. Van Der Laan et al. (1999) ont étudié les effets de la variabilité de la demande et des retours, le coût de la refabrication et divers coûts d’inventaire dans un système hybride de fabrication-refabrication. Ils ont ainsi comparé les politiques en flux tiré et flux poussé en supposant une capacité de refabrication illimitée. Les auteurs ont expliqué que bien que ces politiques ne soient pas optimales, elles sont faciles à mettre en œuvre dans la pratique. Leur étude a également donné un aperçu des circonstances dans lesquelles une politique peut surpasser l'autre et vice versa. Van der Laan et Teunter (2006) ont étudié certaines extensions de la politique (s, Q) et ont présenté des formules de forme fermée simples pour calculer des paramètres de politique sous-optimaux. Les délais de fabrication et de refabrication sont supposés identiques. Corum, Vayvay et Bayraktar (2014) ont comparé les systèmes hybrides de production en flux tiré et ceux en flux poussé avec les systèmes traditionnels basés sur l'inventaire. En utilisant des politiques basées sur un temps continu, plusieurs scénarios, y compris les systèmes hybrides de production en flux tiré, ceux en flux poussé et les systèmes traditionnels (sans refabrication), ont été simulés et évalués en fonction du coût total d’inventaire et de l'écart des délais de production. Dev, Shankar et Choudhary (2017) ont étendu les travaux précédents en comparant les politiques contrôlant les systèmes sur un temps continu avec celles contrôlant les systèmes sur un temps périodique pour différents scénarios supplémentaires. Ils ont conclu que les politiques basées sur un temps continu donnent de meilleurs résultats du point de vue de l'effet dit coup de fouet (en anglais, *Bullwhip Effect*), qui fait référence au phénomène par lequel même de petites variations (par exemple,, de la demande ou de la qualité de retours) peuvent provoquer de forts changements (par exemple, du délai de traitement de la fabrication et de la refabrication). D'autres politiques de gestion de stock ont également été étudiées et comparées à l'aide de la simulation à événements discrets dans (Zanoni, Ferretti, & Tang, 2006) pour les systèmes hybrides où la demande, le taux de retour et les délais de traitement sont aléatoires. Zhou et Yu (2011) ont considéré plusieurs classes de retours en se basant sur leur niveau de qualité. Ils ont montré que la politique optimale de gestion de stock a une structure linéaire simple lorsque les délais de traitement de la fabrication et de la refabrication sont identiques.

La nature aléatoire des retours en matière de quantité a été étudiée par de nombreux travaux de recherche (Fleischmann et al., 1997), mais la plupart d'entre eux supposent que le processus de retour est indépendant du processus de demande des clients (Inderfurth, 1997). Ce type de modélisation peut être convenable pour les situations dans lesquelles aucune information sur une structure de dépendance (entre les deux processus de la demande et de retour des unités récupérées) n'est disponible ou les situations avec plusieurs sources différentes pour les retours. La dépendance de la demande de produits et leur taux de retour est une hypothèse réaliste malgré le manque de données précises sur les modèles de dépendance dans des situations réelles. Il s'agit de nombreux exemples industriels pratiques comme c'est le cas des produits loués ou lorsque les produits d'occasion sont retournés au FEO. Kiesmüller et Van der Laan (2001) ont comparé le cas où les retours dépendent d'une demande stochastique avec celui où les retours et la demande sont indépendants. Ils ont montré qu'il est plus intéressant en matière de coûts d'utiliser des informations sur la structure de dépendance entre les deux processus de la demande et de retour des unités récupérées. Parmi les travaux qui considèrent un taux de retours proportionnel à celui de la demande, Dobos (2003) a proposé une politique optimale de gestion de production et de stock qui minimise la somme des coûts de fabrication, de refabrication et de rejet de certains retours. Dans le même contexte, Feng et al. (2013) ont introduit un système de récupération des unités périssables avec des contraintes de capacité pour les processus de production. Inderfurth (2004) a développé une politique optimale de commande de production afin de maximiser le profit dans le cas où ce serait possible de substituer un produit refabriqué à un nouveau. Guide, Souza, Van Wassenhove et Blackburn (2006) ont analysé la structure appropriée des chaînes d'approvisionnement pour le retour de produits commerciaux avec différentes baisses de prix. Ils ont montré que le traitement plus rapide des retours peut apporter des avantages substantiels au système de refabrication dans deux cas réels. Alinovi, Bottani et Montanari (2012) ont utilisé la simulation pour étudier la politique optimale de retour dans différentes conditions stochastiques. Ils ont proposé un cadre aux industriels afin d'établir la meilleure politique de retour. Guo et Ya (2015) ont étudié la politique optimale de production pour un système hybride lorsque le taux de retour, le coût de rachat et le coût de refabrication dépendent du niveau de qualité. Ils ont montré que l'utilisation de coûts de refabrication plus élevés pour produire la plus basse qualité de produits finis pourrait réduire le coût total moyen. Sans tenir compte de la qualité des retours, Vercraene, Gayon et Flapper (2014) ont inclus l'option de rejet de certains retours et montrent que la politique optimale de commande est caractérisée par deux seuils relatifs au stock pour la fabrication et la refabrication et un seul seuil d'acceptation basé sur l'état des retours. Dans le même contexte, Gayon, Vercraene et Flapper (2017) ont développé une nouvelle politique de commande intégrant différentes options d'élimination.

Tous les travaux cités dans cette section ne tiennent pas compte de l'état des installations de production (par exemple, en panne, en réparation et fonctionnelle). Cependant, la considération des aspects stochastiques relatifs à la dynamique de ces installations de production est nécessaire pour représenter la réalité industrielle.

1.3.3.2 Politiques de commande considérant la dynamique des installations de production

Dans le domaine de la planification et du contrôle de la production, des travaux relativement nombreux ont traité les systèmes hybrides de fabrication-refabrication évoluant dans un contexte dynamique stochastique. Des structures de politiques de commande à rétroaction ont été ainsi développées pour optimiser en fonction d'un certain critère de performance le taux de production des installations qui sont sujettes à perturbations aléatoires. Pour les systèmes traditionnels de production (sans refabrication), les structures développées ont démontré leur efficacité vis-à-vis d’une multitude de phénomènes liés à ces perturbations tels que l’occurrence des pannes, les durées de réparation, la production imparfaite, etc. (Gershwin, 1994). Parmi les pionniers dans ce domaine, il convient de citer Kimemia et Gershwin (1983) qui ont proposé un cadre théorique pour le développement ultérieur de contributions traitant le problème de PCP pour les systèmes manufacturiers stochastiques. Dans la continuité de leur travail, Akella et Kumar (1986) ont réussi à obtenir une première solution analytique pour un cas particulier d’un système manufacturier composé d'une seule machine de production produisant un seul type de produits. Ils ont prouvé de manière analytique que la politique à seuil critique (en anglais, *Hedging Point Policy* ou HPP) est optimale. Une telle politique contrôle le taux de production en fonction de l'état de fonctionnement instantané de la machine de production. Le but est de maintenir un niveau optimal de stock pendant les périodes de disponibilité du système afin de continuer à satisfaire la demande des clients et faire face aux futures pénuries de stocks causées par des pannes. Plusieurs travaux de recherche ont étendu le concept de HPP à d'autres aspects pratiques tels que les machines multi-états (avec plusieurs modes de pannes), les systèmes intégrant les opérations de setup pour basculer entre la production d’un produit à un autre, la maintenance préventive, la sous-traitance et les émissions de gaz à effet de serre (Morad Assid, Gharbi, & Dhouib, 2015 ; Elhafsi & Bai, 1996 ; Entezaminia, Gharbi, & Ouhimmou, 2020 ; Rezg, Dellagi, & Chelbi, 2008 ; A Sharifnia, 1988).

Pour les systèmes hybrides de fabrication-refabrication, Kenné et al. (2012) ont été parmi les premiers à intégrer la dynamique des installations de production sujettes à des pannes et des réparations aléatoires. Ils ont développé les conditions d'optimalité sous la forme d'équations d’Hamilton-Jacobi-Bellman (HJB) qui permettent de résoudre le problème de commande optimale stochastique en se basant sur la programmation dynamique stochastique. Sur la base d'une méthode numérique, ils ont obtenu la politique optimale de commande de production minimisant la somme des coûts d’inventaire et de pénurie. Kouedeu et al. (2015) ont utilisé la même approche pour développer un modèle d'optimisation stochastique en considérant que les pannes des machines dépendent du taux de production. Leur modèle a été appliqué dans une étude de cas réel d’une entreprise produisant des cartouches d’encre pour les imprimantes.

Polotski, Kenné et Gharbi (2018) ont étendu la méthodologie précédente pour développer une politique optimale de commande pour les systèmes hybrides non fiables sujets à des taux de demande et de retour variables. Ouaret, Kenné et Gharbi (2019) ont traité le problème d’optimisation conjointe de la production et du remplacement en raison de la détérioration de l'installation de refabrication. Ils ont montré que la politique optimale de commande de la production et du remplacement est également de type seuil critique. En intégrant des aspects environnementaux des systèmes hybrides peu fiables produisant des émissions nocives de gaz à effet de serre, Turki et al. (2018) ont traité l’enjeu majeur en matière de prise de décisions conjointe de fabrication, de refabrication et de stockage conformément aux contraintes industrielles des réglementations sur les émissions de carbone. Dans le même contexte, Ndhaief, Rezg, Hajji et Bistorin (2019) ont proposé un compromis entre une planification écologique et économique de la production et de la maintenance en se basant sur des solutions de sous-traitance dans le but d'éviter les excès d'émissions de carbone et d’assurer un niveau élevé de satisfaction de la demande des clients.

Contrairement aux travaux cités dans cette section, ceux de la section suivante s’attarderont sur l’importance de considérer la variabilité de la qualité des retours dans la planification et le contrôle des activités de production.

1.3.3.3 Effet de la qualité des retours sur la planification de la production

La variabilité de la qualité des retours est un problème majeur pour la planification de la production et la politique de gestion de stock puisque l'effort requis de la refabrication (par exemple, le coût et le délai de traitement) dépend directement de l'état des retours. Dans la pratique, les différences dans les conditions de qualité des retours signifient que ces derniers n'ont pas besoin des mêmes actions de traitement et impliquent des délais de refabrication très variables (Korugan et al., 2013). Un exemple de l'industrie automobile montre que le coût et le temps de traitement lors de la refabrication d'un bloc moteur qui a été refabriqué dans le passé sont souvent beaucoup plus élevés, car la refabrication doit être effectuée avec des tolérances plus strictes (Akçali & Çetinkaya, 2011). À cet égard, la prise en compte d'une telle variabilité de la qualité, en particulier pour la planification et le contrôle des activités de production, pourrait entraîner des économies importantes.

La recherche sur l'effet de la qualité des retours sur la fabrication et la refabrication optimales est relativement nouvelle. Dans la littérature, la plupart des travaux traitant ce sujet important en considérant des systèmes hybrides de fabrication-refabrication, continuent d'ignorer la variabilité des processus de refabrication (Dominguez, Cannella, Ponte, & Framinan, 2019). Dans ce contexte, l'interdépendance entre la condition des retours en matière de qualité, leur délai et coût de traitement crée un défi majeur pour une planification appropriée de la production (planifier de manière efficace et à chaque instant de temps les activités de fabrication, de refabrication en utilisant des retours de haute et /ou basse qualité, etc.). Kiesmüller (2003) a montré que l'utilisation de deux variables différentes représenter les délais de fabrication et de refabrication permet un contrôle plus efficace de l'inventaire des produits finis et une économie significative, en particulier lorsque la différence entre ces délais est grande. Dans la même logique, Aras, Boyaci et Verter (2004) ont expliqué qu'effectuer un classement des retours selon leur niveau de qualité avant le processus de refabrication pourrait réduire considérablement les coûts d'exploitation. Les auteurs ont utilisé la classification des retours pour déterminer ceux nécessitant moins d'efforts de refabrication et ceux de faible qualité afin de minimiser le coût total. Le travail de Behret et Korugan (2009) allait dans le même sens en analysant les activités de refabrication selon le niveau de qualité des retours. En considérant trois catégories différentes de retours (bonne, moyenne et mauvaise qui nécessite plus d'efforts de refabrication), les auteurs ont montré que la classification conduit à des économies importantes, en particulier en cas de taux élevés de retours. El Saadany et Jaber (2010) ont proposé un ensemble de modèles basés sur le concept de la quantité de production économique en considérant que le volume des retours dépend de leur prix d'achat et du niveau de qualité d'acceptation. Cependant, le coût de la refabrication considéré n'est pas influencé par les niveaux de qualité des retours et les contraintes de capacité ne sont pas prises en compte. Les auteurs ont montré la supériorité des stratégies combinant à la fois les activités de fabrication et de refabrication en matière de coûts. Contrairement à la majorité des travaux dans la littérature, la dynamique des systèmes hybrides impliquant des interactions variant dans le temps a été peu étudiée. Korugan et al. (2013) ont analysé l'impact de la variation de qualité des retours sur le processus de refabrication lorsque l'installation peut être arrêtée soit en raison d'une défaillance opérationnelle ou de la production d'unités de mauvaise qualité. Dominguez et al. (2019) ont étudié le comportement dynamique et les performances opérationnelles des chaînes d'approvisionnement en boucle fermée caractérisées par la variabilité des délais de refabrication. Ils ont étudié l'impact de cette variabilité dans les chaînes d'approvisionnement et ont observé la nécessité d'intégrer cette caractéristique dans les hypothèses de modélisation afin de mieux représenter la dynamique de tels systèmes.

Il ressort de l'analyse des travaux cités plus haut que malgré leur pertinence, il est absolument nécessaire de poursuivre les recherches dans le domaine de PCP des systèmes hybrides de fabrication-refabrication. Cette thèse trouvera son originalité en intégrant simultanément plusieurs éléments clés qui existent entre les différents composants de cette classe de systèmes et les niveaux de décisions impliqués dans le but de mieux refléter la réalité industrielle. Ces éléments font référence aux politiques d'approvisionnement en matières premières, de setup et de rejet de certains produits récupérés ainsi qu'aux aspects associés à des événements stochastiques (par exemple, ceux liés à la dynamique des installations de production) et à la variabilité de retours en matière de qualité, de quantité et de temps d'acquisition. Or, cela a un prix, un niveau important d'accroissement de la complexité. La section suivante présente la méthodologie adoptée pour réaliser notre travail de recherche.

1.4 Méthodologie proposée

Cette section présente la méthodologie adoptée pour l'atteinte des objectifs de cette thèse. Notre démarche comprend cinq étapes principales, comme illustrées à la Figure 1.2.

- étape 1 : cette étape consiste à définir la problématique, les variables, les paramètres et les différentes caractéristiques détaillant le système étudié. Elle consiste également en une revue de la littérature afin de dégager l'originalité de notre travail.

- étape 2 : cette étape vise à formuler analytiquement le problème de PCP en considérant l'ensemble des variables, des paramètres et des caractéristiques définis lors de l'étape précédente. Cela comprend la description de la dynamique du système et des interactions entre ses variables ainsi que la formulation de la fonction-objectif, des contraintes du problème et des hypothèses de modélisation considérées.

- étape 3 : la théorie de commande optimale stochastique est utilisée pour déterminer les équations fondamentales de commande qui découlent des conditions d'optimalité du problème étudié. Ensuite, des méthodes numériques sont appliquées, face à l'absence d'une solution analytique, afin d'approximer la structure optimale des politiques de commande ainsi que leurs paramètres minimisant le coût total engendré (la fonction-objectif). Dans d'autres contextes plus complexes où l'obtention d'une solution numérique est très difficile, nous nous basons sur la littérature pour déterminer des structures heuristiques de politiques de commande plus efficientes que l'existant.

- étape 4 : cette étape vise à optimiser les paramètres des politiques de commande considérées et ainsi à évaluer la performance économique du système étudié lorsqu'il est soumis au contrôle de chacune d'entre elles. Cette étape intègre deux parties distinctes. La première partie consiste à développer des modèles de simulation capable d'imiter le comportement de système en se basant sur la formulation analytique du problème et de calculer sa performance. La deuxième combine des analyses statistiques basées sur les plans d'expériences et des techniques d'optimisation telles que la méthodologie de surface de réponse pour déterminer les facteurs significatifs (par rapport au coût total) et optimiser les paramètres de commande en question.

- étape 5 : en utilisant la simulation combinée à des techniques d'optimisation comme dans l'étape précédente, une analyse de sensibilité est réalisée par rapport aux paramètres clés de chaque système étudié dans le but de valider les structures de politiques de commande obtenues. Ces structures feront l'objet de proposition d'implantation mettant en évidence des actions à entreprendre par les gestionnaires pour contrôler conjointement et efficacement les processus de fabrication et de refabrication.

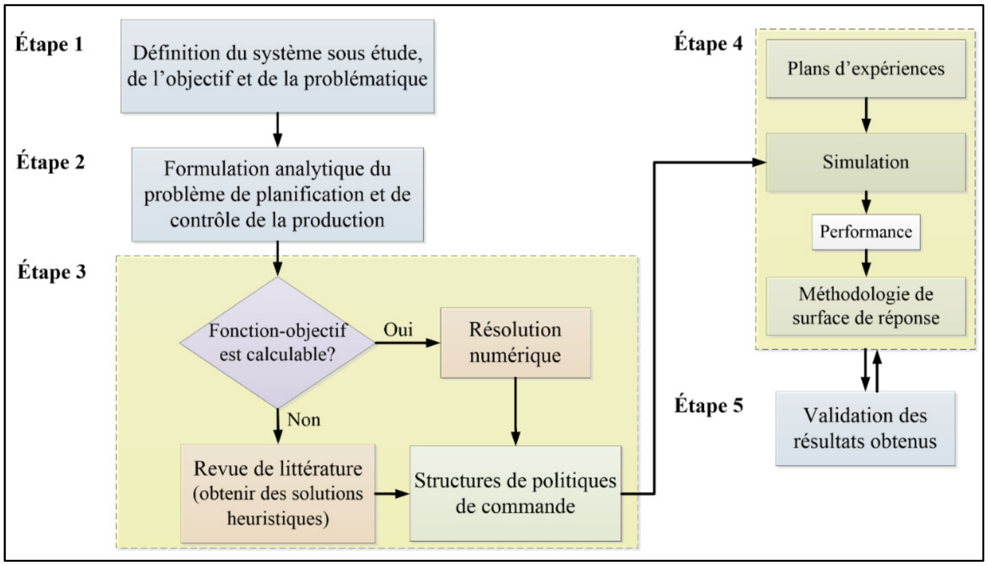

Figure 1.2 Méthodologie proposée

Dans la prochaine section, nous présentons les principales contributions de la thèse ainsi que sa structure.

1.5 Contributions et structure de la thèse

Cette thèse a permis d'apporter des contributions scientifiques originales à la recherche sur la planification et le contrôle de la production pour les systèmes hybrides non fiables intégrant simultanément la fabrication et la refabrication. Dans ce sens, elle a fait l'objet de quatre articles de revue avec comité de lecture et la participation à six conférences internationales avec comité de lecture. Les articles de conférences sont présentés en ANNEXE VI. La suite de la structure de la thèse est constituée de quatre chapitres qui forment le cœur de notre travail. Chaque chapitre représente un de nos articles de revue.

L'article du deuxième chapitre traite le problème de PCP pour les systèmes hybrides non fiables composés d'installations séparées dissociant les activités de fabrication et celles de

refabrication. Il introduit l’option de rejet des retours, l’approvisionnement en matières premières et en retours et considère la dynamique des stocks de ces deux derniers en plus de celui des produits finis. Les objectifs principaux de ce travail sont d’établir une structure efficiente de politiques de commande pour cette classe de systèmes et d’optimiser, via l’application d’une approche d'optimisation basée sur la simulation, ses paramètres de commande incluant le dimensionnement des trois espaces de stockage en matière de coûts. Cet article est publié dans la revue Computers And Industrial Engineering sous la référence:
Assid, M., Gharbi, A., & Hajji, A. (2019). Production planning of an unreliable hybrid manufacturing–remanufacturing system under uncertainties and supply constraints. *Computers & Industrial Engineering, 136*, 31-45.

L’article du troisième chapitre étend les modèles précédents de la littérature pour traiter la planification et le contrôle de production au sein des systèmes hybrides non fiables constitués d’installations communes partageant les activités de fabrication et de refabrication. Dans ce contexte, le rôle des activités de setup pour passer d’un mode de production à un autre devient primordial, d’où l’importance d’étudier leur effet. L'objectif principal de ce travail principal est de déterminer les conditions dans lesquelles les entreprises industrielles doivent produire de nouveaux produits ou de produits refabriqués afin de réaliser des économies. Cet article est publié dans la revue Journal of Manufacturing Systems sous la référence:
Assid, M., Gharbi, A., & Hajji, A. (2019). Production and setup control policy for unreliable hybrid manufacturing-remanufacturing systems. *Journal of Manufacturing Systems, 50*, 103-118.

Dans la continuité des deux travaux des chapitres précédents, l’article du quatrième chapitre traite le problème de PCP pour les systèmes hybrides évoluant dans un environnement dynamique et stochastique en considérant une combinaison d’installations séparées et communes. Un modèle stochastique dynamique est ainsi proposé, puis les conditions d'optimalité développées sont résolues numériquement. L’objectif est de déterminer conjointement les taux de production des installations de fabrication et de refabrication et le processus de prise de décision de setup nécessaire pour passer d'un mode alimenté par les produits récupérés à un mode qui utilise la matière première dans le but de minimiser le coût total. Cet article est publié dans la revue International Journal of Production Economics sous la référence:

Assid, M., Gharbi, A., & Hajji, A. (2020). Production control of failure-prone manufacturing-remanufacturing systems using mixed dedicated and shared facilities. *International Journal of Production Economics, 224*. https://doi.org/10.1016/j.ijpe.2019.107549

L'article du cinquième chapitre étudie les systèmes hybrides de fabrication-refabrication non fiables capables de produire une proportion de produits finis non conformes aux exigences des clients. Cette proportion dépend de la qualité de la matière première et des retours utilisés dans le processus de production. Une classification des retours basée sur la qualité est ainsi considérée pour les classer en deux catégories distinctes selon le temps requis pour leur traitement ainsi que la proportion des unités défectueuses. Le problème prend en compte trois décisions centrales de manière intégrée afin d'optimiser le coût total. Il s'agit de déterminer la structure optimale des politiques de commande combinant la fabrication, la refabrication et le setup requis pour changer la catégorie de retours utilisée. Cet article a été soumis dans la revue Journal of Cleaner Production sous la référence :

Assid, M., Gharbi, A., & Hajji, A. (2020). Production planning and control of unreliable hybrid manufacturing-remanufacturing systems with quality-based categorization of returns. *Journal of Cleaner Production*. Submitted on August 28th, 2020. Submission Confirmation: JCLEPRO-D-20-17785.

Nous terminons cette thèse par une conclusion générale qui résume le bilan de ce travail et présente les perspectives de recherche.

1.6 Conclusion

Le chapitre d'introduction de cette thèse nous a permis d'exposer la problématique de notre recherche ainsi que la revue de littérature qui porte sur des aspects d'ordre général relatifs à notre problématique. Nous avons ensuite résumé la méthodologie privilégiée pour réaliser notre travail. Finalement, nous avons présenté les principales contributions et la structure de cette thèse.

CHAPITRE 2

PRODUCTION PLANNING OF AN UNRELIABLE HYBRID MANUFACTURING-REMANUFACTURING SYSTEM UNDER INCERTAINTIES AND SUPPLY CONSTRAINTS

Morad Assid [a], Ali Gharbi [b], Adnène Hajji [c],

[a, b] Department of Systems Engineering, École de Technologie Supérieure,
1100 Notre-Dame Ouest, Montréal (QC), Canada H3C 1K3
[c] Department of Operations and Decision Systems & CIRRELT. Laval University,
2325, rue de la Terrasse Québec (QC), Canada G1V 0A6

Paper published in *Computers and Industrial Engineering*, October 2019

Résumé

Ce travail porte sur le secteur d'activités en émergence de la refabrication en considérant un système hybride qui utilise à la fois la matière première et des produits récupérés dans le processus de production. Un tel système apporte une plus grande complexité de gestion par rapport aux systèmes de fabrication traditionnels, en particulier avec la présence d'événements aléatoires (par exemple, pannes des installations, délais de livraison de la matière première et des retours). Ainsi, la détermination d'espaces de stockage appropriés et de stratégies adaptatives pour gérer les opérations de fabrication, de refabrication et de rejet ainsi que l'approvisionnement en matières premières et en retours, est un enjeu important. Ce travail vise principalement à proposer une structure efficiente de politiques de commande intégrant simultanément les activités de production et de rejet ainsi que l'approvisionnement en matières premières et en retours. Ce dernier élément n'a pas été pris en compte dans les modèles traitant des systèmes hybrides de fabrication-refabrication. Pour résoudre le problème, des politiques de commande pertinentes développées dans des contextes proches du nôtre ont été adaptées après des études approfondies. Une approche d'optimisation basée sur la simulation est appliquée pour déterminer les paramètres de commande optimaux, y compris l'approvisionnement en matières premières et le dimensionnement de l'espace de stockage des produits finis, des matières premières et des retours tout en minimisant le coût total encouru.

Une analyse de sensibilité approfondie est réalisée montrant le comportement robuste et l'utilité de notre proposition. Pour tous les scénarios testés, les résultats montrent que les politiques de commande proposées entraînent des économies importantes de coûts qui varient entre 6,26% et 54,14% par rapport à celles provenant de la littérature. Ce travail a aussi permis de fournir une meilleure compréhension des interactions impliquant la fabrication, la refabrication, le rejet et l'approvisionnement en des matières premières et en retours.

Mots-clés : refabrication, système hybride de production, politique de commande, simulation, optimisation.

Abstract

This paper falls within the emerging business of remanufacturing by considering a hybrid system that uses both raw materials and returned products in the production process. Such a system brings greater managerial complexity as compared to traditional manufacturing systems especially with the presence of random events (facilities failures, delivery lead times of raw materials and returns). Thus, the determination of appropriate storage spaces and adaptive strategies to manage the manufacturing, remanufacturing and disposal operations as well as the supply of both raw materials and returns, is an important issue. This work mainly aims to propose an efficient structure of joint control policies integrating simultaneously the production and disposal activities as well as the procurement of both return and raw material. The latter has been overlooked in the literature dealing with hybrid manufacturing-remanufacturing systems (HMRS). To tackle the problem, relevant control policies developed in close contexts were implemented and revised after deep studies. A simulation-based optimization approach is applied to determine the optimal control parameters including the raw material supply and the storage space sizing of finished products, raw materials and returns while minimizing the total incurred cost. An in-depth sensitivity analysis is conducted showing the robust behavior and the usefulness of the proposal. For all tested instances, the results show that the proposed control policies lead to important cost savings, which varies between 6.26% and 54.14% compared to those implemented from literature, not considering simultaneous management of raw materials and returns. Valuable insights providing a better understanding

of interactions involving manufacturing, remanufacturing, disposal and procurement of both returns and raw materials are also discussed.

Keywords: remanufacturing, hybrid production system, control policy, simulation, optimization.

2.1 Introduction

Manufacturing companies are continuously seeking efficiency to overcome the difficulties related to the market dynamics and the changing socio-economic environment. On the basis of these factors, and also the awareness of the environment by society, reverse logistics has been the subject of several scientific contributions and practical initiatives in recent decades (Govindan et al., 2015 ; J.-J. Wang, Chen, Rogers, Ellram, & Grawe, 2017). During the same period, the diffusion of environmental legislations became faster (Atasu & Van Wassenhove, 2010 ; Wu & Wu, 2016). Some examples of such legislations are the European Union end-of-life vehicle directives, which require that a certain percentage of each automobile be recyclable, and the e-waste bills, which mandate producer responsibility for their end-of-life products in the United States. Among sustainable manufacturing solutions, the option of remanufacturing requires only 15–20% of the energy that is used to manufacture products from scratch (Lund & Hauser, 2003). It is a business model for sustainable development since it generates incomes from selling the remanufactured products and expands its life cycle. Van Der Laan et al. (1999) explain that compared to a manufacturing system without reverse logistics, simultaneous control of the manufacturing and of the remanufacturing, is very complex. Indeed, companies must consider all systems component interactions ranging from the supply of raw materials and returns to the relationship with customers as well as several stochastic events (machine failures), which are part of its environment. For integrated hybrid systems remanufacturing their own brands only, the decision support models developed in the literature continue to overlook some highly interconnected elements as the procurement of raw materials, the failures and repairs of the production facilities and the starvation of these ones (production activities depend on the availability of returns and/or raw material resources supply). These elements are strongly felt within the production environment.

This paper addresses the production planning and control (PPC) problem of hybrid manufacturing-remanufacturing systems (HMRS) subject to uncertainties. The main objective is to characterize effective control policies for the manufacturing, remanufacturing and disposal operations as well as the procurement of raw materials and to determine the storage spaces requested for finished products, raw materials and returns that minimize the total incurred cost. The optimal structure is not known yet for such a situation, and it is expected to be quite complex. Therefore, there is still a need for efficient control policies that are practical for real-life hybrid systems with failure prone production facilities and a need for an efficient technique to optimize their control parameters.

The remaining sections are organized as follow. Section 2.2 presents the literature about the PPC problem within HMRS. Both the system description and the formulation of the optimal production control problem are presented in Section 2.3. Section 2.4 describes the adopted solution approach as well as the proposed structure of control policies. A numerical example is illustrated in Section 2.5. In Section 2.6, the implementation of the results is discussed, and a sensitivity analysis is performed to assess the proposal. A comparative study between the proposed integrated control policies and those implemented from the literature is conducted in Section 2.7. Conclusions and future research direction are addressed in Section 2.8.

2.2 Literature review

The research on the combined planning and control of manufacturing and remanufacturing operations has been widely discussed recently. We refer to (Esmaeilian et al., 2016 ; Ilgin & Gupta, 2010 ; Lage & Godinho Filho, 2016) for complete reviews. We will focus on the control of production facilities related to HMRS since we deal with the joint control of manufacturing, remanufacturing, and disposal operations. To clarify our contributions to the literature, the selected references related to our research are classified using criteria related to the flow of returns, the proposal of new structures of control policies, the disposal option, the procurement of raw materials, the failure-prone production facilities and the starvation of these ones (see Table 2.1). The rest of this section will be restricted to those papers while underlying our contributions. Most research related to this paper assumes that raw materials are always available when needed and has mainly covered two classes according to the characteristics of the flow of returns: 1) Models that consider continuous availability of returns; 2) Those where the quantity of returns is limited compared to the customer demand.

For HMRS where returned products are assumed available when needed and no disposals are considered, Van Der Laan et al. (1999) present a methodology to compare the well-known Push and Pull control policies. They emphasize that pull policy is preferable as long as the inventory cost of returns is lower than that of finished products. Fleischmann and Kuik (2003) use results related to the Markov decision process formulation to show that the stock-based ordering policy (l, L) is optimal. This policy supplies the finished products stock, as soon as it reaches the lower limit l, with remanufactured products to reach the L level. For a real-life case of an automobile engine remanufacturing factories, Liao et al. (2017) provide useful guidelines to firms for coordinating manufacturing and remanufacturing operations in their production process. Kilic, Tunc and Tarim (2018) propose two heuristic policies to control manufacturing and remanufacturing operations while integrating service level constraints. They use deterministic equivalent mixed integer programming to investigate their cost performance. Unlike paper cited above, Kenné et al. (2012) were the first to consider HMRS where machines are subject to random failures and repairs. Assuming that production machines are never starved, they developed an optimal control policy which minimizes the long-term expected total cost. The work of Ahiska et al. (2017) figures among the few researches where unlimited available returns with disposal options are considered. For systems with product substitution, they propose three heuristic inventory policies and develop a search algorithm to optimize the control parameters under a given profit structure.

HMRS where the quantity of returned products is limited compared to the customer demand, represent many practical industrial examples as the case of rented or leased products, or when used products are returned to the original equipment manufacturer (OEM). Kiesmüller and Van der Laan (2001) compare the case where returns depend on the stochastic demand with that of independent demands and returns and show that it is worth to use information about the dependency structure between them. Among the works where the production system is reliable and the rate of returns at time t is proportional to the rate of demands at the time t-τ (τ is the delivery lead time), Dobos (2003) proposes an optimal production-inventory policy which minimizes the sum of manufacturing, remanufacturing and disposal costs. In the same context, Feng et al. (2013) introduce a recovery system for perishable items with capacity constraints for production processes. Inderfurth (2004) develops an optimal production control policy with the aim to maximize profit in the case where it is possible to substitute a remanufactured product with a new one. Guide et al. (2006) analyze the appropriate supply chain for commercial product returns with different decays in price. They show that processing returns faster may provide substantial benefits for the remanufacturing system in two real life cases. Alinovi et al. (2012) use simulation to investigate the optimal return policy under different stochastic conditions. They propose a framework for industries in order to establish the best return policy. Guo and Ya (2015) investigate the optimal production policy for HMRS when the rate of returns, the buyback cost and the remanufacturing cost depend on the quality level. They show that using higher remanufacturing costs to produce the lowest quality of finished products could reduce the average total cost. Without considering the quality of returns, (Kim, Saghafian and Van Oyen, 2013) and (Vercraene et al., 2014) include the disposal control and show that two state-dependent base-stock thresholds for manufacturing and remanufacturing and one state-dependent return acceptance threshold characterize the optimal joint policy. In the same context, Gayon et al. (2017) develop a new control policy integrating different disposal options. Fang et al. (2017) consider five scenarios based on the production capacity and market demand to find the optimal operation strategy maximizing the total profit for a system with a substitutional relationship between new and remanufactured products.

In this second category of limited returns compared to customer demand, only few recent models integrate stochastic processes related to production facilities using only homogeneous Markov process to describe failure and repair events. As extension of (Kenné et al., 2012), Ouaret, Polotski, Kenné and Gharbi (2013) take into account a failure-prone system and a stochastic demand showing that the optimal production policy is of the hedging-point type. In the same context, Kouedeu, Kenné, Dejax, Songmene and Polotski (2014) integrate the disposal option and develop a stochastic optimization model where the failure rate of the manufacturing machine depends on its production rate. An industrial application of the developed methodology for a real European business case study producing printer cartridges is presented in (Kouedeu et al., 2015). Turki and Rezg (2016) include delivery lead-time between the production warehouse and the finished products stock and apply a perturbation analysis to determine the optimal production inventory level minimizing the sum of inventory, transportation and lost sales costs. More recently, Polotski, Kenné and Gharbi (2017a) propose a general structure of the optimal control policy for a single global unit using setups to switch between manufacturing and remanufacturing modes.

The above developed models still do not consider simultaneously important elements such as: the stochastic process related to the failure of production facilities; the actual quantity and timing of both raw materials and returns and the possibility that they could starve the production activity; as well as the storage space sizing of returns, raw materials and finished products. This line of research is always open, and we argue that it may bring to managers an improved way to control this class of HMRS. In view of the various previous papers, our work contributes to the literature in several ways. First, the jointly efficient structure of manufacturing, remanufacturing and disposal control policies as well as procurement of raw materials is characterized for unreliable HMRS. To the best of our knowledge, it differs from existing models by being the first to consider simultaneously the stochastic process related to production facilities, the starvation possibility of these ones, the procurement of both raw materials and returns with random delivery lead times, and the storage space sizing of finished products, returns and raw materials. Second, the adopted simulation-based optimization approach provides an efficient technique to optimize the parameters of the proposed control policies minimizing the total incurred cost. It also brings valuable insights into interactions involving production and disposal operations as well as the benefits of considering simultaneously the supply of both raw materials and returns and uncertainties in decision-making related to production planning and control (PPC). Understanding these uncertainties and their impacts, which can make it difficult to predict performance metrics, are major concerns when assessing the risk associated with a decision.

Table 2.1 Summary of literature survey

Works	Limited source of returns	Stochastic rate of returns	Non-negligible delivery lead time of returns	Proposal of new policies	Disposal option	Procurement and stock sizing of raw materials	Failure-prone facilities	Starvation of production facilities
(Van Der Laan et al., 1999)		×						
(Fleischmann & Kuik, 2003)		×						
(Liao et al., 2017)						×		
(Kilic et al., 2018)		×		×				
(Kenné et al., 2012)				×			×	
(Ahiska et al., 2017)		×		×	×			
(Kiesmüller & Van der Laan, 2001)	×	×	×		×			
(Dobos, 2003)	×		×	×	×			
(Inderfurth, 2004)	×	×		×	×			
(Guide Jr. et al., 2006)	×		×					
(Feng et al., 2013)	×			×	×			
(Alinovi et al., 2012)	×	×	×	×				
(Guo & Ya, 2015)	×					×		
(Kim et al., 2013)	×	×		×	×			
(Vercraene et al., 2014)	×	×		×	×			
(Gayon et al., 2017)	×	×		×	×			
(C. C. Fang et al., 2017)	×	×		×	×			
(Ouaret et al., 2013)	×	×		×			×	
(Kouedeu et al., 2014)	×			×	×		×	
(Turki & Rezg, 2016)	×		×	×			×	
(Polotski et al., 2017a)	×			×			×	
Our proposal	×	×	×	×	×	×	×	×

2.3 Problem statement

2.3.1 Notation

We list below the notations used in the rest of the paper.

θ_i	: Raw material ith order instant (time)
$\tau_R(t)$	: Random lead time between the sale of finished products at time t and their return to the system
$\tau_{RM}(t)$	: Random delivery lead time of the raw material ordered at time t
c_{FP}^-	: Backlog cost of finished products (\$/time/unit)
c_{FP}^+	: Holding cost of finished products (\$/time/unit)
c_{FP}^{pro}	: Manufacturing cost (\$/unit)
c_{FP}^{rem}	: Remanufacturing cost (\$/unit)
c_{RM}^{ord}	: Raw material ordering cost per order (\$/order)
c_{RM}^{unit}	: Raw material cost per unit (\$/unit)
c_{RM}^+	: Raw material holding cost (\$/time/unit)
c_R^{unit}	: Return cost per unit (\$/unit)
c_R^+	: Return holding cost of returns (\$/time/unit)
c_{dis}	: Scrap cost of disposals (\$/unit)
c_{FP}^e	: Storage space cost of finished products (\$/space area)
c_{RM}^e	: Storage space cost of raw materials (\$/space area)
c_R^e	: Storage space cost of returns (\$/space area)
d	: Finished product demand rate (product/time)
$P_R(t)$	: Random proportion of used products available on the market at time t ready to be returned.
Q_{Pro}	: Average manufacturing rate
Q_{Rem}	: Average remanufacturing rate
Q_{dis}	: Average rate of disposals
Q_{RM}	: Raw material lot size ordered (product)
S_{RM}	: Raw material ordering point (product)
T_f	: Time to failure
T_{cm}	: Time to repair
$u_{pro}(t)$	: Manufacturing rate at time t (product/time)
$u_{rem}(t)$	: Remanufacturing rate at time t (product/time)
$u_{dis}(t)$	: Disposal rate at time t (product/time)
$u_R(t)$	: Returns rate at time t (product/time)
U_{max}^{pro}	: Maximum manufacturing rate of facility F_1 (product/time)

U_{max}^{rem} : Maximum remanufacturing rate of facility F_2 (product/time)
$x_{FP}(t)$: Inventory level (or backlog) of finished products at time t (product)
$x_{RM}(t)$: Inventory level of raw materials at time t (product)
$x_R(t)$: Inventory level of return at time t (product)
Z_{FP} : Storage space needed for finished products (product)
Z_R : Storage space needed for returns (product)
Z_{RM} : Storage space needed for raw materials (product)

2.3.2 System description

The HMRS studied in this paper and described in Figure 2.1 presents a common problem in many industries (electronics, automotive, aeronautics and textile). It represents the case of OEM with two separate production facilities (F_1 and F_2), each of which has a different production mode: F_1 for manufacturing and F_2 for remanufacturing. The finished products can then be produced from raw materials through F_1 or from returns through F_2. Both F_1 and F_2 are subject to random failures and repairs and may be starved if raw materials and returns are unavailable respectively. Once the finished product is produced, it is stored in a storage area before being delivered to customers. Two other stocks whose size also depends on storage space costs are considered. The first one contains raw material items while the second one contains all items returned from the market.

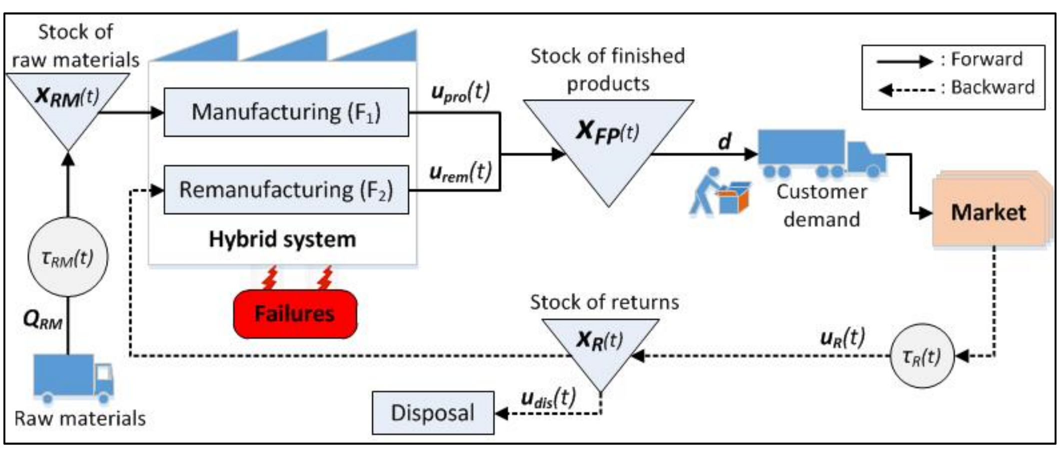

Figure 2.1 Structure of the HMRS under study

A procurement policy of raw materials is considered to ensure the continuity of the manufacturing process using F_1. Similarly, the continuity of the remanufacturing process depends on the flow of returns. Only a random fraction of OEM's used products is collected and the time between the sale of these products and their return to the system is random. Disposal costs may also be applied since the possibility to reject some returned products is considered. Our objective is to determine jointly the production rates of both manufacturing and remanufacturing facilities, the disposal rate of returns, the procurement policy of raw materials and the optimal storage spaces that minimize the total incurred cost. The latter includes manufacturing, remanufacturing, raw materials, returned products, storage spaces and disposal costs as well as inventory and backlog costs of finished products. The solution shall satisfy several constraints related to the dynamic and the feasibility of the system. The following summarizes the main assumptions considered in this system:

- the remanufactured products are the same quality level as the manufactured products;
- the rate of customer demand is known and constant;
- the rate of returns is a random fraction of the sold products;
- returned products and raw materials are of good quality;
- disposal decisions are controlled based on the availability of storage space of returns;
- neither the manufacturing facility nor the remanufacturing one can satisfy alone all demand.

2.3.3 Problem formulation

Considering the randomness of failures and repair activities, the system state can be modelled by two components. On the one hand, the accumulated inventory level of finished products, raw materials and returns $X(t) = (x_{FP}(t), x_{RM}(t), x_R(t)) \in R \times R^+ \times R^+$. On the other hand, the stochastic process $\alpha_i(t) \in \{0,1\}$, $i = \{1,2\}$ that describes the operational mode of the facility F_i. It is a discrete component. When F_i is available $\alpha_i(t) = 1$ while $\alpha_i(t) = 0$ refers to its failure state. The dynamic behaviour of the system may be described by the state variables $\big(X(t), \alpha(t)\big)$ with $\alpha(t) = \big(\alpha_1(t), \alpha_2(t)\big)$. The following represent the dynamics of stocks:

$$dx_{FP}(t)/dt = u_{pro}(t) + u_{rem}(t) - d, \qquad x_{FP}(0) = x_{FP}^0. \tag{2.1}$$

$$dx_R(t)/dt = u_R(t) - u_{rem}(t) - u_{dis}(t), \qquad x_R(0) = x_R^0. \tag{2.2}$$

$$\begin{cases} dx_{RM}(t)/dt = -u_{pro}(t) & i \in N^*, \\ x_{RM}((\theta_i + \tau_{RM}(\theta_i))^+) = x_{RM}((\theta_i + \tau_{RM}(\theta_i))^-) + Q_{RM} & x_{RM}(0) = x_{RM}^0 \end{cases} \tag{2.3}$$

With, x_{FP}^0, x_R^0 and x_{RM}^0 denote the initial inventory level of finished products, returns and raw materials respectively. Two formulas are used to express the inventory level of raw materials (x_{RM}) through a piecewise continuous part. This is particularly useful because x_{RM} faces a continuous downstream manufacturing process and an impulsive upstream supply when a Q_{RM} lot of raw materials is received at the instant $\theta_i + \tau_{RM}(\theta_i)$. This order was launched at θ_i. $(\theta_i + \tau_{RM}(\theta_i))^-$ and $(\theta_i + \tau_{RM}(\theta_i))^+$ represent the negative and positive boundaries of the ith receipt instant respectively. The production rates at every moment satisfy the constraints:

$$\begin{cases} 0 \leq u_{pro}(t) \leq U_{max}^{pro} \\ 0 \leq u_{rem}(t) \leq U_{max}^{rem} \end{cases} \tag{2.4}$$

The set of acceptable control policies Γ depends on the stochastic process of facilities $\alpha(t)$ and the availability of both raw materials and returns in stocks ($x_{RM}(t)$ and $x_R(t)$):

$$\Gamma = \left\{ \begin{matrix} U, \theta_i, Q_{RM}: U = \left(u_{pro}(.), u_{rem}(.), u_{dis}(.)\right), \theta_i, Q_{RM} \geq 0, \\ 0 \leq u_{pro}(t) \leq U_{max}^{pro}. \alpha_1(t). \mathrm{I}(x_{RM}(t) > 0), \\ 0 \leq u_{rem}(t) \leq \widehat{U}^{rem}. \alpha_2(t), \\ u_{dis}(t) \leq u_R(t) \end{matrix} \right\} \tag{2.5}$$

With, $\mathrm{I}(\emptyset(.)) = 1$ if $\emptyset(.)$ is true and $\mathrm{I}(\emptyset(.)) = 0$ otherwise. The index $\widehat{\mathrm{U}}_{\mathrm{rem}}$is formulated by:

$$\widehat{U}^{rem}(\mathrm{t}) = \begin{cases} U_{max}^{rem} & \text{if } x_R(t) > 0 \\ u_R(t) & \text{if } x_R(t) = 0 \end{cases} \tag{2.6}$$

Let $h(.)$ be the instantaneous cost given by:

$$h(X,\alpha,U) = c_{FP}^{+}.x_{FP}^{+} + c_{FP}^{-}.x_{FP}^{-} + c_{RM}^{+}.x_{RM} + c_{R}^{+}.x_R + c_{FP}^{pro}.u_{pro} + c_{FP}^{rem}.u_{rem} + c_{dis}.u_{dis} + c_{R}^{unit}.u_R \tag{2.7}$$

With, $\begin{cases} x_{FP}^{+} = max(0, x_{FP}) & if\ x_{FP} \geq 0 \\ x_{FP}^{-} = max(-x_{FP}, 0) & if\ x_{FP} < 0 \end{cases}$

In addition, we define the cost function which penalizes the supply order at time θ_i as follow:

$$g(\theta_i, Q_{RM}) = c_{RM}^{ord}.\mathrm{I}(t=\theta_i) + c_{RM}^{unit}.Q_{RM} + \int_0^{\tau_{RM}(\theta_i)} e^{-\rho t} h(.)\, dt \tag{2.8}$$

With ρ is the discount rate. The problem is to determine proper control policies minimizing the discounted expected total cost function $J(.)$ over an infinite horizon.

$$J(X,\alpha,U,\theta_i,Q_{RM}) = E\left[\int_0^{\infty} e^{-\rho t} h(.)dt + \sum_{i=1}^{\infty} e^{-\rho\theta_i}\left(c_{RM}^{ord} + c_{RM}^{unit}.Q_{RM}\right)\right] + c_{FP}^{e}(.) + c_{RM}^{e}(.) + c_{R}^{e}(.) \tag{2.9}$$

As in (Assid et al., 2015 ; Lavoie, Gharbi, & Kenné, 2010), storage spaces costs are considered to get a better representation of the cost structure. Our model considers three storage spaces costs $c_{FP}^{e}(.)$, $c_{RM}^{e}(.)$ and $c_{R}^{e}(.)$ which are related to the storage space allocated to maintain finished products, raw materials and returns respectively. Compared to inventory cost related to conservation actions, the invested storage space cost is linked mainly to storage space size and equipment. It is a fixed cost that increases in step to a new level with the significant changes in the storage space size. For example, suppose that the proposed joint control policies will use Z_{FP} as the storage space allocated to finished products for the base case. So, if $Z_{FP} \in [250, 300[$ then $\mathrm{c}_{\mathrm{FP}}^{\mathrm{e}}(Z_{FP}) = 54$, else if $Z_{FP} \in [300,\ 350[$ then $\mathrm{c}_{\mathrm{FP}}^{\mathrm{e}}(Z_{FP}) = 63$, etc. For illustrative purposes, we assume that the three costs of storage spaces are identical.

As mentioned above, this PPC problem consists of establishing proper combined control policies $U, \theta_i, Q_{RM} \in \Gamma$ which minimize the total cost (2.9). The problem can be formulated as follow:

$$\begin{cases} \text{Minimize} & J(X, \alpha, U, \theta_i, Q_{RM}) & & (2.10) \\ \text{Subject to} & \text{Equations (2.1) - (2.2)} & \text{(continuous stocks dynamic)} & \\ & \text{Equation (1.3)} & \text{(piecewise continuous and impulsive stock dynamic)} & \\ & \text{Equations (2.4)-(2.6)} & \text{(constraints and set of admissible decisions)} & \\ & \alpha_1(t), \alpha_2(t) \in \{0,1\}^2 & \text{(stochastic process)} & \\ & U, \theta_i, Q_{RM} \geq 0 & \text{(decision variables)} & \end{cases}$$

To find an integrated steady state policy to control manufacturing and remanufacturing and disposal actions as a function of the system's state, the Hamilton-Jacobi Bellman (HJB) equations associated with (2.10) have to be solved. However, an analytical solution in this context is very hard. For example, compared to (Kenné et al., 2012) who solved numerically the HJB equations of the control problem for unreliable production facilities while assuming continuous availability of raw materials and returns, we consider new elements that make the system more realistic: raw materials supply with random delivery lead time; random rate and delivery lead time of returns; integration of the disposal option of returns; the fact that both facilities (F_1 and F_2) can be starved and that all storage spaces need to be sized. So, in addition to the combined continuous/discrete nature of our model, more physical component (stocks) and more decisions (impulsive supply of raw materials, frequency and batch size of orders, the possibility of disposal) are to be undertaken. Thus, the state of the system and the dimension of the HJB equations for numerical methods become much larger. This dimension is given by:

$$Dim = 2^m. \; V_{FP}^m . N_h(x_{FP}) \; . \; V_R . N_h(x_R) \; . \; V_{RM} . N_h(x_{RM}) \qquad (2.11)$$

Where $N_h(x_i) = card[G_h(x_i)]$ with $G_h(x_i)$ describing the numerical grid for the state variable x_i. m defines the number of facilities and "2" refers to the number of states of each one. V_i, $i = \{FP, R, RM\}$ represents the number of value combinations this parameter can take to build the stock x_i. For instance, if the production rate can take three values namely maximal production rate, demand rate and zero to build the stock of finished products x_{FP}, then $V_{FP} = 3$. For our case, $V_{FP} \geq 3$ since there are several combinations of $u_{pro}(t)$ and $u_{rem}(t)$ to have a value equal to the demand rate d. Similarly, $V_R \geq 3$ as the rate of returns may be zero and depends on sales as well as a random delivery lead time. Thus, for $N_h(x_i) = 100$, the minimum calculated dimension will be greater than or equal to $Dim = 2^2.(3^2\ .\ 100)\ .\ (3\ .\ 100)\ .\ (1\ .\ 100) = 1.08\ 10^8$. This means that the numerical solution will be difficult to obtain. Rather, to obtain an effective feedback control policy, Kenné et al. (2012) suggest other alternative solution for such a complex problem as the combination of the PPC literature with the simulation-based experimental approach (see next section). The main advantage of this approach is that provides the possibility of establishing more realistic representation of the stochastic and dynamic behaviour of the system. Moreover, it is more suitable for finding the optimal control parameters of the proposed policies in such complex problem. This approach has been successfully applied to various complex manufacturing problems (Assid et al., 2015 ; Kleijnen, 2015 ; Lavoie et al., 2010).

2.4 Solution approach and proposed control policies

In addition to considering several joint control policies found in the literature within different contexts (with or without remanufacturing), the solution approach combines mathematical modelling, simulation tools, design of experiments and response surface methodology with the aim to propose new structure of joint control policies and to optimize its parameters. The proposed control policies are based on related paper from literature to build efficient control policies for the considered system. Works like (Kenné et al., 2012) which develops a hedging-point type control policy for failure-prone HMRS; (Hajji, Gharbi, & Kenné, 2009 ; Hlioui, Gharbi, & Hajji, 2017) which address integrated production and supply control problems in manufacturing systems and (Kim et al., 2013) which proposes effective heuristics where production and disposal decisions are based on both finished products and returns stocks, inspired our proposed structure of joint control policies. It will be shown later in Section 2.7 that this proposed structure gives better results in terms of costs compared to those implemented from literature.

2.4.1 Solution approach

The sequential steps of the proposed approach presented in Figure 2.2 are described as follow:

Step 1: Mathematical formulation of the problem

This step formulates the problem as shown in Section 2.3.3. It describes the system dynamics as a function of its states and the formula of the total cost. This step also highlights interactions between the production, the disposal and procurement processes and the costs generated.

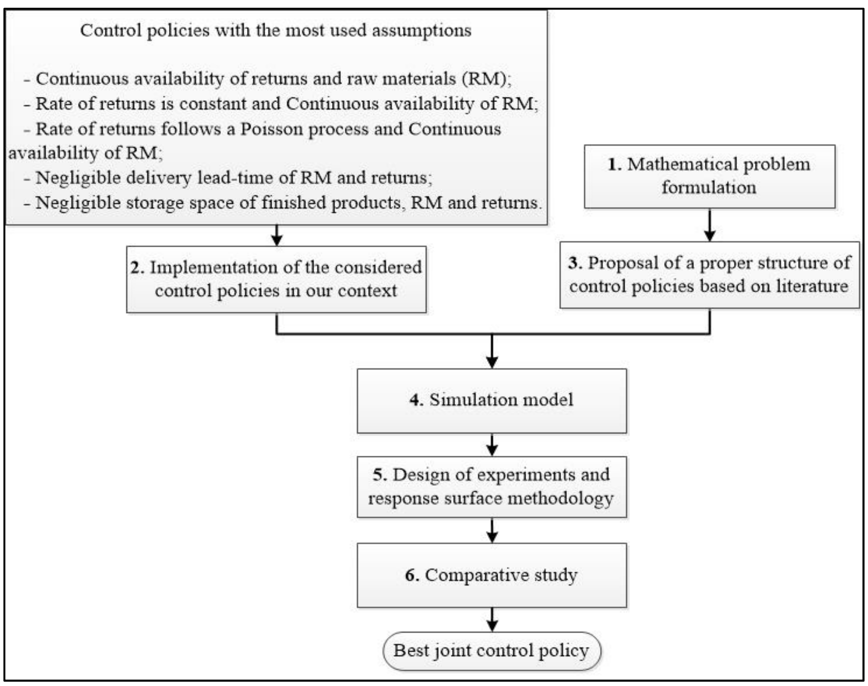

Figure 2.2 Adopted control approach

Step 2: Implementation of the considered control policies

Based on literature, five manufacturing and remanufacturing control policies are considered and implemented in our system (Figure 2.1). The implementation consists of introducing elements related to storage spaces and procurement of both raw materials and returns. These additional elements interact with the other components of the system and are influenced by random events like failures, repairs and delivery lead times. Additional costs are thus involved. The implemented control policies are presented in Section 2.7.

Step 3: Proposal of the proper structure of control policies

The proposed control policies integrate simultaneously all the elements of the system presented in Figure 2.1, like production interruptions (failures), disposal options, delivery lead times of raw materials and returns, etc. An efficient structure of control policies for the considered system is thus developed in Section 2.4.2and should lead to better economic performance.

Step 4: Simulation model

This step transforms the dynamics of the system and its interactions expressed by the mathematical formulation into a discrete-continuous simulation model to evaluate the behaviour and the performance of the manufacturing system (the total cost) for a given combination of control parameters. Section 2.4.3 presents a detailed description of this step.

Step 5: Design of experiments (DOE) and response surface methodology (RSM)

In this step, an appropriate experimental design with a minimal set of simulation runs is elaborated. The objective is to determine the effects of the considered control parameters of the proposed policies, their quadratic effects, and their interactions on the response (the total incurred cost). From the output of the simulation runs, a regression analysis is used in conjunction with the RSM to express the relationship between the cost and the control parameters. The objective is to optimize these control parameters minimizing the total incurred cost. Details are given in sections 2.4.4 and 2.5.

Step 6: Comparative study

The steps 4 and 5 are also used to conduct a comparative study between our proposed structure of control policies and the implemented policy categories used in the literature. The objective is to emphasize the importance of integrating both raw materials and returns supply modes in joint manufacturing, remanufacturing and disposal decision-making as proposed in this work. The comparative study is detailed in Section 2.7.

2.4.2 Proposed structure of control policies

In this section, we propose the structure of joint manufacturing, remanufacturing and disposal control policies for an unreliable single product HMRS operating in a dynamic and stochastic context while integrating the procurement of raw materials. As stated in the first paragraph of section 2.4, we based ourselves on the literature knowing that the optimal policies are found to be of the (s,Q)-policy in inventory control literature and of the hedging-point type in production control literature. Considering the functional state of facilities as well as the availability of raw materials and returns, the proposed structure of joint control policies is formulated by the equations below. We aim for efficient control policies that can be easily implemented in an industrial context. The best approximation of the equation (2.10) is expected for some values of the control parameters S_{RM}, Q_{RM}, Z_{RM}, Z_{FP} and Z_R (see Sections 2.4.2.1-2.4.2.5). Note that S_{RM} represents the expected average reorder point ($x_{RM}(\theta_i)$).

2.4.2.1 Remanufacturing policy (facility F_2)

As in (Kenné et al., 2012), the proposed control policies consider the priority given to the remanufacturing activities by transforming as many returns as possible since they cost less compared to manufacturing using raw materials. When F_2 is operational, the remanufacturing of used products depends only on their availability in stock. This equation assumes that U_{max}^{rem} is lower than the customer demand d but greater than the rate of returns at a given time t.

$$u_{rem}(t) : \begin{cases} U_{max}^{rem}.\alpha_2(t) & if\ (x_R(t) > 0) \\ u_R(t).\alpha_2(t) & if\ (x_R(t) = 0) \\ 0 & otherwise \end{cases} \tag{2.12}$$

2.4.2.2 Manufacturing policy (facility $\mathrm{F_1}$)

The proposed manufacturing control policy is a modified state-dependent hedging point policy. The total production rate of the system is either at the lowest or maximum level, but no more than the demand rate when the surplus is at the threshold level Z_{FP}. Indeed, the manufacturing facility (F_1) considers the remanufacturing rate (u_{rem}), so it can produce just enough to reach the market demand. In this case, Z_{FP} represents the storage space to build and aims to hedge against future possible inventory shortage.

$$u_{pro}(t) : \begin{cases} U_{max}^{pro}.\,\alpha_1(t).\,\mathrm{I}\{x_{RM}(t) > 0\} & if\ (x_{FP}(t) < Z_{FP}) \\ \big(d - u_{rem}(t)\big).\,\alpha_1(t).\,\mathrm{I}\{x_{RM}(t) > 0\} & if\ (x_{FP}(t) = Z_{FP}) \\ 0 & otherwise \end{cases} \tag{2.13}$$

2.4.2.3 Raw materials supply policy

The manufacturing of new finished products depends on the availability of raw materials in stock. Two parameters characterize the proposed raw materials supply policy: Q_{RM} and S_{RM}. The threshold S_{RM} represents the necessity to have a safety stock of raw materials at which a new order of size Q_{RM} is launched and received after a random delivery lead time τ_{RM}. The adopted raw materials supply policy is conducted by a state-dependent economic order quantity as proposed in (Hajji et al., 2009) which addressed an integrated procurement and production control problem for one unreliable transformation unit and one unreliable supplier of raw materials. Hajji et al. (2009) developed a dynamic stochastic model and used a numerical approach to solve the optimality conditions equations. They showed that the optimal control policy is a “modified state-dependent multi-level base stock policy” for production activities, combined with a $(\mathrm{S_{RM}}, \mathrm{Q_{RM}})$ policy structure for procurement decisions. The equation (2.14) describes the considered procurement policy of raw materials.

$$\Omega_{RM}(t) : \begin{cases} Q_{RM} & if\ (x_{RM}(t) = S_{RM}) \\ 0 & otherwise \end{cases} \tag{2.14}$$

With $Q_{RM} > S_{RM} \geq 0$. A storage space with a size of Z_{RM} is used to store all ordered quantities of raw materials and to ensure that the manufacturing facility (F_1) operates smoothly. However, the adoption of using the procurement policy (S_{RM}, Q_{RM}) implies that x_{RM} will never exceed the value of $S_{RM} + Q_{RM}$. This value represents the case where a raw material order is launched just at the failure of F_1 and received before the end of the repair actions. Offline simulations are also carried out to confirm that $S_{RM} + Q_{RM}$ is the highest value reached of x_{RM}. In this sense, the following equation must be satisfied $Z_{RM} = \mathrm{S_{RM}} + \mathrm{Q_{RM}}$ to keep all orders received of raw materials while minimizing their storage space.

2.4.2.4 Returns supply policy

As in the case of raw materials, remanufacturing activities depend on the availability of stored returns. This stock is directly fed by the flow of used products available in the market. We use the parameter $P_R(t) \in [0.1]$ to represent the proportion (compared to products sold) of used products available on the market at the time t ready to be returned to the system for remanufacturing. Thus, if a quantity d' is sold to customers at the time t_d, then the quantity returned after a random delivery lead time is equal to $u_R(t_d + \tau_R(t_d)) = P_R(t_d).d'$. Thus,

$$u_R(t+\tau_R): \begin{cases} P_R(t).d & if\ (x_{FP}(t) \geq 0) \\ P_R(t).\begin{pmatrix} \left(U_{max}^{pro}.\alpha_1(t).I(x_{RM}(t) > 0)\right) \\ +\left(U_{max}^{rem}.\alpha_2(t).I(x_R(t) > 0)\right) \end{pmatrix} & if\ (x_{FP}(t) < 0) \end{cases} \tag{2.15}$$

With, $u_R(t_0) = u_R^0, \forall t_0 \leq \tau_R^0$ is the initial rate of returns from $t = 0$ to $t = \tau_R^0$ which represents the delay before receiving the first returns of products sold. In addition to the time-dependent parameter P_R, equation (2.15) shows that the rate of returns depends on market sales, including the maximum production capacity when the finished product was out of stock for a given period of time. In this case, the rate of returns may also be zero if the market is not supplied for a certain time (shortages). This happens when F_1 and F_2 are down or stocks of raw materials and returns are empty (see section 2.4.3 for an illustrative of this situation).

2.4.2.5 Disposal policy

Disposal decisions are controlled based on the inventory level of returns as considered by several works dealing with the control policies of the flow of returns (Gayon et al., 2017 ; Kim et al., 2013 ; Vercraene et al., 2014). The returned products collected from the market are held on stock for later remanufacturing. However, the disposing of used products is needed when there is no space to accommodate them (the return storage space is full). In this work, no pre-processing actions of returned products are considered. Therefore,

$$u_{dis}(t) : \begin{cases} max(u_R(t) - u_{rem}(t), 0) & if \ x_R(t) = Z_R \\ 0 & otherwise \end{cases} \tag{2.16}$$

According to (14), calculating the optimal level of disposal is equivalent to determining the optimal storage space of returns Z_R^* from which it will be necessary to dispose the returned items. In addition, as we prioritize the remanufacturing because of its low costs, the facility F_2 aims to remanufacture as many as possible of products returned from the market. This also minimizes disposals and associated costs.

2.4.3 Simulation model

A combined discrete-continuous simulation model is developed using the SIMAN simulation language and then executed through the Arena software application. The objectives are to reflect the system functioning and to quantify the performance metrics expressed by (2.9) (the total cost) when the above-formulated control policies are applied. This model is composed of several networks; each describes a specific task or event in the system (failures, repair actions, thresholds crossing of inventories, etc.). Both discrete and continuous components of the simulation model are required to operate simultaneously. For example, the continuous part can cover the updating of the instantaneous inventories level, while the discrete part models maintenance activities. Furthermore, this modelling approach reduces greatly the execution time when compared to the purely discrete models (Lavoie et al., 2010). Because of uncertainties, the duration of simulation runs is set such as to ensure that the steady state is reached. Once the simulation run is stopped, the total cost for the given system's configuration is obtained. The block-diagram representation of the simulation model is illustrated in Figure 2.3.

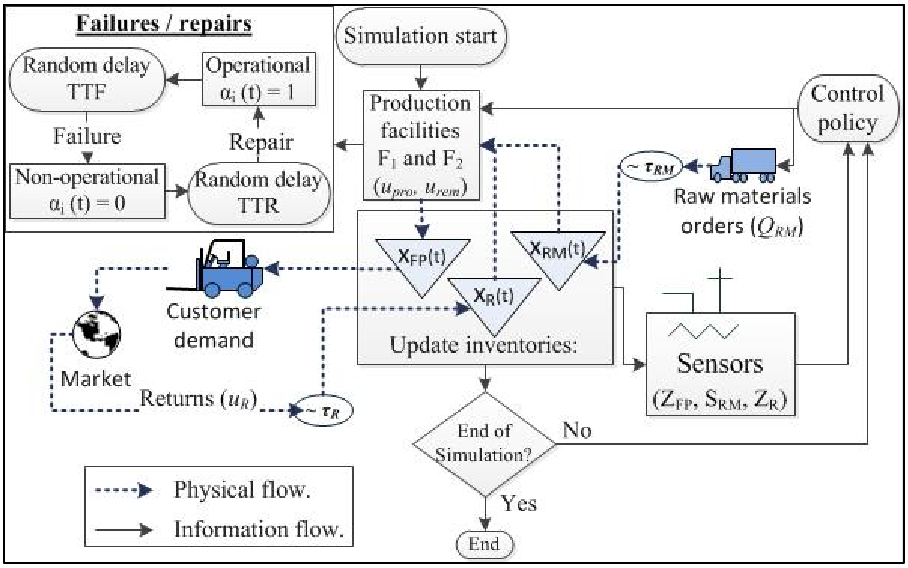

Figure 2.3. Block-diagram representation of the simulation model

The simulation model design requires several steps to assess and validate the system accuracy. An example is illustrated in Figure 2.4 to show that the proposed structure of control policies works correctly and as expected. This figure represents the dynamics of system operations. It is composed of a total of seven subfigures: each represents the variation of one or two system parameters over the same period of time. Putting them in the same column makes it easy to see the complex interaction between the system parameters (u_{rem} may influence u_{pro}) and the effect of some events on the system performance (effect of failures on inventory levels). This model is performed for: $d = 100$, $U_{max}^{pro} = 120$, $U_{max}^{rem} = 50$, $Z_{FP} = 200$, $S_{RM} = 250$, $Q_{RM} = 1000$ and $Z_R = 150$. Note that in order to facilitate representation of the system dynamics, τ_R and P_R are considered constant: $\tau_R = 10$ and $P_R = 0.4$. We use the symbol "arrow X.Z" to locate the phenomenon pointed to by the arrow number X illustrated in the subfigure 4.Z.

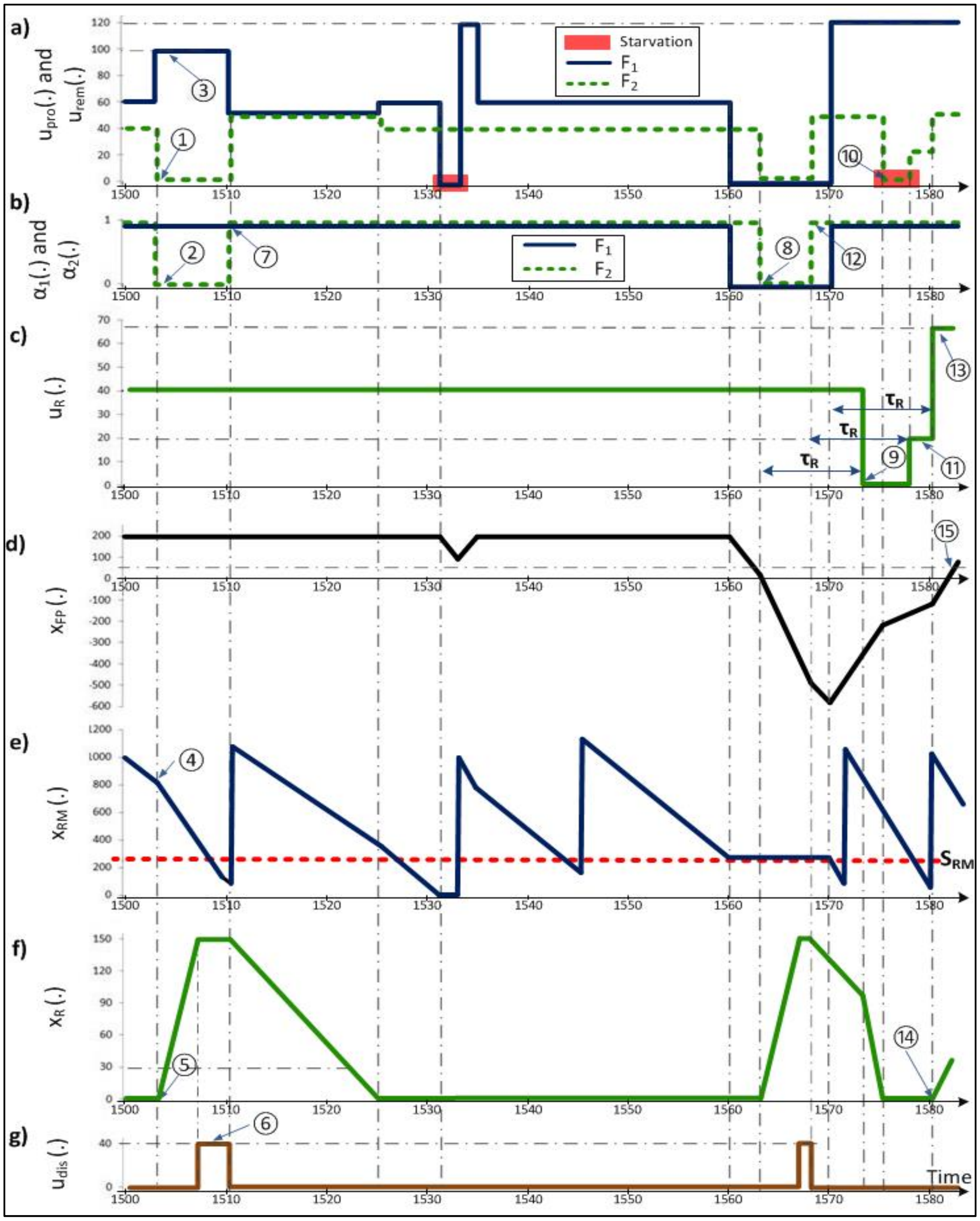

Figure 2.4 Dynamics of operations for an offline simulation run

SubFigure 2.4.a and 2.4.b show that the production process, which includes both manufacturing and remanufacturing activities depends on the states $\alpha_1(.)$ and $\alpha_2(.)$ of F_1 and F_2 respectively (Figure 2.4.b), the inventory level of finished products $x_{FP}(.)$ (Figure 2.4.d), the availability of raw materials (Figure 2.4.e) and the stored returns (Figure 2.4.f). Indeed, the sum of production rates is equal to the customer demand if the storage space of the finished product is full ($x_{FP}(.) = Z_{FP} = 200$). For example, when F_2 breaks down (arrow ①.a), its state automatically changes to $\alpha_2(.) = 0$ (arrow ②.b) and the value of u_{pro} increases to compensate for the production capacity loss of F_2 (arrow ③.a). Two other phenomena are also observed. The first shows the acceleration of raw material consumption (arrow ④.e) since F_1 produces more. As well, the breakdown of F_2 which can no longer remanufacture returns implies an increase in their inventory level $x_R(.)$ (arrow ⑤.f.). This increase stops when the storage space of returns is full ($x_R(.) = Z_R = 150$). As a result, all products returned from that time are disposed. This results in a non-zero disposal rate ($u_{dis}(.) = P_R.d = 40$, arrow ⑥.g). At the end of repair actions of F_2 ($\alpha_2(.) = 1$, arrow ⑦.b), $u_{rem}(.)$ is at its maximum due to stored returns.

Several interesting phenomena also appear in this illustrative example. This is the case where both F_1 and F_2 are down (arrow ⑧.b). $x_{FP}(.)$ continues decreasing until the stock of the finished product runs out. In this case, customers are no longer satisfied because of the finished product shortage. As a result, the flow of used products is stopped after a given delivery lead time τ_R because they are no longer available in the market. Indeed, returns depend on the quantity of the products used in the market. If there are no products in the market at the time t, then the returns will be zero at $t + \tau_R$ (arrow ⑨.c). Unlike the literature where raw materials and returns are available continuously, the last situation implies the starvation of F_2 (the remanufacturing activity is stopped in the interval [1575, 1578], arrow ⑩.a). The rate of returns becomes strictly positive only when F_1 or F_2 or both produce finished products again, which means that a percentage of customers are satisfied (see equation (2.15)). In this example, the first products returned after the starvation period ($u_R = U_{max}^{rem} \times P_R = 20$, arrow ⑪.c) are due to the repair of F_2 (arrow ⑫.b), which benefits from stored returns to operate at maximum capacity. In the same sense, u_R further increases to $u_R = \left(U_{max}^{pro} + U_{max}^{rem}\right).P_R = 68$ (arrow ⑬.c) when F_1 is repaired in turn. Since this rate of returns is greater than the production capacity of the machine, their stock is being replenishing ($x_R(.) > 0$, arrow ⑭.f). Similarly, u_R will change to $u_R(.) = P_R.d = 40$ once x_{FP} becomes positive while considering τ_R. For example, at $x_{FP}(.) = 50$ (arrow ⑮.d), the system satisfies all customer demand in addition to feed the stock of finished products ($U_{max}^{pro} + U_{max}^{rem} > d$). This means that the sold products will supply the market at the demand rate.

2.4.4 Design of experiments (DOE) and response surface methodology (RSM)

The optimization approach applied to find the optimal control parameters of the proposed control policy defined in Section 2.4.2 consists of a combination of the DOE and the RSM. The selected control parameters are Z_{FP}, S_{RM}, Q_{RM} and Z_R, while Z_{RM} will be calculated as follow: $Z_{RM} = S_{RM} + Q_{RM}$ to minimize the cost of raw materials storage space (see the end of Section 2.4.2.3). This will reduce the number of experiments needed to obtain the control parameters minimizing the incurred total cost. The optimization approach is summarized in two steps: (i) determine the relationship between the system response (the total cost), the main factors (Z_{FP}, S_{RM}, Q_{RM} and Z_R), their interactions and their quadratic effects (see equation (2.17)). Only the factors which have a significant effect on the total cost are retained. (ii) Calculate the optimal control policy parameters which minimize the total cost.

2.5 Numerical example

A numerical example is presented for illustrative purposes. The adopted system's data are based on the literature of optimal control and inventory management. They are listed in Table 2.2. Note that in practical situations these parameters can be estimated from historical data. The cost parameters were chosen so that $c_{FP}^{+} < c_{FP}^{-}$ and $c_{FP}^{rem} < c_{FP}^{pro}$. The last inequality is used since the process of remanufacturing is less expensive than the manufacturing of a new product type (Ferguson, 2010). In addition, according to the procurement policy of raw materials which requires $0 \leq S_{RM} < Q_{RM}$, a new variable δ is used to replace S_{RM}. It is defined by: $\delta = \frac{S_{RM}}{Q_{RM}} =,\ 0 \leq \delta < 1$. As explained in the previous section, Z_{RM} is calculated using $\mathrm{S_{RM}}$ and $\mathrm{Q_{RM}}$ and only four control parameters ($\mathrm{Z_{FP}^*}$, $\mathrm{S_{RM}^*}$, $\mathrm{Q_{RM}^*}$, $\mathrm{Z_R^*}$) will be optimized.

Table 2.2 Some parameters for the numerical example

Parameters	c_{FP}^{+}	c_{FP}^{-}	c_{FP}^{pro}	c_{FP}^{rem}	c_{RM}^{unit}	c_{RM}^{+}	T_{cm}	T_f
Values	1	50	10	5	10	0.5	Log-N(5,1)	Log-N(150,10)
Parameters	c_R^{+}	c_R^{unit}	U_{max}^{pro}	U_{max}^{rem}	d	τ_R	τ_{RM}	P_R
Values	0.5	10	120	50	100	N(15,1)	N(15,1)	N(0.4,0.05)

The maintenance parameters (T_f and T_{cm}) follow the log-normal distribution, while delivery lead times (τ_R and τ_{RM}) and the proportion of used products ready to be returned (P_R) follow the normal distribution. Note that these parameters could follow any probability distributions. Based on the statistical analysis (see Appendix I), both DOE and RSM are subsequently carried out to optimize the control parameters (Z_{FP}^*, S_{RM}^*, Q_{RM}^* and Z_R^*) which minimize the total cost function. The total cost function has been divided into two components. The first function C_{FP} represents the costs related to the production process such as manufacturing, remanufacturing, inventory and shortages. The second function $C_{RM\&R}$ covers the remaining costs especially regarding the supply of raw materials and returns. So, two response surface functions are extracted. Using the software Statgraphics, they are formulated as follow:

$$\begin{aligned} C_{FP} = {} & 4786.9 - 0.2\, Z_{FP} - 1745.7\, \delta - 0.6\, Q_{RM} - 0.65\, Z_R + 0.24\, Z_{FP}\delta + 3.74.\, 10^{-5}\, Z_{FP}Q_{RM} \\ & + 2.98\, 10^{-4} Z_{FP}Z_R + 0.685\delta Q_{RM} + 0.579\delta Z_R + 4.3\, 10^{-4} Q_{RM}Z_R \\ & - 4.1\, 10^{-5} Z_{FP}^2 + 1445.4\, \delta^2 + 7.4\, 10^{-5} Q_{RM}^2 + 9.810^{-4} Z_R^2 \end{aligned} \tag{2.17}$$

$$\begin{aligned} C_{RM\&R} = {} & 19{,}960.5 - 24{,}2Z_{FP} - 62{,}486.5\delta - 3{,}9Q_{RM} - 1{,}7Z_R + 38{,}3Z_{FP}\delta + 2.2\, 10^{-3} Z_{FP}Q_{RM} \\ & + 8\, 10^{-4} Z_{FP}Z_R + 5{,}406\delta Q_{RM} + 1{,}970\delta Z_R + 1.3\, 10^{-4} Q_{RM}Z_R - 9.1\ \ 10^{-3} Z_{FP}^2 \\ & + 56{,}132\delta^2 + 2.2\, 10^{-4} Q_{RM}^2 + 7.2\, 10^{-4} Z_R^2 \end{aligned} \tag{2.18}$$

Both C_{FP} and $C_{RM\&R}$ are summed together to express the total cost function of the considered system. The response surface plot obtained is shown in Figure 2.5. Table 2.3 presents the optimization results. It also contains the Student's t-test performed to cross-check the validity of the model. It confirms that the total cost (4056.49) falls within the 95% confidence interval [4045.30, 4146.42] obtained using 50 replications. Note that Z_{RM}^* is calculated as follow: $Z_{RM}^* = S_{RM}^* + Q_{RM}^* = 4{,}661.71$.

Table 2.3 Optimization results

Factor	Z^*_{FP}	S^*_{RM}	Q^*_{RM}	Z^*_R	**Total cost**	**Confidence interval (95%)**
Value	348.84	892.81	3768.90	209.58	4056.49	[4045.30, 4146.42]

The current numerical example confirms the relevance of the adopted simulation-based optimization approach and its ability to address a parameterized structure of control policies where the control parameters and the associated total cost are optimized providing details of outcomes. These characteristics are well adapted to evaluate the dynamic behaviour of joint decisions across several system configurations (see Section 2.6.2). The practical implementation of the results of this numerical example is discussed in the Section 2.6.1.

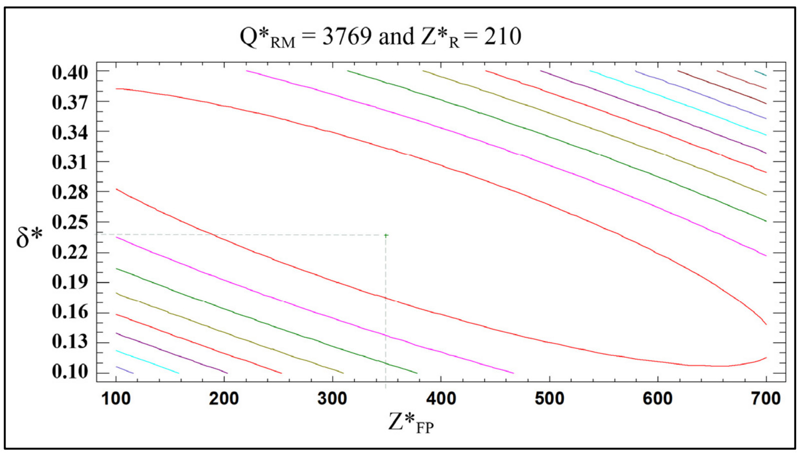

Figure 2.5 Total cost response surface under the proposal

2.6 Application and implementation

This section presents an example of how implementing the proposed structure of control policies in real context and the sensitivity analysis confirming its effectiveness.

2.6.1 Implementation of the proposed control policies

The implementation in real context of our structure of integrated production and supply control policies requires an effective dynamic production-inventory control. This control bears on monitoring stocks level (inventory positions of stocks) and the state of production facilities. The manager should continuously monitor these elements to make proper adjustments to system operations. In this sense, three thresholds are used: two for safety stock decisions of returns and finished products and the other one for raw materials supply. The proposed control policies structure is considered acceptable for practical production control enabling the system to operate smoothly and methodically. A logical schema chart is illustrated in Figure 2.6 to simplify its implementation through decision-making. For the basic case (Section 2.5), it presents how integrated decisions on procurement of raw materials and rates of manufacturing, remanufacturing and disposals setting should be made. For illustrative purpose only, we adopt the obtained average value of P_R that is 0.4 as in Figure 2.4. Thus, $u_{\mathrm{R}} = 40$ at most of the time. The dotted line represents this link between manufacturing and remanufacturing activities. Because of its low operating costs, the facility F_2 remanufactures as many returned products as possible while the remaining quantity to reach customer demand is manufactured by F_1.

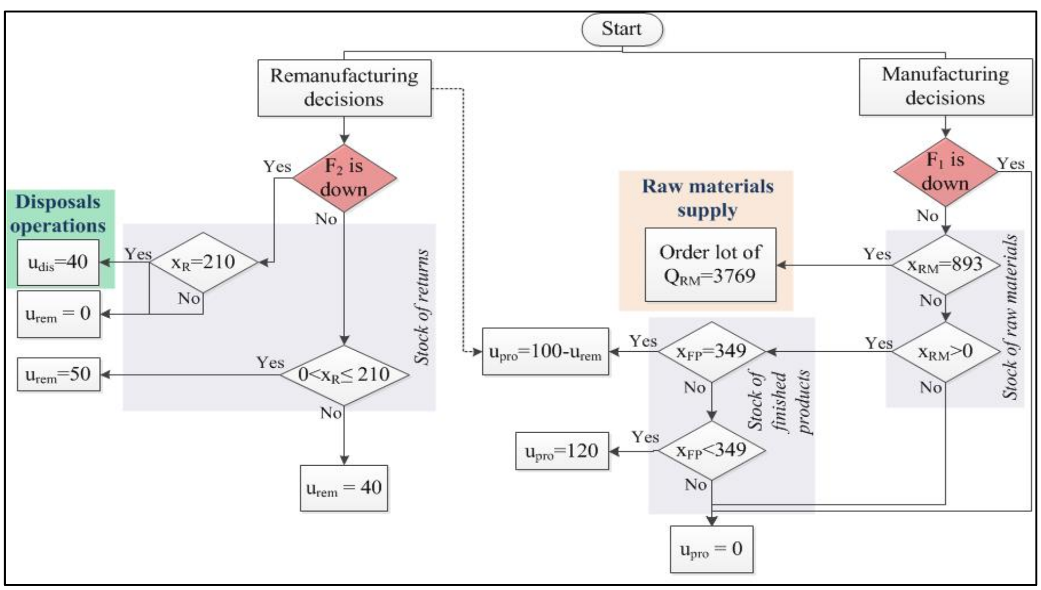

Figure 2.6 Implementation logic chart of integrated control policies

2.6.2 Sensitivity Analysis

A sensitivity analysis is conducted to confirm the effectiveness of the proposed control policy and to assess the influence of different system's variables on control parameters (Z_{FP}^*, S_{RM}^*, Q_{RM}^*, Z_R^*). As shown below, the obtained results make sense and confirm that varying the control parameters evolves as expected with respect to system parameter variations.

2.6.2.1 Effect of the system's cost variation

The system's cost variables chosen to vary for carrying out the analysis are presented in Table 2.4 and the effect of varying each of them is observed. Complementary performance indices are also included: the average manufacturing rate (Q_{Pro}^*), the average remanufacturing rate (Q_{Rem}^*) and the average rate of disposals (Q_{dis}^*). These indices were obtained from the simulation model when the optimal solutions are implemented. Table 2.4 shows that the cost parameters used in this analysis influence the value of the control parameters (Z_{FP}^*, S_{RM}^*, Q_{RM}^*, Z_R^*) and Q_{dis}^*. However, they do not have significant effects on Q_{Pro}^* and Q_{Rem}^* which are subject to several random phenomena (delivery lead times, rate of returns, and failure of facilities). This can be explained by the priority given to the remanufacturing activity expressed by (2.13). Indeed, to satisfy the customer demand (d), F_1 works as a support to F_2, such that the sum of Q_{Pro}^* and Q_{Rem}^* is always equal to d. Furthermore, F_2 operates according to the rate of returns (u_R) and their availability in stock whatever the value of its cost parameters. Therefore, more questions remain to be addressed particularly with regards to how u_R could influence Q_{Pro}^* and Q_{Rem}^* (see Section 2.6.2.2). Besides, the analysis indicates a significant impact of Z_R^* on Q_{dis}^*. When Z_R^* increases, the storage space dedicated to returns is larger, then the system will have fewer disposals (Q_{dis}^* decreases).

The results summarized in Table 2.4 show that the control parameters of the proposed control policy move as predicted from a practical point of view which confirm the validity of our model. For instance, when c_{FP}^+ or c_{FP}^e of finished products (FP) increases (cases 2 and 22), their storage space Z_{FP}^* decreases to avoid additional costs of the penalized inventory. This reduction results in a greater risk of stock-outs, hence the increase of S_{RM}^{*}, Q_{RM}^{*} and Z_{R}^{*}. The goal is to increase the availability of returns and raw materials (RM) in stocks. In relation to the manufacturing activity, when increasing c_{FP}^{pro} (case 6), the system further encouraging prioritization of returns by increasing Z_{R}^{*} and reducing both S_{RM}^{*} and Q_{RM}^{*}. This leads to an increase of the stock-outs and thus Z_{FP}^{*}. c_{FP}^{rem} has an inverse effect since the system produces FP from either RM using F_1 or returns using F_2. Table 2.4 also shows that with the increase of c_{RM}^{ord} (case 10), we should order a larger Q_{RM}^{*}, but less frequently (S_{RM}^{*} decreases) to reduce the number of RM orders. In this way the system has a higher average level of RM stored allowing the model to make savings by reducing Z_{FP}^{*} and Z_{R}^{*}. The increase of c_{RM}^{unit} (case 12) has the same effect as c_{RM}^{+} (case 14) and c_{RM}^{e} (case 24). It causes a reduction of both S_{RM}^{*} and Q_{RM}^{*} to avoid additional costs related to the storage of RM. This increases the probability of starvation of F_1 leading to higher Z_{FP}^{*} and Z_{R}^{*} with the aim to reduce the risk of stock-outs of FP. For the cost parameters related to returns, the increase of c_{R}^{unit} (case 16) does not have a significant effect on Z_{R}^{*}. Indeed, the adopted return policy for used products (see equation (2.15)) does not depend on c_{R}^{unit} or Z_{R}^{*}, but rather on sales. However, at increasing c_{R}^{+} (case 18) or c_{R}^{e} (case 26), it is normal to reduce the total holding costs of returns, thus Z_{R}^{*} decreases. In this situation where the risk of the starvation of F_2 is higher, the model uses RM by storing more quantities of them (Q_{RM}^{*} and S_{RM}^{*} increase). Since disposals are activated when $x_{\mathrm{R}} = Z_{R}^{*}$, the model reacts to the increase of c_{R}^{dis} (case 20) by increasing Z_{R}^{*} to reduce Q_{dis}^{*}.

The sensitivity analysis will be extended to study the effect of the variation of some key variables (the delivery lead time of RM and the rate of returns) which have been overlooked by many works addressing the PPC of HMRS.

2.6.2.2 Effect of the variation of the delivery lead time of both returns (τ_R) and raw materials (τ_{RM}) as well as the rate of returns (u_R)

Another set of the system's configurations is tested to provide a better understanding of how τ_{RM}, τ_R and u_R can influence the control parameters. The results obtained are presented in Table 2.5. They show that the increase of τ_{RM} (case 28) prompts the model to adopt a higher

S_{RM}^* and a larger Q_{RM}^*. In addition, data show that the percentage of FP manufactured from RM is almost 57% of total sales. This situation makes sure that τ_{RM} is an important factor in the generation of FP shortages which are expensive. It is for this reason that the model also increases Z_{FP}^* and Z_R^*. Another interesting phenomenon is that the variation of τ_R (cases 29 and 30) has no significant influence on the control parameters. Unlike RM, this is due to the continuous flow of returns, which depend on P_R (see equation (2.15)). Then, varying τ_R only changes the curve form of u_R, but the total quantity of returns received for remanufacturing will be the same regardless of the value of τ_R. An example of the effect of τ_R on the rate of returns is presented in the ure 4.c. Table 2.5 also shows that the increase of u_R (case 32) which means a larger quantity of used products will return to the system, involves higher Z_R^* to preserve these returns as much as possible. As a result, the system has a greater capacity to produce FP (using these returns). Therefore, Q_{Rem}^* increases while Q_{Pro}^* decreases, such that the sum of Q_{Pro}^* and Q_{Rem}^* is always equal to the customer demand. Unlike other scenarios, the increase of Z_R^* implies the increase of Q_{dis}^*. This is due to higher u_R which fills their stock faster and thus generates more disposals. Moreover, thanks to the reduced price of remanufacturing compared to the manufacturing, the total cost decreases.

Table 2.4 Sensitivity analysis for different costs variations

Cost parameter		Case	value	Optimal control parameters				parameters	Total cost	Remark
				Z_{FP}^*	S_{RM}^*	Q_{RM}^*	Z_R^*	Q_{dis}^*	C_T^*	
		Base		348.84	892.81	3768.90	209.58	0.321	4056.49	Base for the comparison
Finished products	c_{FP}^+	1	0.5	437.72	785.68	3685.44	203.89	0.410	3871.36	$Z_{FP}^* \uparrow, S_{RM}^* \downarrow, Q_{RM}^* \downarrow, Z_R^* \downarrow$
		2	1.5	251.70	1021.21	3867.24	214.98	0.194	4198.89	$Z_{FP}^* \downarrow, S_{RM}^* \uparrow, Q_{RM}^* \uparrow, Z_R^* \uparrow$
	c_{FP}^-	3	40	304.30	933.91	3762.64	204.80	0.325	3988.99	$Z_{FP}^* \downarrow, S_{RM}^* \uparrow, Q_{RM}^* \downarrow, Z_R^* \downarrow$
		4	60	378.12	866.17	3769.60	214.23	0.318	4115.61	$Z_{FP}^* \uparrow, S_{RM}^* \downarrow, Q_{RM}^* \uparrow, Z_R^* \uparrow$
	c_{FP}^{pro}	5	7	345.06	898.33	3774.80	206.40	0.325	3881.86	$Z_{FP}^* \downarrow, S_{RM}^* \uparrow, Q_{RM}^* \uparrow, Z_R^* \downarrow$
		6	13	352.48	887.54	3763.19	212.47	0.315	4231.02	$Z_{FP}^* \uparrow, S_{RM}^* \downarrow, Q_{RM}^* \downarrow, Z_R^* \uparrow$
	c_{FP}^{rem}	7	2	352.53	887.49	3763.17	212.47	0.301	3931.02	$Z_{FP}^* \uparrow, S_{RM}^* \downarrow, Q_{RM}^* \downarrow, Z_R^* \uparrow$
		8	8	345.11	898.21	3774.96	206.49	0.329	4181.85	$Z_{FP}^* \downarrow, S_{RM}^* \uparrow, Q_{RM}^* \uparrow, Z_R^* \downarrow$
Raw materials	c_{RM}^{ord}	9	4500	351.90	898.68	3684.07	210.15	0.290	3978.64	$Z_{FP}^* \uparrow, S_{RM}^* \uparrow, Q_{RM}^* \downarrow, Z_R^* \uparrow$
		10	5500	346.15	885.62	3845.76	208.70	0.352	4132.63	$Z_{FP}^* \downarrow, S_{RM}^* \downarrow, Q_{RM}^* \uparrow, Z_R^* \downarrow$
	c_{RM}^{unit}	11	5	343.00	901.49	3778.66	204.56	0.357	3764.59	$Z_{FP}^* \downarrow, S_{RM}^* \uparrow, Q_{RM}^* \uparrow, Z_R^* \downarrow$
		12	15	354.49	884.44	3759.26	214.18	0.301	4348.14	$Z_{FP}^* \uparrow, S_{RM}^* \downarrow, Q_{RM}^* \downarrow, Z_R^* \uparrow$
	c_{RM}^+	13	0.3	275.28	1033.36	4224.42	206.69	0.324	3641.89	$Z_{FP}^* \downarrow, S_{RM}^* \uparrow, Q_{RM}^* \uparrow, Z_R^* \downarrow$
		14	0.7	409.03	780.76	3310.64	211.94	0.316	4403.48	$Z_{FP}^* \uparrow, S_{RM}^* \downarrow, Q_{RM}^* \downarrow, Z_R^* \uparrow$
Returns	c_R^{unit}	15	5	355.42	883.77	3759.07	209.49	0.334	3845.48	$Z_{FP}^* \uparrow, S_{RM}^* \downarrow, Q_{RM}^* \downarrow, Z_R^* \leftrightarrow$
		16	15	341.95	902.43	3779.24	209.60	0.299	4267.27	$Z_{FP}^* \downarrow, S_{RM}^* \uparrow, Q_{RM}^* \uparrow, Z_R^* \leftrightarrow$
	c_R^+	17	0.3	350.30	889.94	3764.59	218.27	0.311	4049.11	$Z_{FP}^* \uparrow, S_{RM}^* \downarrow, Q_{RM}^* \downarrow, Z_R^* \uparrow$
		18	0.7	347.52	895.65	3773.24	200.15	0.372	4063.58	$Z_{FP}^* \downarrow, S_{RM}^* \uparrow, Q_{RM}^* \uparrow, Z_R^* \downarrow$
	c_R^{dis}	19	50	355.46	888.72	3767.43	141.48	0.645	4031.96	$Z_{FP}^* \uparrow, S_{RM}^* \downarrow, Q_{RM}^* \downarrow, Z_R^* \downarrow$
		20	150	343.04	897.61	3772.91	249.16	0.285	4071.86	$Z_{FP}^* \downarrow, S_{RM}^* \uparrow, Q_{RM}^* \uparrow, Z_R^* \uparrow$
Storage spaces	c_{FP}^e	21	$0.8\ (c_{FP}^e)_b$ (a)	431.76	787.41	3684.45	204.17	0.361	3889.70	$Z_{FP}^* \uparrow, S_{RM}^* \downarrow, Q_{RM}^* \downarrow, Z_R^* \downarrow$
		22	$1.2\ (c_{FP}^e)_b$ (a)	266.01	1002.04	3853.66	214.70	0.200	4189.28	$Z_{FP}^* \downarrow, S_{RM}^* \uparrow, Q_{RM}^* \uparrow, Z_R^* \uparrow$
	c_{RM}^e	23	$0.8\ (c_{RM}^e)_b$ (a)	348.34	893.74	3778.36	209.40	0.332	3991.31	$Z_{FP}^* \downarrow, S_{RM}^* \uparrow, Q_{RM}^* \uparrow, Z_R^* \downarrow$
		24	$1.2\ (c_{RM}^e)_b$ (a)	349.42	891.72	3759.06	209.76	0.317	4121.65	$Z_{FP}^* \uparrow, S_{RM}^* \downarrow, Q_{RM}^* \downarrow, Z_R^* \uparrow$
	c_R^e	25	$0.8\ (c_R^e)_b$ (a)	351.34	890.79	3762.75	269.09	0.240	3988.63	$Z_{FP}^* \uparrow, S_{RM}^* \downarrow, Q_{RM}^* \downarrow, Z_R^* \uparrow$
		26	$1.2\ (c_R^e)_b$ (a)	346.30	894.83	3775.27	149.73	0.576	4112.41	$Z_{FP}^* \downarrow, S_{RM}^* \uparrow, Q_{RM}^* \uparrow, Z_R^* \downarrow$

(a) The cost of the storage space used in the sensitivity analysis is equal to "$k.\ (c_i^e)_b$", $i = \{FP, RM, R\}$, with, $k = 0.8$ or 1.2 and $(c_i^e)_b$ represent the cost of the storage space of i for the base case (see Section 2.3.3 after equation (2.9)).

Table 2.5 Other changes in system settings for sensitivity analysis

Case	Parameter's variation (b)			Optimal control parameters				Other parameters			Total cost C_T^*	Remark
	$\mu_{\tau_{RM}}$	μ_{τ_R}	μ_{u_R}	Z_{FP}^*	S_{RM}^*	Q_{RM}^*	Z_R^*	Q_{Pro}^*	Q_{Rem}^*	Q_{dis}^*		
Base	15	15	0.4	348.84	892.81	3768.90	209.58	58.02	41.98	0.321	4056.49	Base for the comparison
	Sensitivity of the mean of τ_{RM}											
27	10	15	0.4	324.76	721.96	3648.50	166.84	58,13	41,87	0,478	3942.05	$Z_{FP}^* \downarrow, S_{RM}^* \downarrow, Q_{RM}^* \downarrow, Z_R^* \downarrow, C_T^* \downarrow$
28	20	15	0.4	385.02	1075.23	3900.67	270.35	56,99	43,01	0,268	4175.80	$Z_{FP}^* \uparrow, S_{RM}^* \uparrow, Q_{RM}^* \uparrow, Z_R^* \uparrow, C_T^* \uparrow$
	Sensitivity of the mean of τ_R											
29	15	5	0.4	348.36	892.44	3765.74	209.47	57,76	42,24	0,320	4055.95	$Z_{FP}^* \leftrightarrow, S_{RM}^* \leftrightarrow, Q_{RM}^* \leftrightarrow, Z_R^* \leftrightarrow$
30	15	25	0.4	349.70	892.83	3772.38	210.10	57,70	42,30	0,322	4056.84	$Z_{FP}^* \leftrightarrow, S_{RM}^* \leftrightarrow, Q_{RM}^* \leftrightarrow, Z_R^* \leftrightarrow$
	Sensitivity of the mean of $u_R(.)$											
31	15	15	0.3	384.54	998.54	3941.69	185.94	67,65	32,35	0,053	4130.50	$Z_{FP}^* \uparrow, S_{RM}^* \uparrow, Q_{RM}^* \uparrow, Z_R^* \downarrow, C_T^* \uparrow$
32	15	15	0.5	322.23	797.72	3606.08	238.14	52,33	47,67	3,304	3989.61	$Z_{FP}^* \downarrow, S_{RM}^* \downarrow, Q_{RM}^* \downarrow, Z_R^* \uparrow, C_T^* \downarrow$

(b) $\mu_{\tau_{RM}}$, μ_{τ_R} and μ_{u_R} respectively represent the mean of the parameters τ_{RM}, τ_R and u_R following a normal distribution (see Table 2.2).

2.7 Comparative study of proposed policies and those implemented from literature

This section aims primarily to compare the economic performance of our proposed control policy with the closest ones found in the literature after being implemented in our context. It addresses the questions: What happens if we implement the policies of the literature in our system presented in Figure 2.1? What is the economic benefit of the proposed control policy? As mentioned in the introduction, the proposed control policy is inspired by the reality of HMRS by including elements that existing ones have ignored such as procurement and random delivery lead time of RM and returns as well as storage space sizing of FP, RM and returns. Therefore, the implementation of the adopted policies in our context requires adjustments to calculate their total cost. Indeed, they are implemented by including the costs that they did not consider and adding new parameters that should be optimized sequentially to minimize their incurred total cost. A total of five-control policies is considered (see below). The choice of the first three policy categories is due to the proximity of the cases that they considered compared to our system. The consideration of the two others aims to show the importance of considering delivery lead times and storage space costs that are often overlooked in the literature.

- CP_1: Policies that consider continuous availability of RM and returns making the manufacturing and remanufacturing activities start whenever appropriate;
- CP_2: Policies where the returns are a constant proportion of the customer demand (u_R=P_R.d, P_R is a constant) and the RM are always available when needed;
- CP_3: Policies which assume that returns follow a Poisson process with mean P_R.d and continuous availability of RM;
- CP_4: Policies that consider negligible delivery lead-time of RM (τ_{RM}) and returns (τ_R);
- CP_5: Policies that consider negligible storage space costs of FP, RM and returns.

Using the same experimental approach as in Section 2.4.4, additional experiments were then conducted to determine the optimal total cost of these control policies sequentially. At first, only $\mathrm{Z}^*_{\mathrm{FP}}$ is optimized for CP_1 (no disposal policy is considered since CP_1 considers continuous availability of returns) and both $\mathrm{Z}^*_{\mathrm{FP}}$ and $\mathrm{Z}^*_{\mathrm{R}}$ are optimized for CP_2 and CP_3. No costs related to RM supply are considered. The obtained values are used in the second step to constitute the studied system while integrating missing elements like the RM procurement policy, τ_{RM}, τ_R

and the costs involved. The same experimental approach is once again used to optimize both S^*_{RM} and Q^*_{RM} and to calculate the incurred total cost. In total, the four control parameters are optimized but sequentially for $\mathrm{CP_1}$, $\mathrm{CP_2}$ and $\mathrm{CP_3}$. For $\mathrm{CP_4}$ and $\mathrm{CP_5}$, the control parameters are first optimized considering negligible delivery lead times and negligible storage spaces costs respectively. The obtained results are then injected in our model by considering respectively random delivery lead times and storage space costs while calculating the related total cost.

Recall that the goal is to be able to compare the optimal total cost of the five policies with that obtained by our integrated control policies on the same basis (our context) and to establish the appropriate relative performance. For the base case, the optimal total costs obtained by the five policies $\mathrm{CP_i}$, $\mathrm{i} = \{1,2,3,4,5\}$ are 5040.29$, 4743.40$, 4776.10$, 8127.27$ and 4547.74$ respectively compared to 4056.49$ obtained by our integrated control policies. This increase in the total cost generated by the implementation of these five policies from the literature depends on the characteristics of each one. In this sense, assuming continuous availability of RM with continuous availability of returns for $\mathrm{CP_1}$ or limited quantity of returns compared to demand for $\mathrm{CP_2}$ and $\mathrm{CP_3}$, allows the optimization approach to adopt smaller $\mathrm{Z_{FP}}$ and $\mathrm{Z_R}$. Thus, when implemented in our system, their storage space sizes generate greater shortages. The same phenomenon explains the higher total cost generated by $\mathrm{CP_4}$. Indeed, assuming negligible τ_{RM} and τ_R, the results show that $\mathrm{CP_4}$ adopts a smaller $\mathrm{Z_R}$ and a zero $\mathrm{S_{RM}}$. So, when it's implemented in our system, a greater number of returns are disposed, and greater shortages are generated since $\mathrm{Q_{RM}}$ arrives later. For $\mathrm{CP_5}$, the optimization approach shows that when assuming negligible storage space costs, larger $\mathrm{Z_{FP}}$ and $\mathrm{Z_R}$ are adopted. Therefore, when implemented in our system, the total cost of $\mathrm{CP_5}$ is higher due to greater costs of storage spaces.

Table 2.6 summarizes the optimal cost difference between the proposed structure of control policies and five policy categories implemented from the literature for the 26 scenarios of the sensitivity analysis from Table 2.4. This difference in the total cost is expressed by: $\mathrm{DC_i} = [(\mathrm{C_i^*} - \mathrm{C_T^*})/\mathrm{C_i^*}].100$, $\mathrm{i} = \{1,2,3,4,5\}$ with $\mathrm{C_T^*}$ and $\mathrm{C_i^*}$ represent the optimal total cost when our integrated control policies and the policy $\mathrm{CP_i}$ are used respectively. The gain obtained varies between 6.26% and 54.14% and shows the economic advantage of jointly considering manufacturing, remanufacturing and disposal activities as well as storage space sizing and procurement of RM in the decisions-making process. This is due to the significant interactions between these elements, as shown in the analysis of variance (see Appendix I) and in Figure 2.4 which illustrates the functioning of the considered HMRS. In addition, the importance of considering the sizing of stocks (including that of RM and returns) results from the fact that uncertainties (τ_{RM} and τ_R) affect the level of inventories which in turn, influence the continuity of the production process and the total cost incurred. This result is in line with the principle that an integrated control which considers simultaneously several parameters, leads to better performances than following a sequential approach.

Table 2.6 Optimal cost difference (%) between the proposed control policies and five policy categories most close to our system

Control policies	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**	**Case 8**	**Case 9**
DC_1	18,29	20,71	19,12	19,86	16,48	22,34	17,61	21,34	17,63
DC_2	12,73	16,16	14,38	14,53	11,12	17,60	12,25	16,60	12,49
DC_3	13,38	16,69	14,79	15,28	11,75	18,14	12,87	17,16	13,07
DC_4	49,75	50,42	45,25	54,14	48,94	51,18	49,36	50,80	49,54
DC_5	6,26	14,92	10,78	10,82	7,32	14,03	8,20	13,26	9,24
	Case 10	**Case 11**	**Case 12**	**Case 13**	**Case 14**	**Case 15**	**Case 16**	**Case 17**	**Case 18**
DC_1	21,27	14,33	24,12	14,59	23,59	16,16	22,62	19,52	19,52
DC_2	16,33	8,72	19,56	8,97	19,06	10,65	17,99	14,42	14,54
DC_3	16,90	9,38	20,09	9,54	19,49	11,30	18,53	15,01	15,12
DC_4	50,62	48,16	51,87	48,72	51,38	48,83	51,28	50,03	50,15
DC_5	12,31	6,84	14,06	6,56	14,03	6,35	14,85	10,54	11,06
	Case 19	**Case 20**	**Case 21**	**Case 22**	**Case 23**	**Case 24**	**Case 25**	**Case 26**	
DC_1	18,26	20,73	18,22	20,78	18,57	20,44	18,87	20,15	
DC_2	14,11	14,85	12,26	15,89	13,02	15,17	13,11	15,81	
DC_3	14,67	15,46	13,25	13,25	13,99	16,12	13,99	16,12	
DC_4	49,85	50,32	49,47	50,69	49,74	50,43	49,72	50,45	
DC_5	10,55	11,05	6,70	14,56	9,53	12,04	9,00	12,53	

2.8 Conclusion

The integration of procurement strategies of raw materials (RM) as well as storage space sizing of RM, returns and finished products (FP) has been overlooked in previous works addressing the PPC within HMRS. Nevertheless, these components are often observed simultaneously in real-life supply chain of an original equipment manufacturer where both RM and returns are used in their production process. In this paper, a new structure of joint control policies is proposed integrating simultaneously the manufacturing, remanufacturing and disposal operations as well as the procurement of RM. It can be applied in several industries where unreliable HMRS must manage the flow of RM, returns and FP in a dynamic and stochastic context. An experimental approach combining simulation, experimental design and response surface methodology is then applied. It allows determining the optimal values of control parameters (including the storage space sizing of FP, RM and returns) which minimize the total incurred cost. The latter includes manufacturing, remanufacturing, RM orders, returned products from the market, storage spaces and disposal costs as well as inventory and backlog costs of FP.

Based on a series of numerical examples, an extensive sensitivity analysis is conducted to assess the effectiveness of the proposed structure of joint control policies and to study the reaction of the optimal control parameters in response to changes of system's configurations. A comparative study is also performed including five policy categories most close to our system after being implemented from the literature. In addition to the economic benefit obtained, it shows that having an overview of the HMRS including uncertainties and both RM and returns procurement in decision-making as proposed, is very important to represent the current reality and to provide a better understanding of interactions involving manufacturing, remanufacturing and disposal activities. Our research could be embellished in several ways. Future research can incorporate uncertainty in customer demand involving multiple products. It can also explore several return policies with different percentage of returns as well as the extent to which returns are no longer economically beneficial for different system's configurations.

CHAPITRE 3

PRODUCTION AND SETUP CONTROL POLICY FOR UNRELIABLE HYBRID MANUFACTURING-REMANUFACTURING SYSTEMS

Morad Assid [a], Ali Gharbi [b], Adnène Hajji [c],

[a, b] Department of Systems Engineering, École de Technologie Supérieure,
1100 Notre-Dame Ouest, Montréal (QC), Canada H3C 1K3
[c] Department of Operations and Decision Systems & CIRRELT. Laval University,
2325, rue de la Terrasse Québec (QC), Canada G1V 0A6

Paper published in *Journal of Manufacturing Systems*, January 2019.

Résumé

Ce travail porte sur le problème de planification et de contrôle de la production dans les systèmes hybrides de fabrication-refabrication où la demande clientèle peut être satisfaite par deux sources alternatives de production : la fabrication de nouvelles unités (mode de fabrication) et la refabrication d'unités récupérées (mode de refabrication). Malgré son importance et son impact économique majeur, ce problème reste à peine exploré pour les systèmes composés d'une installation commune non fiable utilisant des opérations de setup pour basculer entre les deux modes. Par rapport aux systèmes de fabrication traditionnels, le développement de stratégies adaptatives pour gérer simultanément les opérations de fabrication, de refabrication, de rejet et de setup ainsi que la détermination des espaces de stockage appropriés, devient plus difficile. L'objectif principal est d'établir une nouvelle politique de commande pour une coordination efficace de ces opérations. Ce travail vise également à déterminer le dimensionnement de l'espace de stockage des produits finis et des retours, tout en minimisant le coût total encouru. En observant la complexité des solutions analytiques et numériques, trois politiques de commande de production et de setup trouvées dans la littérature sont adaptées à notre contexte puis analysées. La politique de commande proposée est ensuite développée en utilisant une approche d'optimisation basée sur la simulation qui offre une technique puissante pour contrôler le système considéré, tout en reflétant mieux la réalité industrielle. La proposition identifie les conditions dans lesquelles le fabricant doit produire de nouveaux produits ou des produits refabriqués pour réaliser des économies. Une étude approfondie comparant les politiques de commande considérées à travers une large gamme de paramètres système est également réalisée. Les résultats obtenus donnent aux directeurs de production un aperçu intéressant des interactions qui existent entre les processus de production, les décisions de rejet des retours, les conditions de setup. Ils montrent également que la politique de commande proposée conduit aux meilleurs résultats en matière de coûts.

Mots-clés : politique de commande, système hybride de production, refabrication, setup, simulation, optimisation.

Abstract

This paper addresses the production planning and control problem within hybrid manufacturing-remanufacturing systems where demand can be met via two alternative sources of production: manufacturing of new items (manufacturing mode) and remanufacturing of returned items (remanufacturing mode). Despite its importance and economic impact, this problem remains scarcely explored for systems composed of one unreliable common facility using setup operations to switch between the two modes. Compared to traditional manufacturing systems, the development of adaptive strategies to manage simultaneously the manufacturing, remanufacturing, disposal and setup operations as well as the determination of appropriate storage spaces, becomes more challenging. The main objective is to elaborate a new control policy for an effective and efficient coordination of these operations. It also aims to determine the storage space sizing of both finished products and returns, while minimizing the total incurred cost. Observing the complexity of analytical and numerical solutions, three joint production and setup control policies found in the literature are adapted to our context and then analyzed. The proposed control policy is then derived by using a simulation-based optimization approach that offers a powerful technique to control the considered system, while better reflecting the industrial reality. It identifies the conditions under which the manufacturer should produce new products, or remanufactured products to gain cost savings. An in-depth study comparing the considered control policies across a wide range of system parameters is

also conducted. It gives insights to the related production managers and shows that the obtained control policy leads the best results in terms of costs.

Keywords: production control policy, remanufacturing, hybrid production system, setup policy, simulation, optimization.

3.1 Introduction

On the basis of the market dynamics, the diffusion of environmental legislations and the changing socio-economic environment, an increasing number of manufacturing enterprises are undertaking product recovery activities into their manufacturing systems (Atasu, Sarvary, & Van Wassenhove, 2008). The resulting production systems are known as hybrid manufacturing-remanufacturing systems (HMRS) and have become an important topic in the advanced manufacturing industry (Esmaeilian et al., 2016). Indeed, the option of remanufacturing is believed to recover as much as possible the economic and the ecological value due to the extension of the product's life and reduced energy and ultimate quantities of waste (Lund & Hauser, 2003). Companies such as IBM, Xerox, Hewlett Packard, Kodak, BMW are some examples to underline this economic and environmental importance of the remanufacturing industry (Atasu et al., 2008 ; Guide Jr & Van Wassenhove, 2009).

A major issue in HMRS is whether to perform both manufacturing and remanufacturing operations in a common facility or to devote each production mode in dedicated and separate facilities (Teunter et al., 2008). In this work, we consider HMRS where both manufacturing and remanufacturing activities reside on a common facility. Such systems are observed in several industries as the copier industry and in Hewlett Packard which remanufactures high-end servers on the same production facilities as new servers (Debo et al., 2006). They can reduce start-up costs for remanufacturing and lead to more savings in low returns rates situations (Teunter et al., 2008). A challenging problem in this context is the production planning and control (PPC) within HMRS, which should assist a manager coordinating and jointly controlling the production alternative sources for efficient management of productivity, inventories and resource utilization. Indeed, the coordination between the production processes when they are carried out in a common facility becomes particularly important to meet customer demand while achieving greater economy. However, this has a price, a significant level of increased complexity, which is reflected in control challenges as the interconnected actions of disposal operations and setup changes between the production modes. It is also linked to storage space sizing to avoid too large spaces where to store returns and finished products and to hedge against future capacity shortages caused by random facilities failures. Such spaces could be associated respectively with underused, and therefore more expensive, stocking positions or unmet customer demand including penalties generated by insufficient stock, and even the loss of customers. To the best of our knowledge, no work has addressed the PPC problem while simultaneously considering manufacturing, remanufacturing and disposal activities in the case of common facilities subject to random failures and non-negligible setup operations. Our main objective is to determine the manufacturing, remanufacturing and disposal rates, the storage space sizing of both returns and finished products as well as the sequence of setup operations minimizing the total incurred cost. This will be achieved considering previous works from the literature and an efficient simulation-based optimization approach, better aligned with the concerns of production managers.

The rest of the paper is structured as follows. Section 3.2 presents a brief overview of previous works related to the problem under study. The system description and the mathematical formulation of the control problem are presented in Section 3.3. Section 3.4 presents the control policies adapted to our context from the literature. In Section 3.5, the solution approach used to elaborate an efficient control policy is summarized. Section 3.6 describes the simulation model evaluating the system operation when each control policy is applied. A numerical example is presented in Section 3.7. Following a critical analysis, an improved control policy is proposed in Section 3.8. This is followed by an in-depth comparative study of the considered control policies for a wide variety of system settings in Section 3.9. The usefulness of the proposed solution approach and its extension to random customer demand and any failure and repair time distributions are presented in Section 3.10. Section 3.11 concludes the paper.

3.2 Literature review

There is a vast literature on the PPC problem within HMRS. Detailed literature reviews can be found in (Ilgin & Gupta, 2010 ; Lage & Godinho Filho, 2016). The literature on HMRS has also been growing at an increasing rate over the past two decades due to its challenging nature (see (Van Der Laan et al., 1999)). Although our research focus here is on HMRS performing both manufacturing and remanufacturing operations in common facilities, other research efforts, devoting each production mode in dedicated and separate facilities are also presented. Based on this mention, the most relevant works to this paper are grouped in two categories as presented in the summary Table 3.1. Another class dealing with manufacturing systems (without remanufacturing activities) will be further discussed, specifically focusing on setup policies. The considered papers are presented using comparison criteria related to the remanufacturing operation, the dependence between demands and returns rates, the disposal option, the non-negligible setup time and cost, the proposal of new structures of control policies, the failure-prone systems, the storage space sizing, the general probability distributions of failure and repair times and the random customer demand. In the rest of this section, we will be focusing on those papers while underlining our contributions.

Much attention has centred on PPC problems for HMRS where manufacturing and remanufacturing operations are devoted to dedicated facilities. Among the works of this category, Van Der Laan and Salomon (1997) extended the well-known Push and Pull control policy to efficiently coordinate production, remanufacturing and disposal operations. They showed that cost reductions can be obtained by means of disposals, which occur when the system inventories become too high. Dobos (2003) also integrated disposal activities and proposed an optimal production-inventory policy for HMRS minimizing the total cost. Teunter et al. (2008) showed that dedicated production lines for manufacturing and remanufacturing can lead to significant reductions in holding costs and increased scheduling flexibility. Guo and Ya (2015) investigated the optimal production policy for HMRS when the returns rate, the buyback cost and the remanufacturing cost depend on the quality level. Kim et al. (2013) and Vercraene et al. (2014) studied disposal decisions without considering the quality of returns.

They showed that state-dependent base-stock thresholds for manufacturing, remanufacturing and return acceptance characterize the optimal control policy. In the same sense, Gayon et al. (2017) developed a new structure of control policies integrating two different disposal options. These disposal options are related to conditions making it possible to decide to either dispose the returned products upon arrival, stock or remanufacture them. Fang et al. (2017) used five scenarios based on the production capacity and market demand to find the optimal operation strategy maximizing the total profit for a hybrid system with a substitutional relationship between new and remanufactured products. Kilic et al. (2018) addressed the stochastic economic lot sizing problems and proposed two heuristic policies to control manufacturing and remanufacturing operations while integrating service level constraints. As far as we know, Kenné et al. (2012) were the first who investigate the stochastic dynamics of facilities (subject to random failures and repairs). They used the methodology of stochastic dynamic programming and developed optimal manufacturing and remanufacturing control policy, which minimizes the expected discounted cost including the inventory holding and backlog costs. Ouaret et al. 2013) extended the previous work to HMRS with stochastic demand and showed that the optimal production policy is also of hedging-point type. Kouedeu et al. (2015) used a similar approach to develop a stochastic optimization model for the printer-cartridge industry. More recently, Ouaret et al. (2018) developed a stochastic optimization production planning and replacement model for an unreliable deteriorating hybrid system with random quality parts produced. They showed that the optimal production and replacement control policy is of hedging-point type.

In literature, the PPC problem for HMRS composed of common facilities with setup policy remains scarcely explored. Among the works of this category (see Category 2 in Table 3.1), Teunter et al. (2006) addressed the lot-sizing problem with setup costs and provide an algorithm to solve this problem. The main setup activities consist of calling new materials and changing of the workbench. Tang and Teunter (2006) addressed the multi-product economic lot-scheduling problem with returns based on a case study of a company, which manufactures and remanufactures car parts. Teunter et al. (2009) extended the results of (Tang & Teunter, 2006) and proposed simple heuristics that are very fast and can be applied in a spreadsheet package. In the same sense, Francas and Minner (2009) studied a multi-product network design problem and conclude that it is more advantageous to configure a single flexible production site if all the products are destined for the same market. The author's work investigated capacity planning and the advantages of the different network configurations for remanufacturing. Flapper et al. (2014) studied the optimal scheduling for HMRS with negligible setup times and costs using an approach based on the queueing theory. They proposed a production schedule that minimizes the average discounted long-term cost. Polotski et al. (2015) presented an optimal control model for HMRS integrating the system dynamics. For hybrid systems with low return rates, Polotski et al. (2017a) extended the results of (Polotski et al., 2015) by proposing a general structure of the optimal control policy that combines both setup and production activities. Analyses integrating the failure-prone systems case with non-negligible setup time are also conducted, but the failure and repair events are limited to homogeneous Markov processes. Systems characterized by a high level of return flow are addressed in (Polotski et al., 2017b).

The second class of the considered papers deals with manufacturing systems (without remanufacturing activities) which usually consist of one facility producing different product types to meet the corresponding customer demands. Thus, setup operations are intended to switch production from one product type to another. However, the conditions for switching between two products may change as well as the production rates. The first paper dealing with this class is Sharifnia et al. (1991) which investigated a single flexible machine setup scheduling problem and proposed a feedback setup scheduling policy using the surplus/backlog space of stocks to determine the times of setup changes. Several related studies have been conducted since then. For example, Elhafsi and Bai (1996) developed an optimal production and setup control policy with intervals of production at only maximal rates, while Gharbi et al. (2006) and Yang et al. (2000) proposed to use on-demand production rates in order to minimize the total cost. The advantages of choosing on-demand production rates over maximal production rates are discussed in (Assid et al., 2014). Further studies are still needed to take advantage of these works in the context of HMRS using setup operations to switch between production modes.

Table 3.1 Bibliographic review of the most relevant works to this research

Research works	Remanufacturing	Dependency of demands and returns	Random demand	Disposal option	Setup time and cost	Proposal of new policies	Failure-prone facilities	General probability distributions for failures	storage space sizing
Class I. Hybrid systems **Category 1. With dedicated facilities**									
(Van Der Laan and Salomon, 1997)	×		×	×		×			
(Dobos, 2003)	×	×		×		×			
(Teunter et al., 2008)	×	×							
(Guo & Ya, 2015)	×	×							
(Kim et al., 2013)	×		×	×		×			
(Vercraene et al., 2014)	×		×	×		×			
(Gayon et al., 2017)	×		×	×		×			
(C. C. Fang et al., 2017)	×	×	×	×		×			
(Kilic et al., 2018)	×		×			×			
(Kenné et al., 2012)	×					×	×		
(Ouaret et al., 2013)	×	×	×			×	×		
(Kouedeu et al., 2015)	×			×		×	×		
(Ouaret et al., 2018a)	×	×	×	×		×	×		
Category 2. With common facilities									
(Teunter et al., 2006)	×				×				
(Tang & Teunter, 2006)	×	×			×				
(Teunter et al., 2009)	×	×			×	×			
(Francas & Minner, 2009)	×	×	×	×					
(Flapper et al., 2014)	×	×	×			×			
(Polotski et al., 2015)	×	×			×				
(Polotski et al., 2017a)	×	×			×	×	×		
(Polotski et al., 2017b)	×	×			×	×	×		
Class II. manufacturing systems with setups									
(Sharifnia et al., 1991)					×	×	×		
(Elhafsi & Bai, 1996)					×	×			
(Yang et al., 2000)					×	×			
(Gharbi et al., 2006)			×		×	×	×	×	
(Assid et al., 2014)					×	×	×	×	
Our proposal	×	×	×	×	×	×	×	×	×

Unlike the above-developed models, the current work integrates simultaneously disposal options and storage space sizing of both finished products and returns, while considering general distributions of failures and repairs (given that all paper dealing the PPC within unreliable HMRS have assumed Markov processes for random events). These elements will better reflect the industrial reality but will bring greater managerial complexity. This paper contributes to the literature in several ways. It investigates the effective joint manufacturing, remanufacturing, disposal and setup control policies for unreliable HMRS composed of one common facility with the consideration of the related costs. It also generates valuable insights providing a better understanding of interactions involving manufacturing, remanufacturing, disposal and setup operations as well as storage space sizing of both returns and finished products. This will be achieved through a simulation-based optimization approach that offers a powerful technique to model such complex systems, gaining a better perspective of the needs of production managers.

3.3 Formulation of the control problem

This section defines the notations and assumptions used throughout this paper, as well as the problem statement.

3.3.1 Notation

We list below the notations used in the rest of the paper. Let $i \in \{M, R\}$ where "M" defines the manufacturing mode and "R" represents the remanufacturing mode.

γ_R	: Constant return proportion of customer demand, $0 \leq \gamma_R < 1$
c_F^+	: Finished products holding cost (\$/time unit/product)
c_F^-	: Finished products backlog cost (\$/time unit/product)
c_R^+	: Holding cost of returns (\$/time unit/product)
c_{dis}	: Disposal cost (\$/product)
c_{man}	: Manufacturing cost (\$/product)
c_{rem}	: Remanufacturing cost (\$/product)

c_F^e	: Storage space cost of finished products (\$/area)
c_R^e	: Storage space cost of returns (\$/area)
c_S^{ij}	: Setup cost while switching from mode i to mode j (\$/setup operation)
d	: Finished product demand rate (product/time unit)
N_S	: Number of setups over a period of 1000 units of time ($\mathrm{N}_S \in N$)
P_{man}	: Percentage of manufactured products compared to demand (%)
P_{rem}	: Percentage of remanufactured products compared to demand (%)
P_{dis}	: Percentage of disposed products compared to returns (%)
Q_F^+	: Average inventory of finished products (product)
Q_R^+	: Average inventory of returns (product)
Q_F^-	: Average shortage of finished products (product)
T_S^{ij}	: Setup time while switching from mode i to mode j (time unit)
$u_{man}(t)$	: Manufacturing rate at time t (product/time unit)
$u_{rem}(t)$	: Remanufacturing rate at time t (product/time unit)
$u_{dis}(t)$	: Disposal rate at time t (product/time unit)
$u_R(t)$	: Returns rate at time t (product/time unit)
U_{man}^{max}	: Maximum manufacturing rate (product/time unit)
U_{rem}^{max}	: Maximum remanufacturing rate (product/time unit)
$x_F(t)$	: Inventory level (or backlog) of finished products at time t (product)
$x_R(t)$	: Inventory level of returns at time t (product)
Z_F	: Storage space needed for finished products (product)
Z_R	: Storage space needed for returns (product)

3.3.2 System description

The structure of the considered HMRS is described in Figure 3.1. It consists of one facility subject to random failures and repairs. In such case, setup operations become unavoidable to switch from one production mode to another in order to fill the customer demand. It also presents common features encountered in many Original Equipment Manufacturers, which can remanufacture their own brands only as the fact that returns are limited compared to the quantity of sold products. Such a system is known as the main manufacturing system where remanufacturing process is characterized by a relatively low percentage of remanufactured products compared to demand (P_{rem}) and used mainly to meet environmental requirements and to improve the overall production performance.

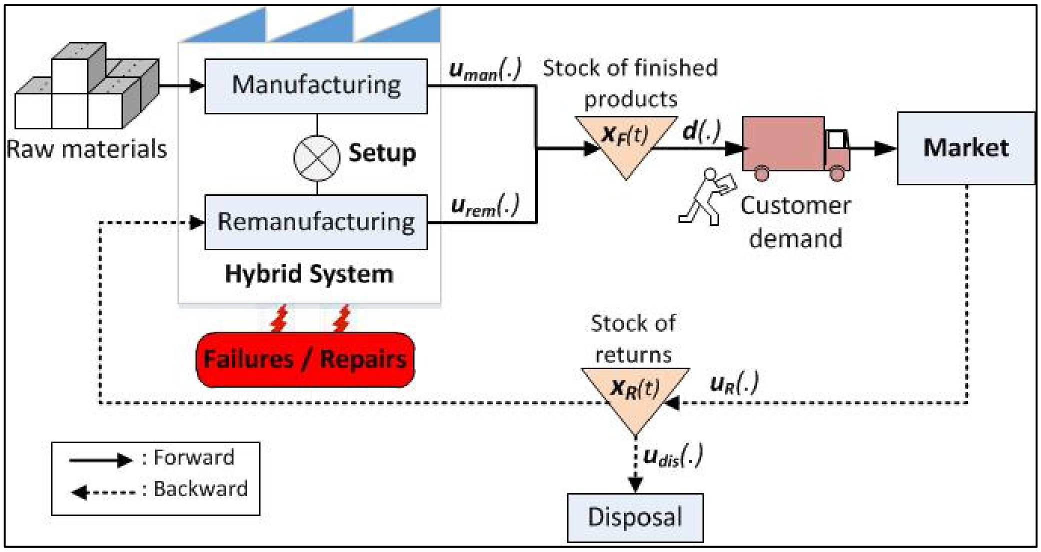

Figure 3.1 System structure

Two stocks are considered. The first one contains finished products ready to be delivered to customers, while the second one contains collected returns, which will be used for remanufacturing. The possibility to reject some returned products is not related to quality but is considered in order to manage the continuous flow of returns. This simply means that the returned products will be disposed of and will not be forwarded to the remanufacturing facility. Disposal costs are thus incurred. The main assumptions considered in this system are:

- in both production modes, the same product is produced and can be distributed like new with the same quality level to meet customer demand;
- the customer demand rate is constant;
- the return rate is proportional to the demand rate with the factor γ_R ($u_R = \gamma_R . d, \gamma_R \in]0,1[$);
- the setup time $T_S^{ij}, i \in \{M, R\}$ while switching from mode i to mode j is constant;
- disposal decisions are controlled based on the availability of storage space of returns.

Assumption 1 is encountered in the literature and many industrial sectors (aerospace and cartridges remanufacturing industries). Assumption 2 is common in PPC literature, especially at high levels of complexity such as in the considered problem and most papers presented in Table 3.1 (Class I). Assumption 3 highlights the dependence structure between customer demands and returns. It is based on industrial examples (rented or leased products) or when used products are returned to the original manufacturer only. Assumption 4 is used for illustrative purpose and aims to reduce the complexity of the problem. Assumption 5 aims to avoid excess inventory of returns and to control their flow. It indicates that the disposal decisions depend on the inventory of returns according to threshold rules, as considered by several works dealing with the production and inventory management (see (Gayon et al., 2017 ; Kim et al., 2013 ; Van Der Laan & Salomon, 1997) and references therein).

The main objective of this paper is to determine, for the studied HMRS, the optimal two storage spaces, the three manufacturing, remanufacturing and disposal rates as well as the sequence of setup operations in order to minimize the incurred total cost. The latter includes manufacturing, remanufacturing, setup, storage spaces, returns inventory and disposal costs as well as inventory and backlog costs of the finished product. Given the complexity of the considered control problem (see next section), an alternative solution approach is privileged based on literature, simulation and optimization techniques. In the next section, the control problem is formulated mathematically to better describe the system dynamics and to provide details on the total cost function.

3.3.3 Problem formulation

The state of the HMRS can be described by two continuous-time components. On the one hand, a discrete-state stochastic process $\{\alpha(t), t \geq 0\}$ defining the operational mode of the facility. $\alpha(t) = 1$, if the facility is available for production at the time t and $\alpha(t) = 0$, if it is not operational (under setup operations or/and repair after a failure). On the other hand, the level of accumulated inventory of both finished products and returns $X(t) = (x_F(t), x_R(t)) \in R \times R^+$. Thus, the system dynamics may be described by the state variables $(X(t), \alpha(t))$. The following equations represent the temporal evolution of the system:

$$\begin{aligned} \dot{x}_F(t) &= u_{man}(t) + u_{rem}(t) - d, && x_F(0) = x_F^0 \\ \dot{x}_R(t) &= u_R(t) - u_{rem}(t) - u_{dis}(t), && x_R(0) = x_R^0, \end{aligned} \tag{3.1}$$

With x_F^0 and x_R^0 respectively defining the initial inventory level of finished products and returns. Setup operations are modelled using the time τ_k at which the k^{th} ($k \in N$) setup action begins and the pair $i_k j_{k+1}$, $i, j \in \{M, R\}, i \neq j$ which represents the transition from one production mode i to another j. The sequence of setup operations is denoted by $\varphi = \{(\tau_0, i_0 j_1), (\tau_1, i_1 j_2), \ldots\}$. The setup time sequence function may also be defined by the indicator S_{ij} as follows:

$$
\begin{aligned}
S_{MM} &= \begin{cases} 1 & \textit{if the system is in manufacturing mode} \\ 0 & \textit{otherwise} \end{cases} \\
S_{MR} &= \begin{cases} 1 & \textit{if the system is being setup from mode M to mode R} \\ 0 & \textit{otherwise} \end{cases} \\
S_{RR} &= \begin{cases} 1 & \textit{if the system is in remanufacturing mode} \\ 0 & \textit{otherwise} \end{cases} \\
S_{RM} &= \begin{cases} 1 & \textit{if the system is being setup from mode R to mode M} \\ 0 & \textit{otherwise} \end{cases}
\end{aligned}
\tag{3.2}
$$

Knowing that the facility cannot be in two different production modes at the same time, the following equations must be valid: $\sum_{i,j} S_{ij} = 1$, $i, j \in \{M, R\}$ and $u_{man}(t).u_{rem}(t) = 0$, $\forall t$. The three manufacturing, remanufacturing and disposal rates ($u_{man}(t)$, $u_{rem}(t)$ and $u_{dis}(t)$) as well as the time sequence of setup operations (φ) constitute the decision variables. As mentioned previously, the disposal option is considered to manage the continuous flow of returns.

Let $U = \left(u_{man}(t), u_{rem}(t), u_{dis}(t)\right)$ and let i denote the initial setup mode and S the remaining setup indicator ($S = S_{ij}$, $i, j \in \{M, R\}$). The setup cost c_s^{ij} is assumed to be charged at the beginning of the setup.

The set of admissible control policies $\Gamma(.)$, including U and the sequence of setup operations φ, depends on the stochastic process $\alpha(t)$ and the setup indicator S. It is given by:

$$\Gamma(\alpha,S)=\left\{\begin{matrix}(U,\varphi):\\ 0\le u_{man}(t)\le U_{man}^{max}.I(\alpha(t)=1).I(S_{MM}=1),\\ 0\le u_{rem}(t)\le \widehat{U}_{rem}(x_R).I(\alpha(t)=1).I(S_{RR}=1),\\ 0\le u_{dis}(t)\le u_R(t)\\ u_{man}(t).u_{rem}(t)=0\end{matrix}\right\} \tag{3.3}$$

Where $\mathrm{I}(\omega)=1$ if ω is true while $\mathrm{I}(\omega)=0$ if not. The index $\widehat{\mathrm{U}}_{\mathrm{rem}}$ is formulated by:

$$\widehat{U}_{rem}(x_R)=\begin{cases}U_{rem}^{max} & if\ x_R(t)>0\\ u_R & if\ x_R(t)=0\end{cases} \tag{3.4}$$

Our objective is to find in $\Gamma(\alpha,S)$ the control policies $(\mathrm{u}_{man}^{*},\mathrm{u}_{rem}^{*},\mathrm{u}_{dis}^{*},\varphi^{*})$ which minimizes, for each initial condition (α, S, X), the following expected discounted total cost $\mathrm{J}(.)$ given by:

$$J(\alpha,S,X,U,\varphi)=c_F^e(Z_F)+c_R^e(Z_R)+E\left[\int_0^{\infty}e^{-\rho t}g(.)dt+\sum_{k=0}^{\infty}e^{-\rho\tau_k}\,c_S^{i_k j_{k+1}}\right] \tag{3.5}$$

Subject to Equation (3.1) with the instantaneous cost function $\mathrm{g}(.)$ given by:

$$g(X,U)=c_F^{+}.x_F^{+}+c_F^{-}.x_F^{-}+c_R^{+}.x_R+c_{man}.u_{man}+c_{rem}.u_{rem}+c_{dis}.u_{dis} \tag{3.6}$$

Where, ρ is the discount rate, $\mathrm{x_F^+}=\max(0,\mathrm{x_F})$ and $\mathrm{x_F^-}=\max(-\mathrm{x_F},0)$. As in (Lavoie et al., 2010), our model takes into account storage spaces costs. $\mathrm{c_F^e(Z_F)}$ and $\mathrm{c_R^e(Z_R)}$ are linked to the storage spaces (facilities used to storage, equipment, personnel, etc.) needed to maintain both finished products and returns respectively, and not to conservation actions. Indeed, it is inadequate to associate a cost to inventory only when it is used. In addition, penalizing the storage space itself, allows a better representation of the cost structure, especially when comparing different control policies. The considered storage spaces costs are in fact fixed costs that increase to a new level in step with the substantial changes in the storage space ($\mathrm{Z_F}$ and $\mathrm{Z_R}$). For example, if $\mathrm{Z_R^*}\in[200,400[$ $\mathrm{c_R^e(Z_R)}=320$ and may be equal to 400 if $\mathrm{Z_R^*}\in[400,700[$.

The value function of such a problem is defined as follows:

$$v(\alpha, S, X) = \inf_{U,\varphi \in \Gamma(\alpha,S)} J(\alpha, S, X, U, \varphi) \tag{3.7}$$

For optimal control of hybrid systems composed of a common facility with setups, the properties of the value function $v(.)$ given by (3.7) and how to obtain the optimality conditions can be found in (Polotski et al., 2017a). It was shown that $v(.)$ is the unique viscosity solution to the related Hamilton-Jacobi Bellman (HJB) equations of the problem. Moreover, to handle possible non-differentiability of the gradients of $v(.)$ a solution to the HJB equations is interpreted as a viscosity solution and numerical methods are used following the policy iteration method proposed in (Kushner & Dupuis, 1992). In our case and compared to (Polotski et al., 2017a), three new aspects reflecting the industrial reality are considered: (1) storage spaces sizing of finished products and returns (2) disposal option and (3) general random events distributions. The presence of state constraint related to storage spaces needs to be dealt with separately and it leads to some boundary conditions to be considered at inner points of the completely state space. This means that the storage spaces needed to be sized are more complicated to handle from a mathematical and numerical point of view. On the other hand, the disposal option is an additional decision variable, which may bring more complexity to a possible numerical resolution as in (Polotski et al., 2017a). Regarding the general distribution of failures and repairs and given that all the aforementioned papers have assumed Markov processes for random events, one needs much more analytical efforts to prove the optimality conditions and develop optimal control policies. The reader is referred to (Polotski et al., 2015) to appreciate the complexity of the problem without the three new aspects (1), (2) and (3). For the above reasons, an analytical or numerical solution in our context is very hard. The adopted solution approach should allow to:

- link the interpretation of boundary conditions dictated by the new considered aspect of storage spaces sizing to enrich the adapted existing policies;
- consider a feedback decision of the new decision variable (disposal rate);

- develop parameterized production, disposal and setup control policies where the control parameters and the associated total cost will be optimized.

Inspired by works as (Assid et al., 2015), we prioritize an alternative solution approach which consists first in using the literature to obtain and adapt parameterized control policies. We will analyze their strengths and weaknesses with the aim to propose a more efficient control policy in terms of costs. To this end, a combination of simulation, design of experiments and response surface methodology is used to conduct an in-depth comparative study of the considered control policies. This choice is due to its accuracy and strength while addressing such complex problems. It uses simulation as a powerful tool to imitate the dynamic and stochastic aspects, by relaxing assumptions (as the consideration of non-markovian processes for random events) and integrating important elements (like the disposal option and the stock sizing of both returns and finished products). The optimization of the control parameters and the associated total cost, obtained through simulation, is conducted thanks to the design of experiments and the response surface methodology. By comparison, optimizing these control parameters for further comparative study would be too time-consuming to be applicable at the operational level when applying numerical methods, as discussed in (Rivera-Gómez, Gharbi, Kenné, Montaño-Arango, & Hernández-Gress, 2018). This is principally due to the accuracy of the numerical results, which depend on the size of the discrete grid step. Our approach is well adapted to study the dynamic behaviour of joint decisions and to accurately compare the control policies in a wide range of system configurations. The control policies adapted from previous works are presented in the next section while the solution approach is detailed in Section 3.5.

3.4 Adapted control policies

As mentioned above, our PPC problem consists of establishing an efficient control policy for the considered hybrid system (see Section 3.3.2) minimizing the total average cost. In this section, we investigate the characteristics of three control policies of critical level type (up-to-threshold) inspired by literature while adapting their structure to our context. The first one was developed originally in a context more like ours (see Section 3.4.1), while we are interested in the two others in order to benefit from their advantages in joint production and setup control (see Sections 3.4.2 and 3.4.3). The optimal control policies are found to be of the hedging-point type in production control literature.

3.4.1 Polotski's Adapted Policy

The control policy adapted from that of (Polotski et al., 2017a) is formulated mathematically by equations (3.8)-(3.12). It combines maximal manufacturing and remanufacturing rates with both on-demand manufacturing and on-return remanufacturing rates. Changes have been made to the original formulation in order to adapt their policy to our context (integration of the possibility of disposing returned products when necessary and the storage space sizing of both returns and finished products). Indeed, the stored returned products are used to remanufacture them at the maximum remanufacturing rate (U_{rem}^{max}), but when the inventory of returns (x_R) empties the remanufacturing rate is adapted to the rate of returns (u_R) (see equation (3.8)). Similarly, the system adapts the manufacturing rate to customer demand when the inventory of finished products is empty to avoid inventory costs of finished products and uses the maximum manufacturing rate (U_{man}^{max}) when there are shortages or the stock of returns is full (see equation (3.9)).

$$u_{rem} = \begin{cases} U_{rem}^{max}.I\{S_{RR} = 1\} & if\ (x_R > 0) \\ u_R.I\{S_{RR} = 1\} & if\ (x_R = 0) \\ 0 & otherwise \end{cases} \tag{3.8}$$

$$u_{man} = \begin{cases} U_{man}^{max}.I\{S_{MM} = 1\} & if\ (x_F < 0)\ or\ (x_R = Z_R) \\ d.I\{S_{MM} = 1\} & if\ (x_F = 0)\ and\ (x_R < Z_R) \\ 0 & otherwise \end{cases} \tag{3.9}$$

Moreover, when the storage space of returns is full, all returned products are disposed of (see equation (3.10)).

$$u_{dis} = \begin{cases} u_R & if\ (x_R = Z_R) \\ 0 & otherwise \end{cases} \tag{3.10}$$

Knowing that the facility cannot be in two different production modes at the same time, rules are established to organize the switching from one mode to another. In this sense, as soon as the inventory of finished products (x_F) reaches its allocated storage space ($\mathrm{Z_F} \geq 0$) (this safety stock aims to reduce the risk of shortages if a failure of the production facility occurs), a setup action is performed to switch from manufacturing mode to that of remanufacturing (see equation (3.11)). However, x_F must decrease and reach the threshold Z_F^{pol} (Z_F^{pol} is considered negative in (Polotski et al., 2017a)) in order to switch to the manufacturing mode (see equation (3.12)). Recall that in remanufacturing mode, the production rate is lower than the customer demand because it is limited by the flow of returns ($u_R < d$). Consequently, the inventory level of finished products decreases during the remanufacturing activity.

$$S_{MR} = \begin{cases} 1 & if\ (x_F = Z_F)\ and\ (x_R > 0) \\ 0 & otherwise \end{cases} \tag{3.11}$$

$$S_{RM} = \begin{cases} 1 & if\ \left(x_F = Z_F^{pol}\right) \\ 0 & otherwise \end{cases} \tag{3.12}$$

3.4.2 Variable manufacturing rate (VMR) adapted policy

The VMR policy is adapted from (Gharbi et al., 2006 ; Yang et al., 2000) which deal with manufacturing systems (without remanufacturing activities) for which setup is related to the different product types to be manufactured. Its expression is given by equations (3.13)-(3.17). Changes were required in order to operate setup actions for changing the production mode and to include all activities related to the remanufacturing. Unlike the previous control policy, the VMR policy involves building the buffer stock of finished products of size $\mathrm{Z_F}$ as soon as the system switches to the manufacturing mode (see equation (3.14)). Manufacturing at the rate of demand is also used but only when the inventory of finished products is full ($\mathrm{x_F} = \mathrm{Z_F}$). This aims to stock them much longer in order to prevent the unavailability of the facility caused primarily by random failures.

$$u_{rem} = \begin{cases} U_{rem}^{max}.I\{S_{RR} = 1\} & if\ (x_R > 0) \\ u_R.I\{S_{RR} = 1\} & if\ (x_R = 0) \\ 0 & otherwise \end{cases} \tag{3.13}$$

$$u_{man} = \begin{cases} U_{man}^{max}.I\{S_{MM} = 1\} & if\ (x_F < Z_F) \\ d.I\{S_{MM} = 1\} & if\ (x_F = Z_F) \\ 0 & otherwise \end{cases} \tag{3.14}$$

$$u_{dis} = \begin{cases} u_R & if\ (x_R = Z_R) \\ 0 & otherwise \end{cases} \tag{3.15}$$

In the same sense, the switch to the manufacturing mode is conducted when the stock of finished products is empty ($x_F = 0$) (see equation (3.17)). It thus differs from the first control policy (see previous section) where the switch may take place when the stock is negative.

$$S_{MR} = \begin{cases} 1 & if\ \ (x_R = Z_R) \\ 0 & otherwise \end{cases} \tag{3.16}$$

$$S_{RM} = \begin{cases} 1 & if\ (x_F = 0) \\ 0 & otherwise \end{cases} \tag{3.17}$$

3.4.3 Maximum manufacturing rate (MMR) adapted policy

The MMR policy is adapted from (Elhafsi & Bai, 1996) where setup operations are also performed to change the product type manufactured. In our case, adaptations have been made in order to introduce the remanufacturing activity and to integrate the switching between the manufacturing and remanufacturing modes. The MMR policy is formulated by equation (3.18)-(3.22). In operational state, it uses the maximum capacity facility in manufacturing mode (see equation (3.19)) while in the remanufacturing mode; its production rate is constrained by the availability of returns (the remanufacturing rate may be at maximum value or at the rate of returns).

$$u_{rem} = \begin{cases} U_{rem}^{max}.I\{S_{RR} = 1\} & if\ (x_R > 0) \\ u_R.I\{S_{RR} = 1\} & if\ (x_R = 0) \\ 0 & otherwise \end{cases} \tag{3.18}$$

$$u_{man} = \begin{cases} U_{man}^{max}.I\{S_{MM} = 1\} & if\ (x_F < Z_F) \\ 0 & otherwise \end{cases} \tag{3.19}$$

$$u_{dis} = \begin{cases} u_R & if\ (x_R = Z_R) \\ 0 & otherwise \end{cases} \tag{3.20}$$

Equation (3.18) shows that as in the two previous control policies, the MMR policy uses the maximum remanufacturing rate when $\mathrm{x_R} > 0$ and the return rate when $\mathrm{x_R} = 0$. This allows the system to spend more time in the remanufacturing mode and so limit the number of switching to the manufacturing mode. However, MMR policy operates at maximum capacity in manufacturing mode, which can be advantageous in terms of inventory costs of finished products. The transition to the manufacturing mode is carried out only when the inventory level of the finished products is zero.

$$S_{MR} = \begin{cases} 1 & if\ (x_F = Z_F) \\ 0 & otherwise \end{cases} \tag{3.21}$$

$$S_{RM} = \begin{cases} 1 & if\ (x_F = 0) \\ 0 & otherwise \end{cases} \tag{3.22}$$

3.5 Solution approach

This section presents the proposed solution approach used to analyze the strengths and the weaknesses of the adapted control policies found in the literature and to propose a more efficient one in terms of costs. It is based on the literature and relies on both simulation and optimization techniques (design of experiments and response surface methodology). The main sequential steps of this approach are depicted in Figure 3.2. They are described through the following steps:

3.5.1 Mathematical Problem Formulation

This step aims to formulate analytically the problem as shown in Section 3.3.3. It describes the dynamics of the system as a function of its states and defines the decision variables and the total cost function to be minimized. Thereby, the strong interactions between the system variables (production processes, setup operating conditions, and the costs generated) are highlighted. The objective of determining an efficient control policy for the considered hybrid system (see Section 3.3.2) is thus detailed.

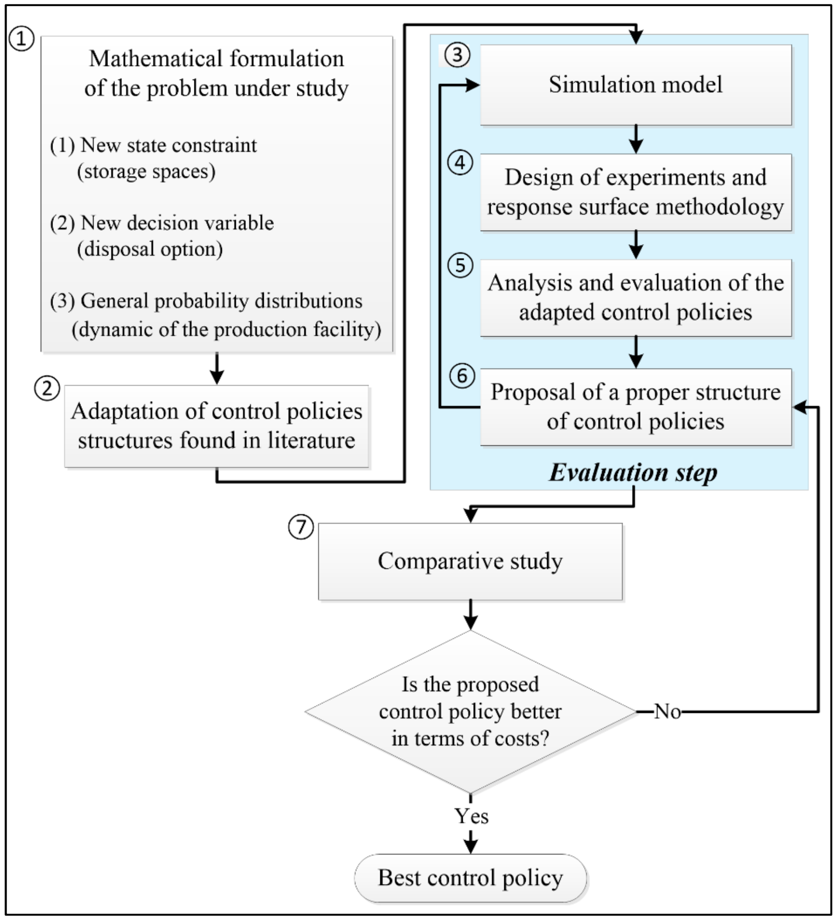

Figure 3.2 Proposed approach

3.5.2 Adaptation of Control Policies Found in Literature

Based on the previous objective, three joint production and setup control policies are considered. They are adapted to our context by introducing the possibility to reject some returns and to optimize the storage space size needed for both returns and finished products. General probability distributions are also considered to describe random events of failures and repairs. The adapted control policies are detailed in Section 3.4.

3.5.3 Simulation model

In this step, discrete-continuous simulation models are developed to imitate the behaviour of the HMRS managed by the adapted control policies and to evaluate its performance (incurred total cost) for given system parameters. The system operation is then simulated to evaluate its performance when each of these control policies is applied. A description of the simulation model is presented in Section 3.6.

3.5.4 Design of experiments and response surface methodology

This step combines design of experiments and response surface methodology in order to describe the total cost of each control policy by a second-order regression model according to control policies parameters. This regression model includes the factors and interactions that have significant effects on the total cost. For each selected control policy, the optimal solution (best values of control parameters Z_F and Z_R which minimize the total cost) is calculated within the feasible region defined by the problem constraints and the region of the design of experiments. This step is detailed in Section 3.7.1.

3.5.5 Analysis and evaluation of the adapted control policies

The previous two steps are used to assess the characteristics and the strengths of each considered control policy. The analysis of the obtained evaluation results may show that the adapted control policies have many disadvantages and can be improved. This step is detailed in Section 3.7.2.

3.5.6 Proposal of an Efficient Control Policy

Following the analysis of results, the objective is then to propose a more efficient control policy based on improvements to the adapted control policies of the previous step. The proposal which is detailed in Section 3.8 should lead to better economic performance.

3.5.7 Comparative study

An in-depth comparative study is also performed to study the considered control policies across a wide range of system configurations and to ensure that the proposed control policy always gives the best result in terms of costs. The comparative study is detailed in Section 3.9.

3.6 Simulation model

The three above-formulated control policies are evaluated and considered in our comparative study in order to propose a more efficient control policy for HMRS considering disposals. In order to evaluate the performance (calculate the incurred total cost) of each of the above-control policies, a simulation-based methodology is developed using Arena software. Combined discrete-continuous simulation models are designed to faithfully represent the system operation presented in Section 3.3.3 and to provide an accurate representation of the system dynamics described by the state variables $\left(X(t), \alpha(t)\right)$. Each model is controlled by one of the above-control policies and uses both discrete and continuous components which work synchronously as for calculating the variations in the inventories (x_F and x_R). In such case, the continuous part may determine the instantaneous inventories level using equation (3.1), while the discrete part models discrete events as breakdowns. In fact, the model is composed of various networks (update inventories levels, production facility, failures/repairs, Sensors, etc.), each performs specific tasks in order to calculate instantaneously the surplus and the backlog of finished products, to determine the three manufacturing, remanufacturing and disposal rates, to check the state of the production facility, to count the flow of disposed products, etc. This combined discrete-continuous modelling approach is known for its ability of reducing greatly the running time when compared to the purely discrete models (Lavoie et al., 2010). Once the simulation run is stopped, the system performance (expected total cost) is calculated. Figure 3.3 includes the block-diagram representation of the simulation model. A set of verification techniques is also conducted in order to check the accuracy of our simulation models.

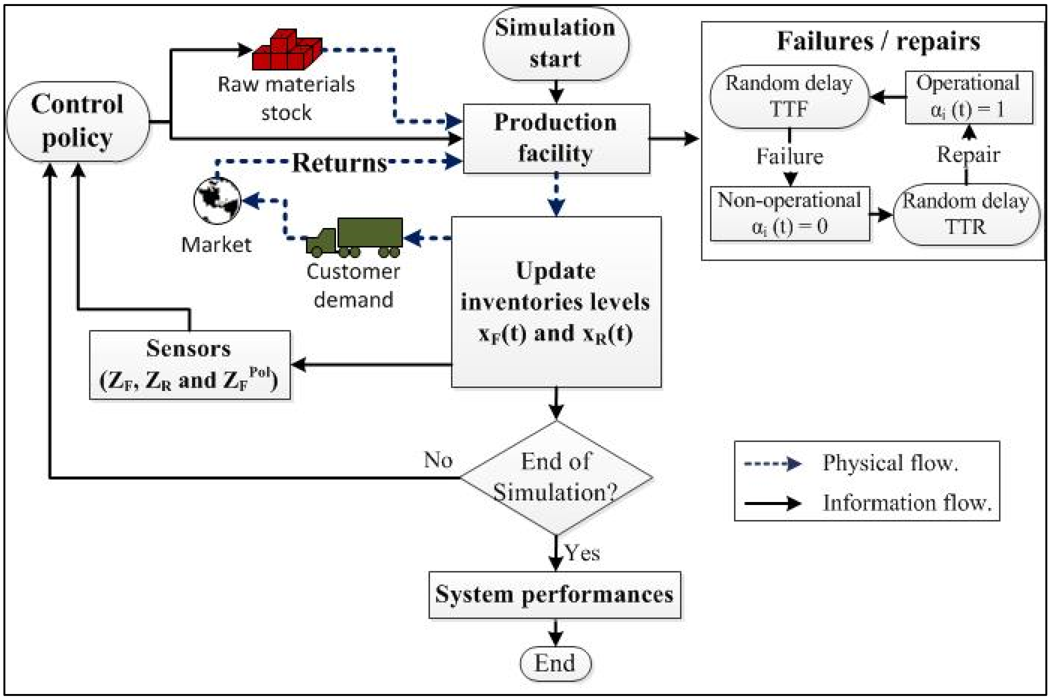

Figure 3.3 Diagram of simulation

Based on dynamic testing which includes the monitoring of the model data evolution and the application of debugging features, we ensure the proper behaviour of the developed simulation models. For example, the dynamics of system operations using the MMR policy (see Section 3.4.3) over time are collected and a sample is presented in Figure 3.4 using the subfigures form. 6 subfigures were generated so that we can observe the influence of a given phenomenon (e. g. failures and repairs, setup operations, shortages, etc.) on several system parameters. The considered sample was performed for $U_{man}^{max} = 125$ products/time unit, $U_{rem}^{max} = 95$ products/time unit, $u_R = 30$ products/time unit, $d = 100$ products/time unit, $Z_F = 1000$ products, and $Z_R = 1000$ products. For ease reading, the symbol "arrow X.Y" is used to emphasize the phenomenon pointed by the arrow number X and illustrated in the Figure 3.4.Y.

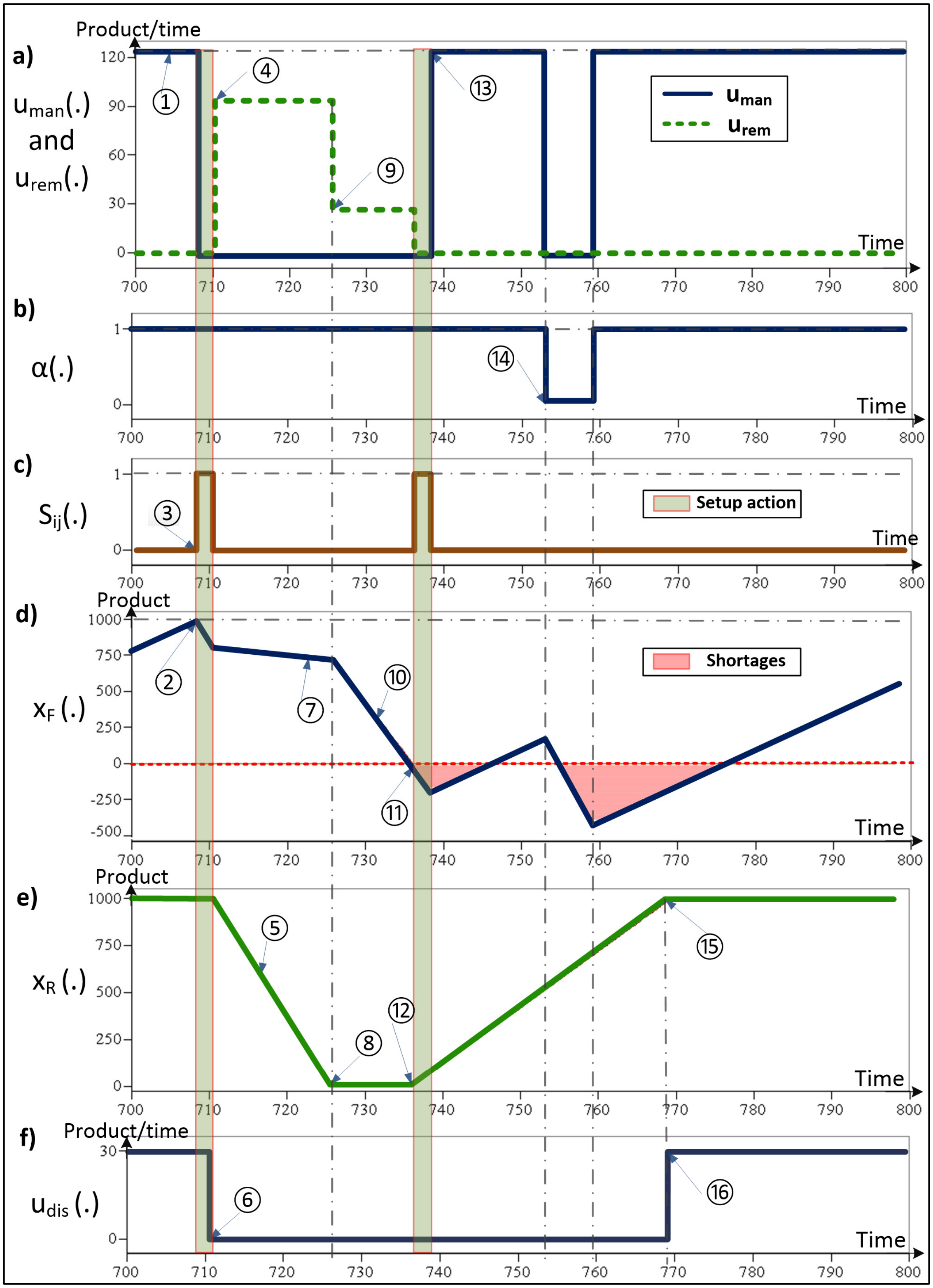

Figure 3.4 Dynamics of operations during the simulation run

Figure 3.4 shows that the production process depends on the facility's state $\alpha(.)$ (Figure 3.4.b), the setup actions (Figure 3.4.c), the inventory level of finished products $x_F(.)$ (Figure 3.4.d) and the availability of stored returns (Figure 3.4.e). This is manifested by the variation of both manufacturing and remanufacturing rates, knowing that the production facility cannot be in two different production modes at the same moment. As shown by arrow ①.a, the remanufacturing rate is zero while the manufacturing rate is at the maximum ($U_{man}^{max} = 120$ products / time unit) since the inventory level of finished products (x_F) is not yet full (see equation (3.19)). As soon as the stock of finished products is full (x_F reaches Z_F, with $Z_F = 100$ products) (arrow ②.d), a setup action is performed to switch from manufacturing mode to that of remanufacturing (arrow ③.c). The end of this setup action involves that the facility operates at maximum capacity ($U_{rem}^{max} = 90$ products / time unit) (arrow ④.a) thanks to the availability of returns in stock. At each moment, the quantity transformed is equal to the sum of a portion of the stored returned products plus an equivalent amount of the rate of returns ($u_R = 30$ products / time unit). Therefore, the inventory level of returns decreases (arrow ⑤.e) and the disposal activity of returned products is stopped (arrow ⑥.f). During this period, the level of inventory of finished products decreases at a rate equal to $U_{rem}^{max} - d = 95 - 100 = -5$ products / time unit (arrow ⑦.d). However, when the inventory of returns empties (arrow ⑧.e), it is normal that the remanufacturing rate becomes equal to u_R (arrow ⑨.a). Hence the acceleration of the stock consumption of finished products (decreases at a rate equal to $u_R - d = 30 - 100 = -70$ products / time unit) (arrow ⑩.d). The decrease of x_F continues and triggers a setup action when $x_F = 0$ product (arrow ⑪.d) to switch to the manufacturing mode.

The interruption of the returns processing implies their storage (x_R increases) (arrow ⑫.e). Since $x_F < Z_F$, the manufacturing process resumes at U_{man}^{max} (arrow ⑬.a). Figure 3.4 also illustrates the case of the facility failure (arrow ⑭.b). It shows that when the production facility is under repairs (as in some cases of setup action) the system may record shortages (subfigure 3.4.d). As long as the manufacturing mode is activated, x_R increases until it reaches the threshold Z_R (arrow ⑮.e) which starts the disposal of returns (arrow ⑯.f). In short, the assessment of the operational graphics illustrated in Figure 3.4 indicates that our simulation model reproduces the system dynamics accurately.

3.7 Numerical Example

A numerical example is provided to illustrate the experimental approach and to compare the studied control policies. As in stated earlier our simulation model is used to conduct a statistical analysis and to optimize in the next step the considered policies by calculating the best values of control parameters (Z_F, Z_R and Z_F^{pol}) which minimize the incurred total cost expressed by (3.5).

3.7.1 Design of experiments and response surface methodology

The optimization part is conducted thanks to the design of experiments and the response surface methodology. The system's data are listed in Table 3.2. These data represent the base case on which comparison analysis will be conducted. The cost parameters are also selected so that $c_F^+ < c_F^-$ and $c_{rem} < c_{man}$. The first condition is associated with unmet customer demand, which includes penalties due to insufficient stock or even customer losses. The second condition refers to the fact that the remanufacturing process, which reuses many parts and components, is less expensive than the production of a new product type (Ferguson, 2010).

Table 3.2 Value of system parameters for the base case

Parameters	c_F^+	c_F^-	c_{man}	c_{rem}	c_{dis}	c_R^+	γ_R
Values	3	30	35	5	30	0.2	0.15
Parameters	U_{man}^{max}	U_{rem}^{max}	d	T_f (time unit)	T_r (time unit)	c_S^{ij}	T_S^{ij}
Values	125	95	100	Log-N(85,25)	Log-N(10,2)	500	2

T_f and T_r define random variables denoting the time to failure and the corrective maintenance duration respectively. They follow the continuous probability distribution log-normal but any probability distributions could be applied. γ_R represents the proportion of used products ready to be returned to the system for remanufacturing which means that $u_R = d.\gamma_R = 15$. Different offline simulation experiments are conducted for the base case to explore the admissible experimentation region including the optimal values of the control parameters (Z_F, Z_R and Z_F^{pol}). As a result, Z_F^{pol} is set at the zero level in order to avoid great shortage costs. Recall that Z_F^{pol} (considered negative in (Polotski et al., 2017a)) represents the transition point from the remanufacturing mode to that of manufacturing (see Section 3.4.1). The original problem is then reduced to define two control factors (Z_F and Z_R) for the three considered control policies (Polotski's, VMR and MMR). This leads to apply for a full-factorial design 3^2 in order to estimate each interaction separately. Using 5 replications, 45 simulation runs for each design is planned. The simulation horizon for a run is set to 1,000,000 units of time to ensure steady-state conditions. Note that one simulation run takes on average less than two seconds on a computer with a 3.30 GHz CPU. The statistical software Statgraphics is used based on the simulation output in order to produce the multi-factor analysis of variance (ANOVA) and to determine the response surface function F in a second-order regression model relating the total cost to the control parameters (Z_F and Z_R). F takes the following equation:

$$F \cong \beta_0 + \beta_1 Z_F + \beta_2 Z_R + \beta_{12} Z_F Z_R + \beta_{11} Z_F^2 + \beta_{22} Z_R^2 + \varepsilon \qquad (3.23)$$

With, β_0, β_i and β_{ij} $(i, j \in \{1,2\})$ are the estimated coefficients and ε presents the error. The fitness of the regression model is also confirmed in three steps. First, we based on the adjusted R-squared coefficient to evaluate the model's overall performance. Second, the homogeneity of the variances and the residual normality are checked in terms of fitted values plot and a normal probability plot of residuals respectively. Third, once the optimization is carried out on the regression model, a Student's t-test is conducted to crosscheck its validity. Figure 3.5 presents the standardized Pareto chart and the adjusted R-squared coefficients (R^2) for the responses (total costs). ANOVA analyses show that except the factor Z_R under the VMR policy, all the main factors (Z_F and Z_R), their interactions ($Z_F.Z_R$) and their quadratic effects (Z_F^2 and Z_R^2) are statistically significant for the response variable at a 95% confidence level.

The obtained R^2 values state that the model explains more than 97% of the observed variability in the expected total cost. From the statistical software Statgraphics, the obtained response functions are:

$$C_{Pol} = 12530 - 4.10\,.Z_F - 1.13\,.Z_R - 6.64.\ 10^{-4}\,.Z_F.Z_R + 1.17.\ 10^{-3}.Z_F^2 + 9.6.\ 10^{-3}.Z_R^2 \tag{3.24}$$

$$C_{VMR} = 13297.6 - 5.14\,.Z_F - 1.34\,.Z_R + 5.87.\ 10^{-4}.Z_F.Z_R + 1.46.\ 10^{-3}.Z_F^2 + 1.12.\ 10^{-4}.Z_R^2 \tag{3.25}$$

$$C_{MMR} = 13389.8 - 4.81\,.Z_F - 1.17\,.Z_R + 4.96.\ 10^{-5}.Z_F.Z_R + 1.41.\ 10^{-3}.Z_F^2 + 3.30.\ 10^{-4}.Z_R^2 \tag{3.26}$$

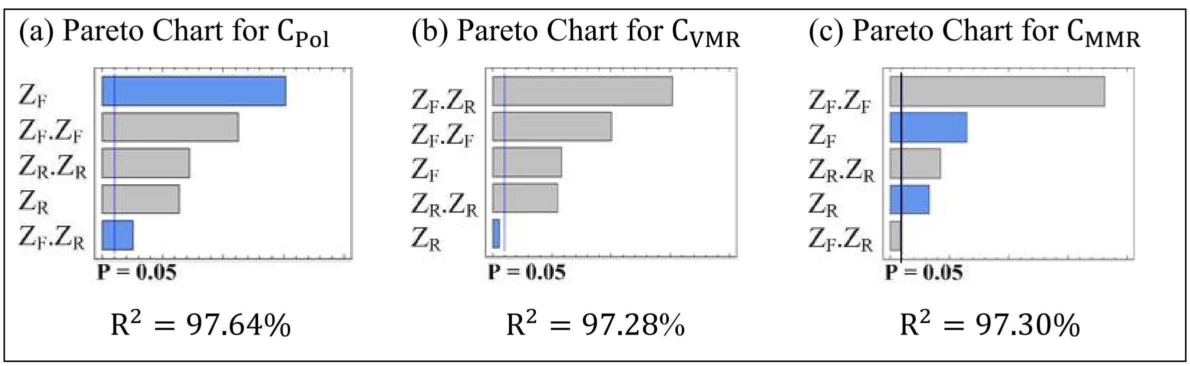

Figure 3.5 Standardized Pareto chart under the considered control policies

3.7.2 Optimization results and analysis

The optimal solutions of the three adapted control policies obtained by minimizing the equations (3.24)-(3.26) and the crosscheck validation from 45 extra-replication results are presented in Table 3.3. Recall that the notations used in this paper are presented in the Section 3.3.1. Table 3.3 shows that the best control parameters values differ depending on the applied control policy and that the VMR policy is more advantageous in terms of cost than Polotski and MMR policies with a reduction of 5.20% and 0.74% respectively. These results definitely bear further comparative study to check whether this conclusion holds for a wide range of system parameters (see Section 3.9).

Table 3.3 Optimization results and crosscheck validation

Policies	Z_F	Z_R	Q_F^+	Q_R^+	Q_F^-	P_{man} (%)	P_{rem} (%)	P_{dis} (%)	N_S	**Total Cost ($)**	**Confidence Interval (95%)**
Polotski	**1787**	**120**	665	106	76	97.83	2.17	85.56	113	**8794.34**	**[8789.94 ; 8802.88]**
MMR	**1669**	**1652**	697	934	55	88.21	11.79	21.38	116	**8399.21**	**[8394.12 ; 8412.27]**
VMR	**1176**	**2887**	630	1710	46	86.55	13.45	10.34	99	**8337.29**	**[8326.18 ; 8343.46]**

Table 3.3 shows that the VMR policy leads to improved economic results compared to the Polotski's policy at all levels except for remanufacturing (P_{rem}) and inventory costs of returns (Q_R^+). This is due to larger storage space of returns adopted by the VMR policy ($Z_R = 2887$ products against $Z_R = 120$ products for the Polotski's policy). However, since the system retains more returned products (Q_R^+), the percentage of disposed products compared to returns (P_{dis}) decreases and the remanufacturing activities increase. In fact, simulation data show that for the optimal control parameters, 89.67% of the returned products are remanufactured representing 13.45% of total demand when the VMR policy is applied versus 14.47% for the Polotski's policy which represents only 2.17% of total demand. These remanufacturing activities cost less than that of manufacturing, resulting in lower production costs (sum of manufacturing and remanufacturing costs). In addition, the improved economic results achieved by the VMR policy is due in particular to its ability to significantly reduce stock-outs (lower Q_F^- for the VMR policy) as it builds the buffer stock of finished products stock of size Z_F as soon as possible (see equation (3.14)) and not until the next setup operation as in Polotski's policy (see equation (3.9)). As the VMR and MMR policies seem to be much better

than the Polotski's policy in terms of cost, the remainder of the comparative analysis will focus on both of them.

According to Table 3.3, the optimal VMR policy uses a smaller storage space of finished products ($\mathrm{Z_F}$) compared to that of MMR involving lower inventory of finished products $\mathrm{Q_F^+}$. Moreover, it reduces the risk of shortages (lower $\mathrm{Q_F^-}$) even if its $\mathrm{Z_F}$ is smaller. That is actually normal because when the VMR policy completes the stock recovery of the finished products of size $\mathrm{Z_F}$ it will maintain it until the machine fails or the stock of returns is filled (see equations (3.14)-(3.15)). However, the MMR policy operates only at the maximum manufacturing rate and switches to the remanufacturing process as soon as its inventory level of finished products ($\mathrm{x_F}$) reaches $\mathrm{Z_F}$ (see equations (3.19)-(3.20)). It means that when a failure occurs, the probability that $\mathrm{x_F}$ is at a maximum level of $\mathrm{Z_F}$ is higher for the VMR policy. In connection with this clarification, the MMR policy yields larger numbers of setup operations (lower N_S for the VMR policy). Further referring to these two control policies, the condition of switching to the remanufacturing mode differs from one policy to another. Indeed, for the VMR policy, this switching is made when the storage space of returns is full while the MMR policy executes it when that of finished products is empty. In addition to having higher storage space of returns ($\mathrm{Z_R}$), the continuous check of the inventory level of returns ($\mathrm{x_R}$) allows the VMR policy to reduce the amount of disposals (lower P_{dis}) and to increase the remanufacturing activities (higher P_{rem}) which cost less than those of manufacturing, thus resulting in savings reflected in the production cost (sum of manufacturing and remanufacturing costs).

As mentioned above, a thorough comparative study will be conducted in order to determine the best control policy. Section 3.9 summarizes the obtained results which consist of analyzing the impact of the variation in the value of several system parameters (setup time, mean time to failure, rate of returns, backlog and manufacturing costs, etc.) on the performance of the considered control policies. It shows that depending on the selected system parameter, the MMR policy indeed can become better in terms of costs compared to the VMR policy, taking advantage of its ability to generate lower inventory costs for both returned and finished products. Note that for the same value of $\mathrm{Z_F}$, the inventory cost of finished products will be more costly for the VMR policy because its Q_F^+ is higher. Following the analysis and the assessment of the three previous policies, a new and improved control policy is proposed in the next section.

3.8 The proposed control policy

The analysis of the three adapted control policies and the effect of a wide range of system configurations on the estimated total cost of these policies (see Sections 3.7.2 and 3.9) leads us to benefit from the strengths of both VMR and MMR policies in order to propose a more efficient policy. We focus on the conditions for executing setup operations, as these may generate significant additional costs that should be minimized (such as those related to the facility operating cost and to the indispensable time between the start of a setup action and the start of the production process). We then integrate both maximal and on-demand manufacturing rates (see equation (3.28)) as in the VMR policy in order to reduce the number of switching to the remanufacturing mode. Moreover, these setup actions must be triggered before filling the storage space of returns in order to reduce or eliminate disposals during setup operations. However, this decision will also take into account the inventory level of finished products as in the MMR policy (see equation (3.21)). The objective is twofold: to reduce the inventory cost and the risk of shortages. As a result, two new parameters a_F and a_R are considered in the transition to remanufacturing mode (see equation (3.30)). a_F represents the inventory level deemed sufficient to switch to the remanufacturing mode while a_R denotes the inventory level of returned products needed to ensure this switching and to minimize the loss of returned products. The proposed policy also aims to reduce the risk of shortages when switching to the manufacturing mode. Thus, the concerned setup operations will be advanced in time compared to the moment when the stock of finished products is empty (see equations (3.17) and (3.22)). In this sense, a third parameter b_F is introduced. It defines the stock level required to perform a setup operation in the remanufacturing mode before shortages (see equation (3.31)). The following equations represent the proposed policy.

$$u_{rem} = \begin{cases} U_{rem}^{max}.I\{S_{RR} = 1\} & if\ (x_R > 0) \\ u_R.I\{S_{RR} = 1\} & if\ (x_R = 0) \\ 0 & otherwise \end{cases} \tag{3.27}$$

$$u_{man} = \begin{cases} U_{man}^{max}.I\{S_{MM} = 1\} & if\ (x_F < Z_F) \\ d.I\{S_{MM} = 1\} & if\ (x_F = Z_F) \\ 0 & otherwise \end{cases} \tag{3.28}$$

$$u_{dis} = \begin{cases} u_R & if\ (x_R = Z_R) \\ 0 & otherwise \end{cases} \tag{3.29}$$

$$S_{MR} = \begin{cases} 1 & if\ \ (x_F \geq a_F)\ and\ (x_R \geq a_R) \\ 0 & otherwise \end{cases} \tag{3.30}$$

$$S_{RM} = \begin{cases} 1 & if\ (x_F = b_F) \\ 0 & otherwise \end{cases} \tag{3.31}$$

Note that $0 \leq a_R < Z_R$, $0 \leq b_F$ and $0 < a_F < Z_F$. In addition, since the setup times T_S^{RM} and T_S^{MR} while switching from one mode to another are assumed to be constant ($T_S^{RM} = T_S^{MR} = T_S = 2$) as in Table 3.2 the parameters b_F and a_R can be expressed as follows: $b_F = d.T_S$ and $a_R = Z_R - (u_R.T_S)$. Indeed, both b_F and a_R depend on the setup time (T_S) and the demand rate (d). They are respectively introduced to minimize shortages and disposals. These assumptions do not lose the generality of the problem but reduce the number of control parameters to optimize while leading more quickly and easily to the same conclusions.

Figure 3.6 shows an example of the variation in inventory levels of finished products (x_F) and returns (x_R) under the proposed control policy. It shows that when x_F reaches $Z_F = 1000$, the manufacturing rate (u_{man}) is adapted to that of customer demand ① (x_F levels off at Z_F). Meanwhile, x_R continues to increase at the return rate (u_R) due to the flow of returned products. However, when the stock of returns reaches a_R ② and since $x_F \geq a_F$, a setup operation (of duration$T_S = 2$) is triggered in order to switch to the remanufacturing mode (see equation (3.30)). a_R made it possible to minimize disposals during some setup operations. These operations stop the production activity, hence the decrease of the inventory level of finished products according to customer demand ③. At the end of the setup operation, the facility operates at maximum capacity (U_{rem}^{max}), thus benefiting from the availability of stored returns ($x_R > 0$), but when this stock is empty the remanufacturing rate (u_{rem}) is adapted to the flow of returns ④. Moreover, x_F always decreases in the remanufacturing mode depending on the value of u_{rem} which is due to the fact that U_{rem}^{max} is lower than customer demand. If x_F continues to decrease and reaches b_F, a setup operation is triggered but this time to switch to the manufacturing mode with no backlog costs ⑤. In this mode, the manufacturing facility operates at maximum capacity (U_{man}^{max}) as long as $x_F < Z_F$ (the stock of finished products is not yet full). However, random failures may occur ⑥, causing shortages. Recall that the switch to the remanufacturing mode is possible only if $x_F \geq a_F$ ⑦ and $x_R \geq a_R$ ⑧.

The same cost function estimation and optimization method considered in Section 3.7 is adopted, except that the objective is to determine the optimal value of three control parameters of the proposed policy (Z_F, a_F and Z_R) which minimize the incurred total cost (3.5). Note that the parameter $\delta \in [0,1[$ will replace a_F in the design of experiments in order to comply with the constraint $a_F < Z_F$. Thus, $a_F = \delta . Z_F$. The second order cost function related to the proposed control policy is given by:

$$\begin{aligned} C_{proposed} &= 20286.2 - 7.17 . Z_F - 22022.4 . \delta - 2.25 . Z_R + 5.1 . Z_F . \delta \\ &+ 2.94.\ 10^{-4} . Z_F . Z_R + 0.13 . \delta . Z_R + 1.15.\ 10^{-3} . Z_F^2 \\ &+ 14066.3 . \delta^2 + 4.55 . 10^{-4} . Z_R^2 \end{aligned} \tag{3.32}$$

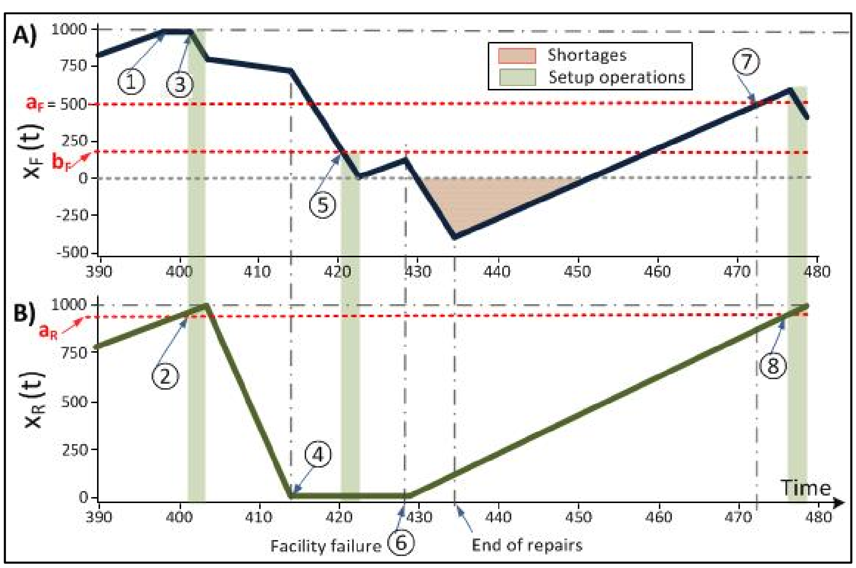

Figure 3.6 Evolution of both finished products and returns inventories under the proposed control policy

The optimization result shows that for the base case (see Table 3.2) $Z_F^* = 1189$ products, $\delta^* = 0.5574$ ($a_F^* = 662$ products) and $Z_R^* = 2010$ products are the best parameters for the proposed control policy which orders simultaneously manufacturing, remanufacturing and setup operations at a minimum cost of 7615.83. This represents an economic gain of 8.65%, 9.33% and 13.40% compared to VMR, MMR and Polotski's control policies respectively. However, other studies are necessary in order to draw meaningful conclusions and to determine if the proposed policy is always more advantageous in terms of cost (see next section).

3.9 Comparative study

The objective of this section is to compare the considered control policies by extending the base case study (see Table 3.2) to a wide range of system parameters and to highlight the evolution of the proposed control policies in relation to others. Figure 3.7 summarizes the different scenarios tested. It presents the effect of several cost parameters (subfigures 3.7.a-3.7.d), setup time (subfigure 3.7.e), mean time to failure (subfigure 3.7.f) and rate of returns (subfigure 3.7.g) on the total cost incurred of each studied control policy.

As stated earlier, Figure 3.7 confirms that the VMR and MMR control policies give a better result in terms of cost than Polotski's (see Table 3.3 and the paragraph that follows it for more details). Actually, the Polotski policy is the costliest across all the system settings presented in Figure 3.7. Data from Figure 3.7 also confirms that the total cost of the MMR policy may fall below that of the VMR policy (see subfigures 3.7.a, 3.7.c, 3.7.e and 3.7.f). Indeed, with the decrease of the backlog cost (c_F^-) (subfigure 3.7.a), failures of the production facility become less significant since backlogs cost less. This means that the VMR control policy is increasingly losing its advantage of reducing the risk of shortages until the total cost of MMR policy is lower. The MMR policy also becomes better in terms of costs in the case of low disposal cost (c_{dis}) (subfigure 3.7.c) compared to the VMR policy. This can be explained by the fact that when c_{dis} decreases, the VMR policy benefits less and less from its advantage of having a larger stock of returns resulting in inventory penalties. The same phenomenon is observed when the setup time (T_S^{ij}, $i = \{M, R\}$) exceeds 3 (Figure 3.7.e) or when the mean time to failure (MTTF) falls below 75 (subfigure 3.7.f).

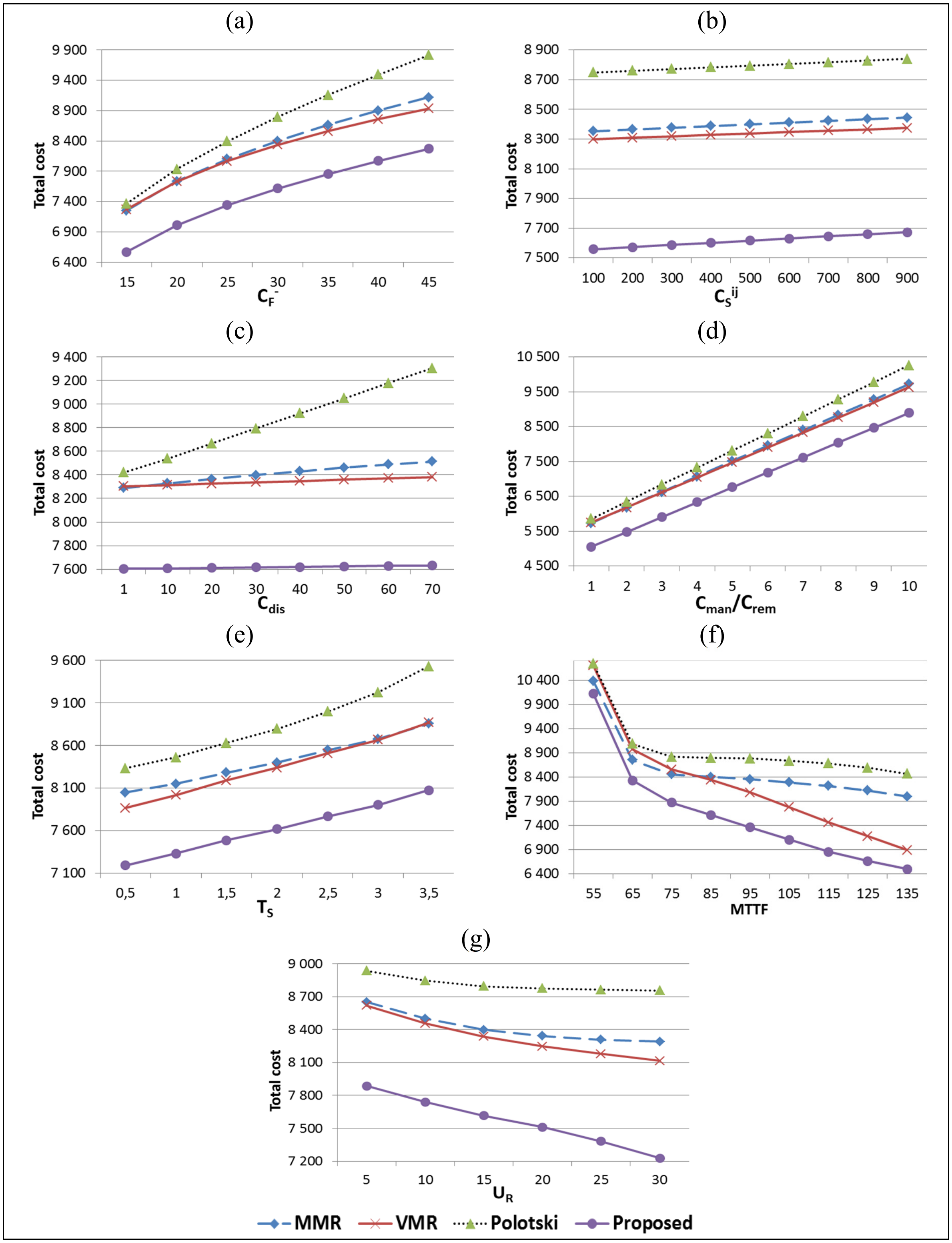

Figure 3.7 Effect of system parameters on the incurred total cost of the control policies

For T_S^{ij}, this is mainly due to the remarkable reduction in the number of setup operations (less setup costs) and thus to the improved availability of the system for the MMR policy. Recall that the manufacturing rate under this policy is always at its maximum which means that the increase of T_S^{ij} will generate less setup operations since the control thresholds are reached less quickly. Reducing the MTTF has the same effect mainly by decreasing the VMR policy advantage of generating less setup operations. Indeed, for lower MTTF the system is down more often, which decreases its availability. This means for the VMR policy more backlogs, more setup operations since they are activated as soon as the stock of returns is full (see equation (3.16)) and more inventory costs of returns. This ensures that when $\mathrm{MTTR} \leq 75$, the MMR policy becomes more advantageous in terms of cost in comparison with the VMR one. It is interesting to note that the increase of MTTF reduces the total cost incurred of all the considered control policies, thanks in particular to improving the availability of the production system and reducing the risk of shortages. Similarly, the total cost decreases with the increase in the rate of returns (u_R) since the production system works more in remanufacturing mode transforming more returned products.

Figure 3.7 shows also the economic advantage of the proposed control policy since its total cost is the lowest, regardless of the value of settings. This policy improves the VMR policy by recalculating the start of setup operations (see equations (3.30) and (3.31)). It also benefits from strengths of the MMR policy by using only the maximum manufacturing capacity if it is economical in some cases (the system uses three more control parameters (a_F, a_R and b_F) and does not have to fill all the stock of finished products). Therefore, our proposed control policy minimizes the risk of shortages especially during the transition to the manufacturing mode, and disposals when switching to the remanufacturing mode. This explains the increase in the total cost difference between the proposed policy on one side and the MMR and VMR policies on the other when backlog cost (c_F^-) (subfigure 3.7.a), setup time (T_S) (subfigure 3.7.e) and disposal cost (c_{dis}) (subfigure 3.7.c) increase. In the same sense, the proposed control policy can also take advantage of its ability to minimize the risk of disposals in order to maximise the processed quantity of returned products, which cost less. This explains the increase in the total cost difference between the proposed policy and both MMR and VMR policies when the value of c_{man}/c_{rem} (subfigure 3.7.d) and the rate of returns (u_R) (subfigure 3.7.g) increase. This phenomenon confirms what was stated in the introductory section that encouraging remanufacturing activity may enhance both economic and environmental (minimization of disposals) benefits. Minimizing the risk of disposals also reflects the fact that the system spends more time in the remanufacturing mode when the proposed policy is applied.

In summary, the proposed control policy which integrates both production and setup activities for unreliable HMRS with disposals, gives the best result in terms of costs for a wide range of system configurations. It also reflects control policies that seek the best economic performance (minimization of shortages, setups, disposals, etc.) using remanufacturing as an environmentally friendly method of recovering and reusing parts after a product's life cycle has ended. These benefits become much more significant when c_F^-, T_S, c_{dis}, c_{man}/c_{rem} and/or u_R increase.

3.10 Extension to random customer demand and more general failure and repair time distributions

In the previous numerical example (Section 3.7) and comparative study (Section 3.9), we considered a constant customer demand and only the log-normal distribution to describe the occurrence of failures and the duration of repair actions. However, this situation does not usually reflect the industrial reality. This section aims primarily to confirm the usefulness of the proposed solution approach and to compare the economic performance of the considered control policies for random demand and different time distributions of failures and repairs. It addresses the questions: What happens if customer demand is random? How does random demand affect the optimal value of the control parameters? Is the economic benefit of the proposed control policy maintained, when failures and repairs are described by different time distributions of failures and repairs?

Table 3.4 Optimization results considering random customer demand

Policies	Demand	Z_F	a_F	Z_R	Total cost ($)
Proposed	Normal (100,3)	1218	691	2023	7650.20
	Normal (100,6)	1283	749	2084	7823.77
	Normal (100,10)	1409	845	2301	8674.30
Polotski's	Normal (100,3)	1820	-	132	8838.88
	Normal (100,6)	1893	-	146	9189.87
	Normal (100,10)	1980	-	169	10305.70
MMR	Normal (100,3)	1700	-	1671	8453.38
	Normal (100,6)	1741	-	1719	8722.00
	Normal (100,10)	1816	-	1776	9786.67
VMR	Normal (100,3)	1193	-	2936	8383.00
	Normal (100,6)	1232	-	3008	8591.82
	Normal (100,10)	1431	-	3144	9533.44

Table 3.5 Optimization results considering different probability distributions for failure and repair times

Policies	T_f	T_r	Z_F	a_F	Z_R	Total cost ($)
Proposed	Weibull (85,3)	Weibull (10,3)	1273	729	1150	8045.05
	Gamma (1.3,60)	Gamma (1.3,7.5)	1385	742	2287	8083.55
Polotski's	Weibull (85,3)	Weibull (10,3)	1842	-	134	9025.25
	Gamma (1.3,60)	Gamma (1.3,7.5)	1854	-	141	9155.44
MMR	Weibull (85,3)	Weibull (10,3)	1720	-	1681	8763.35
	Gamma (1.3,60)	Gamma (1.3,7.5)	1772	-	1720	8795.71
VMR	Weibull (85,3)	Weibull (10,3)	1200	-	2938	8640.65
	Gamma (1.3,60)	Gamma (1.3,7.5)	1279	-	3073	8685.11

As in Section 3.7, the optimization of the control parameters is performed using simulation-based optimization approach, which offers a powerful technique that can handle any failure and repair time distributions as well as the randomness of the demand. The corresponding output is then given by the simulation model (the total incurred cost), which affects the response surface model. Additional experiments are then conducted to determine the optimal control parameters and the related total cost of each policy when the customer demand is random (Normal distribution) and the studied system is subject to non-exponential failure and repair time distributions (Weibull and Gamma probability distributions are often used to model machine's failures (Law & Kelton, 1991)). The optimization results are respectively presented in Table 3.4 and 3.5. The results shows that the proposed control policy gives a lower optimal cost in all the studied scenarios. They also show that considering random demand instead of constant one, has mainly increased storage capacity needed for finished products (Z_F) and returns (Z_R). Indeed, the system in this case, aims to face the growth of the risk of shortages caused by demand variability. The higher the standard deviation, the more Z_F and Z_R increase. The total incurred cost increases accordingly. These results are consistent with those found in the literature as in (Kenne & Gharbi, 2000 ; Ouaret, Kenné, & Gharbi, 2018b ; Presman & Sethi, 2006), which showed that the control policy structure considering variable and random demand remains of hedging-point type. Table 3.5 goes in the same direction by showing that when the facility is less available (88.87% for Gamma distribution cases against 89.45% for Weibull distribution), the system adopts a larger storage capacity to avoid additional costs of shortages.

3.11 Conclusion

This work investigates the PPC problem for hybrid systems with setups. It is motivated by the need for better production control in many industrial applications where an unreliable production facility, evolving in a dynamic and stochastic environment, necessitates setup actions each time it switches between the manufacturing and the remanufacturing modes. The main objective is to elaborate a more efficient manufacturing, remanufacturing and setup control policy minimizing the total cost. The considered costs include production, setup, storage spaces, returns inventory and disposal costs as well as inventory and backlog costs of the finished product.

The PPC problem is tackled using an alternative solution approach. The proposed approach adapts three joint production and setup control policies from the literature to the considered context integrating simultaneously the disposal option and the storage space sizing of both finished products and returns. General probability distributions are also considered to describe the stochastic events related to failures and repairs of the production facility. An analysis is then conducted to investigate the strengths and weaknesses of each one and to improve their characteristics. A combination of the simulation tool and optimization techniques (design of experiments and response surface methodology) is also used to develop the best production and setup control policy in terms of costs. This flexible solution approach that offers a powerful technique to control such complex systems, allows the comparison of the effects of a wide range of system settings on the optimal control parameters. It also highlights the strong interactions between production processes, disposal decisions, setup operating conditions, risk of shortages and the costs generated. The obtained results show that the proposed control policy gives the most important benefits of cost savings.

A possible extension of this work can be envisaged investigating the joint design of production and setup control for manufacturers considering differentiated pricing strategies for new and remanufactured products as well as uncertainties in setup times and quality of returns. Another research direction is to integrate replenishments of both raw materials and returns including equivalent uncertainties (variation of the rate of returns, delivery lead-times, etc.) and to study their influence on the optimal control parameters.

CHAPITRE 4

PRODUCTION CONTROL OF FAILURE-PRONE MANUFACTURING-REMANUFACTURING SYSTEMS USING MIXED DEDICATED AND SHARED FACILITIES

Morad Assid [a], Ali Gharbi [b], Adnène Hajji [c],

[a, b] Department of Systems Engineering, École de Technologie Supérieure,
1100 Notre-Dame Ouest, Montréal (QC), Canada H3C 1K3
[c] Department of Operations and Decision Systems & CIRRELT. Laval University,
2325, rue de la Terrasse Québec (QC), Canada G1V 0A6

Paper published in *International Journal of Production Economics*, June 2020.

Résumé

Ce travail traite un problème du contrôle au sein des systèmes hybrides de fabrication-refabrication évoluant dans un environnement dynamique et stochastique. Contrairement aux travaux précédents, il contribue à la littérature par la combinaison d'installations de production séparées et communes. Ce travail est motivé par la nécessité d'intégrer le processus de refabrication tout en augmentant la capacité du système à réagir aux incertitudes (par exemple, pannes et réparations aléatoires des installations, taux de retour des produits récupérés). Le problème est de déterminer les taux de production des installations de fabrication et de refabrication ainsi que les décisions de setup nécessaires pour que l'installation de refabrication passe d'un mode alimenté par les produits récupérés à un mode alimenté par la matière première. L'objectif est de minimiser le coût total encouru. Un modèle stochastique dynamique est ainsi proposé, et les conditions d'optimalité développées sont résolues numériquement. La politique de commande obtenue combine des politiques à seuils critiques et une stratégie de setup selon laquelle la transition entre les modes de production est basée sur le niveau de stock des produits finis. Cette politique de commande est ensuite analysée et comparée à la littérature en considérant trois politiques différentes. Deux d'entre elles ont été développées dans d'autres contextes utilisant uniquement des installations séparées ou communes dans un environnement dynamique et stochastique tandis que l'autre a été adaptée au nôtre. Pour une étude de comparaison efficace, une approche d'optimisation basée sur la simulation est adoptée et mise en œuvre pour le problème à l'étude. Les résultats obtenus suggèrent que la combinaison d’installations de production séparées et communes et l’utilisation de la politique de commande proposée donnent les meilleures performances en matière de coûts.

Mots-clés : commande optimale stochastique, planification de la production, système hybride de fabrication-refabrication, setup, simulation, optimisation.

Abstract

This paper addresses a control problem within hybrid manufacturing-remanufacturing systems (HMRS) evolving in a dynamic and stochastic environment. Unlike previous works, it contributes to the discourse by considering mixed dedicated and shared facilities (MDSF). It is motivated by the need to integrate the remanufacturing flow while increasing the capacity of the system to react to uncertainties (random failures and repairs of facilities, rates of returned products, etc.). The problem is to determine the production rates for the manufacturing and remanufacturing facilities as well as the setup decisions required to switch the remanufacturing facility from a mode supplied by returned products to a mode supplied by raw materials. The objective is to minimize the expected total cost. A dynamic stochastic model is thus proposed, and the developed optimality conditions are solved numerically. The obtained control policy combines hedging point policies and a stock-based setup strategy, under which switching is based on the finished products stock, according to threshold rules. Such control policy is then analyzed and compared to the literature by considering three different control policies. Two of those were developed in other contexts using only dedicated facilities or shared facilities in a dynamic and stochastic environment while the other is adapted to ours. For an effective comparison study, a simulation-based optimization approach is adopted and implemented for the problem under study. Extensive numerical results suggest that the use of MDSF managed by the proposed control policy gives the best performance in terms of costs.

Keywords: stochastic optimal control, production planning, hybrid manufacturing-remanufacturing system, setup policy, simulation, optimization.

4.1 Introduction

Today, an increasing number of production companies in almost every major sector is perceiving the potential business value from implementing the remanufacturing process in their existing system (Geyer et al., 2007). This paper falls within this context by considering a hybrid manufacturing-remanufacturing system (HMRS) that uses both raw materials (manufacturing mode) and returned products (remanufacturing mode) in its production process. Some industrial examples representing this practice are those producing high-value products such as computers, automotive parts, aviation and military equipment, medical instruments, cell phones, tires and toner cartridges (Ferguson & Toktay, 2006). However, compared to classic manufacturing systems, HMRS are more difficult to manage and to control due to the need for synchronizing complex interrelated processes (activities of manufacturing, remanufacturing and disposal) in order to meet customer demand while dealing with several stochastic events (random failures and repair of facilities, rates of returned products) (Ahiska et al., 2017).

Another major question for implementing the remanufacturing process in the existing production system arises as to whether to perform both manufacturing and remanufacturing operations in shared facilities (SF) or to dedicate each production process to a separate facility. Current practices tend to use two dedicated facilities (DF) to perform both manufacturing and remanufacturing operations when a high volume of returned products is ensured (Teunter et al., 2008). In the same sense, uncertain and limited returned products may reveal major underutilization of the dedicated remanufacturing facility, leading to significant inefficiency. On the other side, working with SF capable of supporting both manufacturing and remanufacturing activities when needed seems to be the best solution based on many studies. However, in such situations, to switch between manufacturing and remanufacturing modes, setup operations would be costly and complex to manage. Furthermore, even if remanufacturing costs are low, the system may need a high volume of returned products involving high storage cost. The present paper must be viewed in this context. It investigates how firms could benefit from the advantages of each system configuration (DF versus SF) by considering mixed settings composed of dedicated production facilities with (partially) shared resources. Such a configuration is inspired by the concept of reserve production capacity which is defined by the use of standby machines as the provision of support when the central machine breaks down and until reparation ends (Freiheit, Shpitalni, Huyz, & Korenyz, 2004). In the same sense, this work aims to determine the optimal control policy to coordinate the activities of both manufacturing and remanufacturing facilities for the system under study. Challenges remain, however, in integrating setup decisions to find out how to use the remanufacturing facility, often underutilized, to support the manufacturing one.

The paper is organized as follows. A literature overview is presented in the next section. Section 4.3 introduces the notation and presents a formulation of the optimal control problem. Section 4.4 provides the results of the numerical resolution approach used to illustrate the optimal control policy structure for the studied HMRS composed of mixed dedicated and shared facilities (MDSF). A characterization of the considered control policies, including those found in the literature for HMRS when applied to their corresponding system configurations, is summarized in Section 4.5. The simulation-based optimization approach used to obtain the optimal control parameters and the associated expected total cost is detailed in Section 4.6. Section 4.6.3 presents the simulation model evaluating the performance of each system configuration when it is managed by the appropriate control policy. A numerical example is given in Section 4.6.5. A comparative study between the considered control policies when they are applied to their corresponding system configuration is presented in Section 4.6.6. In Section 4.8, we conclude the paper.

4.2 Literature review

The production planning and control (PPC) problem within HMRS has been the subject of several scientific contributions and practical initiatives in recent decades. Detailed literature reviews can be found in (Ilgin & Gupta, 2010 ; Lage & Godinho Filho, 2016). To better position our contribution, our literature review focuses on works covering the findings related to the subject under study, as presented in Table 4.1.

Table 4.1 Bibliographic review related to the PPC within HMRS

Research works	Mixed dedicated and shared facilities	Dedicated production facilities	Shared production facility	Dependency of demands/ sales and returns rates	Disposal option	Setup time and cost between production modes	Proposal of new policies	Failure-prone facilities
Class I. Dedicated facilities								
(Van Der Laan et al., 1999)		×						
(Dobos, 2003)		×		×	×		×	
(Kiesmüller, 2003b)		×			×			
(Inderfurth, 2004)		×			×		×	
(Aras et al., 2006)		×		×	×		×	
(Teunter et al., 2008)		×		×				
(Feng et al., 2013)		×		×	×		×	
(Guo & Ya, 2015)		×		×				
(Vercraene et al., 2014)		×		×	×		×	
(Gayon et al., 2017)		×		×	×		×	
(Liao et al., 2017)		×						
(Kilic et al., 2018)		×					×	
(Kenné et al., 2012)		×					×	×
(Ouaret et al., 2013)		×		×			×	×
(Kouedeu et al., 2014)		×		×	×		×	×
(Ouaret et al., 2018a)		×		×	×		×	×
(Polotski et al., 2018)		×		×	×		×	×
Class II. Shared facilities								
(Teunter et al., 2006)		×	×			×		
(Francas & Minner, 2009)			×	×	×			
(Flapper et al., 2014)			×	×			×	
(Polotski et al., 2015)			×	×		×		
(Macedo, Alem, Santos, Junior, & Moreno, 2016)		×	×	×	×	×		
(Polotski et al., 2017a)			×	×		×	×	×
(Polotski et al., 2017b)			×	×		×	×	×
(Turki et al., 2018)			×	×		×		×
(Assid et al., 2019)			×	×	×	×	×	×
Our proposal	×	×	×	×	×	×	×	×

The selected works are categorized into two classes: HMRS where each production mode is affected to its DF and those with SF for both manufacturing and remanufacturing operations. Different comparison criteria related to the characteristics of this work are used to classify the considered papers: the system structure (DF and/or SF), the dependence between customer demand rate and that of returns, the disposal option, the consideration of time and cost of setup operations, the proposal of new control policies and the failure-prone system.

There has been considerable interest in the PPC within HMRS using DF for each production mode. Among the works of this category, Van Der Laan et al. (1999) presented a methodology to compare two control policies: a Push policy in which all returned products are remanufactured as early as possible and a Pull policy in which all returned products are remanufactured as late as convenient. They showed that pull policy is preferable if the inventory cost of returns is lower than that of finished products. Dobos (2003) proposed an optimal production-inventory policy for an HMRS with disposal activities. The objective is to minimize the sum of manufacturing, remanufacturing and disposal costs. Integrating different lead-times for production modes, Kiesmüller (2003b) presented an algorithm for the computation of the optimal manufacturing, remanufacturing and disposal rates for systems with stochastic demand and return. Inderfurth (2004) developed a model in which new and remanufactured (lower quality, lower price) products must be differentiated and therefore dedicated to two distinct markets, with a possibility of substitutions. They proposed an optimal joint manufacturing and remanufacturing control policy with the aim to maximize profit. Aras et al. (2006) considered a policy that rejects returned products if the remanufacturable inventory exceeds some threshold. They modelled and compared through a simulation-optimization experiment, two heuristic control policies that use either manufacturing or remanufacturing as the primary means of satisfying customer demand. Teunter et al. (2008) studied the coordination between manufacturing and remanufacturing activities in a multi-product economic lot scheduling problem. Feng et al. (2013) introduced a recovery system for perishable items with capacity constraints for both manufacturing and remanufacturing processes. Guo and Ya (2015) analyzed the optimal production strategy when the remanufacturing cost, the buyback cost and the rate of returned products are affected by their quality level. They showed that using higher remanufacturing costs to produce lower quality of finished products could reduce the average total cost. Vercraene et al. (2014) also used disposal decisions to avoid excess inventory of returns, without being related to their quality level. They showed that the optimal policy is characterized by two state-dependent base-stock thresholds for manufacturing and remanufacturing and one state-dependent return acceptance threshold. In the same context, Gayon et al. (2017) investigated the optimal structure of control policies considering two disposal options which can be used for returned products or finished ones. Liao et al. (2017) calculated the effect of uncertainties in procurement and demand on net profit for an automobile engine-remanufacturing factory and provided useful guidelines for effective coordination of manufacturing and remanufacturing activities. More recently, Kilic et al. (2018) proposed two heuristic control policies to manage manufacturing and remanufacturing activities while considering service level constraints.

Among the works of this class that use two dedicated facilities (to manufacturing and remanufacturing respectively), only a few recent models integrate aspects related to the stochastic dynamics of facilities. Kenné et al. (2012) developed the optimality conditions in the form of Hamilton Jacobi–Bellman (HJB) equations for an HMRS where both facilities are subject to random failures and repairs. They used a numerical approach to determine the optimal manufacturing and remanufacturing control policy which minimizes the sum of the holding and backlog costs. The optimal control problem, such as formulated in this work, belongs to a class of problems widely studied in the literature as those dealing with joint control of production and : preventive maintenance (Berthaut, Gharbi, Kenné, & Boulet, 2010 ; Polotski, Kenné, & Gharbi, 2019 ; Rivera-Gómez et al., 2018), quality (Ouaret et al., 2018a), setup (Hajji, Gharbi, & Kenne, 2004), subcontracting (Rivera-Gómez et al., 2016 ; 2018). Other problems dealing with joint inventory control and dynamic pricing of perishable products have also used the same approach based on the Pontryagin's maximum principle or the HJB formulation (Feng, Zhang, & Tang, 2016 ; S. Li, Zhang, & Tang, 2015 ; Zhang, Wang, Lu, & Tang, 2015), etc. Ouaret et al. (2013) showed that the optimal production policy is of hedging-point type, for HMRS with stochastic demand, similarly to the known case of a constant demand as in (Kenné et al., 2012). Kouedeu et al. (2014) developed a stochastic optimization model while considering that the failure rate of the manufacturing facility depends on its production rate. The developed methodology is applied to a real European business case study producing printer cartridges (Kouedeu et al., 2015). More recently, Polotski et al. (2018) improve the numerical technique for policy optimization of failure-prone manufacturing systems under time-varying demand. They apply the developed framework to determine the optimal control policies for failure prone HMRS with variable demand and return rates.

The PPC problem for SF of HMRS with setup policy to switch between the production modes remains scarcely explored. Among papers dealing with this class, Thierry et al. (1995) used a case study methodology to investigate a recovery system in the copier industry where remanufactured and new products use the same assembly lines. They showed that such a system could reduce start-up costs for remanufacturing. Teunter et al. (2006) addressed the dynamic lot sizing problem with remanufacturing by considering two scenarios for setup costs: a joint setup cost for manufacturing and remanufacturing (single production line) or separate setup costs (dedicated production lines). Macedo, Alem, Santos, Junior and Moreno (2016) dealt with the same problem using stochastic demand and return. For the multi-product network design problem, Francas and Minner (2009) studied the capacity planning for different network configurations with remanufacturing. They showed that single flexible production sites are more beneficial when finished products are destined for the same market. Flapper et al. (2014) addressed the optimal scheduling for HMRS with negligible setup times and costs based on the queueing theory. They proposed an optimal production schedule that minimizes the average discounted long-term cost. Polotski et al. (2015) integrated system dynamics and developed an optimal control model for an HMRS with setups. Polotski et al. (2017a) extended the results of (Polotski et al., 2015) by proposing an optimal structure of joint production and setup control policy for HMRS with low rates of returns. The authors also discussed the case of failure-prone systems, but only when failure and repair events are limited to homogeneous Markov processes. Joint production and setup control policy for HMRS with a high level of return rates can be found in (Polotski et al., 2017b). More recently, Turki et al. (2018) proposed a manufacturing-remanufacturing system by addressing the issues of manufacturing, remanufacturing, and storage decisions in accordance with industrial constraints of carbon emission regulations. Assid, Gharbi and Hajji (2019) elaborated a new manufacturing, remanufacturing and setup control policy showing its superiority in terms of costs compared to several control policies adapted from the literature.

The main observation of the above-mentioned works is that none of them considers mixed settings where systems combine both dedicated and shared production facilities. In addition to capturing the benefits of each setting (when only DF or SF are adopted), this paper is motivated by the need to equip production managers with better tools to effectively control this class of systems. To the best of our knowledge, no work has addressed the PPC problem for unreliable HMRS composed of MDSF, evolving in a dynamic stochastic context. In such a context, our main contribution lies in providing the structure of an integrated optimal control policy to simultaneously manage manufacturing, remanufacturing, disposal and setup activities. Since an analytical solution of the control problem is not generally available, a numerical approach is applied to illustrate the structure of the developed control policy. This paper also contributes by generating valuable insights into coordinating interrelated decisions of when to manufacture a new product, when to remanufacture or to dispose a returned one, and when SF should conduct setup operations to switch from one production mode to another. After developing the proposed control policy, a simulation-based optimization approach is used to optimize the associated control parameters, which minimize the expected total cost. This approach offers a powerful technique to control such a complex system while better reflecting the industrial reality (describing failure and repair events by any probability distribution). It is also used to conduct an in-depth comparative study, for a wide range of system parameters, considering three other control policies adapted from the literature. They were developed for different system configurations (DF, SF and MDSF). The obtained results show the advantage of combining both dedicated and shared facilities as well as the effectiveness of the related control policy developed in this paper, which provides firms with a simple tool that effectively helps them to achieve more saving.

4.3 Problem description and formulation

4.3.1 Notation

The notations used in this paper are defined below. $\forall i, j = \{1,2\}$:

$\gamma_R(t)$	: Proportion of fulfilled demand returned to facility F_2 at time t
ρ	: Discount rate
c_F^+	: Finished products holding cost (\$/time/unit)
c_F^-	: Finished products backlog cost (\$/time/unit)
c_R^+	: Returns holding cost of returns (\$/time/unit)
c_{dis}	: Disposal cost (\$/unit)
c_1	: Manufacturing cost at the facility F_1 (\$/unit)
c_{2man}	: Manufacturing cost at the facility F_2 (\$/unit)
c_{2rem}	: Remanufacturing cost at the facility F_2 (\$/unit)
c_S^{ij}	: Setup cost while switching from mode i to mode j (\$/ setup operation)
d	: Finished product demand rate
D_S^{ij}	: Setup time (duration) while switching from mode i to mode j
$u_1(t)$	: Manufacturing rate of the facility F_1 at time t
$u_2(t)$	: Production rate of the facility F_2 at time t
$u_{2man}(t)$	: Manufacturing rate of the facility F_2 at time t
$u_{2rem}(t)$	: Remanufacturing rate of the facility F_2 at time t
$u_R(t)$	: Returns rate at time t
$u_{dis}(t)$	: Disposal rate at time t
U_1^{max}	: Maximum manufacturing rate of the facility F_1
U_{2man}^{max}	: Maximum manufacturing rate of the facility F_2
U_{2rem}^{max}	: Maximum remanufacturing rate of the facility F_2
$x_F(t)$	: Inventory level (or backlog) of finished products at time t
$x_R(t)$	: Inventory level of returns at time t

4.3.2 System description

The HMRS under study (illustrated in Figure 4.1) consists of two unreliable facilities supplied by two upstream stocks. Facility F_1 is supplied by new raw materials considered available when needed and operated under a single mode to transform raw materials to finished products stored in a downstream storage space. Facility F_2 operates under two modes. The manufacturing mode (mode 1) operates in the same conditions as F_1 but with higher costs. The remanufacturing mode (mode 2) is supplied by an upstream stock of returned products. The use of F_2 in manufacturing mode is a major concern due to limited rate of returns and because of limited production capacity of F_1. Setup time and cost are required to switch between the two production modes of F_2. The whole system faces the demand for one type of product. The considered PPC problem is a continuous-time failure-prone manufacturing-remanufacturing system with demand dependant returns.

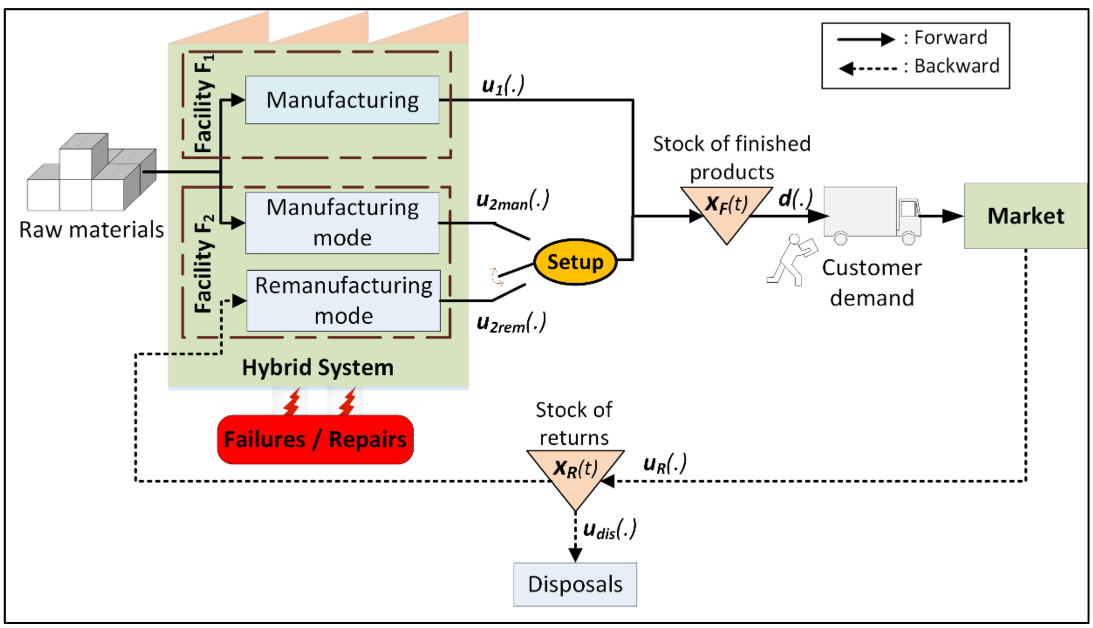

Figure 4.1 Unreliable hybrid manufacturing-remanufacturing system

The following summarizes the general context and main assumptions considered in this paper:

- the remanufactured products are of the same quality level as the manufactured products (from both facilities);
- returned products and raw materials are of good quality;
- the rate of customer demand is known and constant;
- the rate of returns is proportional to that of customer demand ($u_R = \gamma_R . d$, $0 < \gamma_R < 1$);

- neither the manufacturing facility nor the remanufacturing one can satisfy alone all customer demand.

4.3.3 Problem formulation

The state of the system at time *t* has three components including:

- a continuous part, which describes the cumulative finished products level (inventory if positive and backlog if negative) and measured by $x_F(t)$.
- a continuous part, which describes the inventory level of returns and measured by $x_R(t)$. This part faces the continuous downstream remanufacturing rate when the facility F_2 is in remanufacturing mode and an upstream continuous supply with rate $u_R(t)$. Even if it is available, F_2 in the remanufacturing mode cannot process parts when $x_R(t)$ is equal to zero. Let $0 \leq x_R(t) \leq x_R^{cap}$ be the capacity constraint of the stock of returns.
- a discrete part which describes the whole system state (F_1 and F_2) and given as follows: the operational mode of two facilities at time t can be described by the random variables $\xi_1(\mathrm{t})$ and $\xi_2(\mathrm{t})$ with value in $M_1 = \{1,2\}$ and $M_2 = \{1,2\}$ respectively, where:

$$\xi_1(\mathrm{t}) = \begin{cases} 1 & \mathrm{F_1 \text{ is available}} \\ 2 & \mathrm{F_1 \text{ is unavailable}} \end{cases}, \quad \xi_2(\mathrm{t}) = \begin{cases} 1 & \mathrm{F_2 \text{ is available}} \\ 2 & \mathrm{F_2 \text{ is unavailable}} \end{cases}$$

The transition rates matrix of the stochastic processes $\xi_1(\mathrm{t})$ and $\xi_2(\mathrm{t})$ are denoted by $\mathrm{T_1}$ and $\mathrm{T_2}$ such that $\mathrm{T_i} = \{q_{\alpha\vartheta}^i\}$, with $q_{\alpha\vartheta}^i \geq 0$ if $\alpha \neq \vartheta$ and $q_{\alpha\alpha}^i = -\sum_{\alpha\neq\vartheta} q_{\alpha\vartheta}^i$, where $\alpha, \vartheta \in M_i$. This summation equation derives directly from the definition of the transition matrix for continuous time discrete state Markov chain (Ross, 2014). The transitions rates matrix $\mathrm{T_i}$ is expressed as follows:

$$T_i = \begin{vmatrix} -q_{12}^i & q_{12}^i \\ q_{21}^i & -q_{21}^i \end{vmatrix}$$

The operational mode of the whole system can be described by the random vector $\xi(t) = (\xi_1(t), \xi_2(t))$ taking values in $M = \{1,2,3,4\}$, where:

$$\xi(t) = \begin{cases} 1 \;\; Both\ F_1\ and\ F_2\ are\ available\ (1,1) \\ 2 \;\; F_1\ is\ available\ and\ F_2\ is\ unavailable\ (1,2) \\ 3 \;\; F_1\ is\ unavailable\ and\ F_2\ is\ available\ (2,1) \\ 4 \;\; Both\ F_1\ and\ F_2\ are\ unavailable\ \ (2,2) \end{cases}$$

The transition rates of the stochastic process $\xi(t)$ ($T = \{q_{\alpha\vartheta}\}, \alpha, \vartheta \in M$) are easily derived from those of $\xi_1(t)$ and $\xi_2(t)$ by using the definition of $\xi(t)$ as follows.

$$T = \begin{bmatrix} q_{11} & q_{12} & q_{13} & q_{14} \\ q_{21} & q_{22} & q_{23} & q_{24} \\ q_{31} & q_{32} & q_{33} & q_{34} \\ q_{41} & q_{42} & q_{43} & q_{44} \end{bmatrix} = \begin{bmatrix} -(q_{12}^1 + q_{12}^2) & q_{12}^2 & q_{12}^1 & 0 \\ q_{21}^2 & -(q_{12}^1 + q_{21}^2) & 0 & q_{12}^1 \\ q_{21}^1 & 0 & -(q_{21}^1 + q_{12}^2) & q_{12}^2 \\ 0 & q_{21}^1 & q_{21}^2 & -(q_{21}^1 + q_{21}^2) \end{bmatrix}$$

For the considered HMRS, the state space is given by (x_R, x_F, α) such that: $x_R \in [0, x_R^{cap}]$, $x_F \in R$ and $\alpha \in M$. Let $S = [0, x_R^{cap}]$ and $\partial S = \{0, x_R^{cap}\}$, and let $S^0 =]0, x_R^{cap}[$ be the interior of S. The dynamic of the stock levels $x_R(t)$ and $x_F(t)$ is given by the following differential equations.

$$\begin{cases} dx_R(t)/dt = u_R(t) - u_{2rem}(t) - u_{dis}(t), & x_R(0) = x_R^0 \\ dx_F(t)/dt = u_1(t) + u_{2man}(t) + u_{2rem}(t) - d, & x_F(0) = x_F^0 \end{cases} \tag{4.1}$$

Where x_F^0 and x_R^0 denote the surplus levels at the initial time. Our decision variables are the manufacturing-remanufacturing production rates of facilities F_1 and F_2: $u_1(t)$, $u_{2man}(t)$, $u_{2rem}(t)$, the disposal rate $u_{dis}(t)$ and a sequence of setups denoted by $\Omega = \{(\tau_0, i_0 i_1), (\tau_1, i_1 i_2), \ldots\}$. A setup (τ, ij) is defined by time τ at which it begins and a pair ij denoting that the facility F_2 was already setup in the mode i and is being switched to be in mode j.

Let i denote the initial setup mode of the facility F_2 and s the remaining setup time ($s = D_s^{ij}$ at the beginning of a setup action). The setup cost c_s^{ij} is assumed to be charged at the beginning of the setup. The sequence function of setup operations may also be defined by the parameter S_{ij}, $i, j \in \{1,2\}$ as follows:

$$
\begin{aligned}
S_{11} &= \begin{cases} 1 & \textit{if the system is in production mode 1, no setup action is performed} \\ 0 & \textit{Otherwise} \end{cases} \\
S_{12} &= \begin{cases} 1 & \textit{if the system is being setup from the mode 1 to the mode 2} \\ 0 & \textit{Otherwise} \end{cases} \\
S_{22} &= \begin{cases} 1 & \textit{if the system is in production mode 2, no setup action is performed} \\ 0 & \textit{Otherwise} \end{cases} \\
S_{21} &= \begin{cases} 1 & \textit{if the system is being setup from the mode 2 to the mode 1} \\ 0 & \textit{Otherwise} \end{cases}
\end{aligned}
\tag{4.2}
$$

Note that the equation $\sum_{i,j} S_{ij} = 1$ must be true since F_2 cannot be in both production modes at the same time. At any given time, the manufacturing and remanufacturing rates have to satisfy the capacity constraints.

$$
\begin{cases} 0 \leq u_1(t) \leq U_1^{max} \\ 0 \leq u_{2man}(t) \leq U_{2man}^{max} \\ 0 \leq u_{2rem}(t) \leq U_{2rem}^{max} \end{cases}
\tag{4.3}
$$

Let A and A_p denote the sets of admissible decisions (Ω, p), that is decisions that respect the constraints of the system capacity:

$$
\mathrm{A} = \left\{ (\Omega, \mathrm{p}), 0 \leq \mathrm{u}_1(\mathrm{t}) \leq \mathrm{U}_1^{\max}, 0 \leq \mathrm{u}_{2\mathrm{man}}(\mathrm{t}) \leq \mathrm{U}_{2\mathrm{man}}^{\max}, 0 \leq \mathrm{u}_{2\mathrm{rem}}(\mathrm{t}) \leq \mathrm{U}_{2\mathrm{rem}}^{\max}, \mathrm{u}_{\mathrm{dis}}(\mathrm{t}) \geq 0, \forall \mathrm{t} \geq 0 \right\}
$$

$$
A_p = \left\{ p, 0 \leq u_1(t) \leq U_1^{max}, 0 \leq u_{2man}(t) \leq U_{2man}^{max}, 0 \leq u_{2rem}(t) \leq U_{2rem}^{max}, u_{dis}(t) \geq 0, \forall t \geq 0 \right\}
$$

With $p = \big(u_1(t), u_{2man}(t), u_{2rem}(t), u_{dis}(t)\big)$. The cost rate function $g(.)$ is the sum of the inventory cost of returns, the production rates of the two facilities, the disposal rate and the inventory (backlog) costs of finished products.

$$g\big(x_R(t), x_F(t), u_1(t), u_{2man}(t), u_{2rem}(t), u_{dis}(t)\big) = c_R^+ \times x_R(t) + c_F^+ \times x_F^+(t) + c_F^- \times x_F^-(t) + c_1 \times u_1(t) + c_{2man} \times u_{2man}(t) + c_{2rem} \times u_{2rem}(t) + c_{dis} \times u_{dis}(t) \tag{4.4}$$

Where, $x_F^+(t) = max\big(0, x_F(t)\big)$ and $x_F^-(t) = max(-x_F(t), 0)$.

The overall cost function including setups, during s units of times is given by:

$$R_{ij}(x_R, x_F, p, s) = C_s^{ij}.I\big(s = D_s^{ij}\big) + \int_0^s e^{-\rho t} g(x_R + (u_R - u_{dis}).t, x_F + (u_1 - d).t, u_1, 0,0, u_{dis})dt \tag{4.5}$$

With $s \in \left[0, D_s^{ij}\right]$, $j \neq i$ and $I\big(s = D_s^{ij}\big) = \begin{cases} 1 & if\ s = D_s^{ij} \\ 0 & otherwise \end{cases}$

We consider the following assumption of the function $g(.)$.

(P4.1): $g(.)$ is a nonnegative jointly convex function (, convex in either z or p or both). For all $z, z' \in S \times R$ and $p, p' \in A_p$, there exist constants C_0 and $K_g \geq 0$ such that:

$$|g(z,p) - g(z',p')| \leq C_0[(1 + |z|^{K_g} + |z'|^{K_g}).|z - z'| + |p - p'|]$$

Using the cost rate functions (4.4)-(4.5), the expected total cost J(.) can be defined by the following expression:

$$J(x_R, x_F, s, \Omega, p, \alpha) = \int_0^s e^{-\rho t} g(x_R + (u_R - u_{dis}).t, x_F + (u_1 - d).t, u_1, 0,0, u_{dis})dt + E_{x_R, x_F, s, \alpha}\left[\int_s^{\infty} e^{-\rho t}.g(x_R, x_F, p).dt + \sum_{l=0}^{\infty} e^{-\rho \tau_l}.C_s^{i_l j_{l+1}}\right] \tag{4.6}$$

Where, $E_{x_R,x_F,s,\alpha}$ is the conditional expectation given the condition (x_R, x_F, s, α) at time s. The control problem considered herein is to find an admissible decision (Ω, p), $p = \big(u_1(t), u_{2man}(t), u_{2rem}(t), u_{dis}(t)\big)$ which minimizes J(.) given by (4.6) subject to (4.1) and (4.3)-(4.4). This is a feedback control that determines the production rates of the two facilities, the disposal decisions and the setup decisions as a function of the system state. The value function of such a stochastic optimal control problem while F_2 is in mode i, is given by:

$$v_i(x_R, x_F, \alpha, s) = \min_{(\Omega,p)\in A} J(x_R, x_F, s, \Omega, p, \alpha) \tag{4.7}$$

The value function given by equation (4.7) satisfies specific properties called optimality conditions. In Appendix II, we develop these optimality conditions which are a set of coupled partial derivatives equations (called Hamilton–Jacobi–Bellman (HJB) equations) very difficult to solve analytically. A numerical method is thus presented and applied in Appendix III to solve them.

4.4 Numerical results

The numerical resolution (see Appendix III) conducted to characterize the optimal production, disposal and setup policies are presented here within a preliminary case. This preliminary data set and results aim to illustrate the optimal control policy in the whole state of the system. Once found, the obtained control policy will be deeply analyzed and compared, in sections 4.6.6 and 0, to the literature by adapting several control policies developed for different system configurations (only DF or SF). (see Table 4.2) presents the value of the set of parameters used in the numerical example.

The computational domain is as follows: $CD = \{(\mathrm{x_R}, \mathrm{x_F})\colon 0 \le \mathrm{x_R} \le 10, -10 \le \mathrm{x_F} \le 10\}$.

Table 4.2 Parameters for the numerical example

Parameters	(c_s^{12}, c_s^{21})	(D_s^{12}, D_s^{21})	U_1^{max}	U_{2man}^{max}	U_{2rem}^{max}	d	$\gamma_R(t)$	ρ
Values	(0.5,0.5)	(0.15,0.15)	8	8	8	10	0.3	0.9
Parameters	h	c_F^+	c_F^-	c_R^+	c_{2man}	c_{2rem}	c_1	c_{dis}
Values	0.1	1	10	1	1.1	0.5	1	2

The transition rate matrix defining the stochastic processes $\xi_1(t)$ and $\xi_2(t)$ related to the state of facilities is as follows: $T_1 = \begin{bmatrix} -0.03 & 0.03 \\ 0.33 & -0.33 \end{bmatrix}$ and $T_2 = \begin{bmatrix} -0.01 & 0.01 \\ 0.33 & -0.33 \end{bmatrix}$. They define the availability rates of F_1 and F_2 to 91.67% and 97.05% respectively. The transition matrix of the whole system T is defined by (4.8).

$$T = \begin{bmatrix} -0.04 & 0.01 & 0.03 & 0 \\ 0.33 & -0.36 & 0 & 0.03 \\ 0.33 & 0 & -0.34 & 0.01 \\ 0 & 0.33 & 0.33 & -0.66 \end{bmatrix} \tag{4.8}$$

The results illustrate the decision variables in the state of the system. That is, each decision variable will be a function of (x_R, x_F) and the state of the stochastic process T. states 1 (F_1 and F_2 are available) and 2 (only F_1 is available) are particularly interesting to show. In fact, in state 4, the two facilities are unavailable whereas in state 3 when the only facility F_2 is available, the system will always use the remanufacturing mode.

Figure 4.2 to Figure 4.5 show the obtained numerical results for the studied case (Table 4.2) when the system is in state 1 (the two facilities are up and available to produce). The resulting production, disposal and setup policies divide the stock space into different regions delimited by three thresh levels.

Figure 4.2 shows the production rate of the facility F_1 as a function of stock levels (x_R, x_F). The obtained policy is of hedging-point type. It is defined by Z_F where facility F_1 must produce at the maximum level to reach it and try to keep it with the support of the facility F_2. This policy is common in failure-prone manufacturing systems. It allows the construction of a stock of the final product to hedge against future capacity shortages. Equation (4.9) describes this policy. Recall that F_1 alone cannot satisfy the demand. For that reason, equation (4.9) is a part of the combined production policy including facility F_2 described in what follows.

$$u_1 = \begin{cases} U_1^{max} & if\ (x_F < Z_F) \\ d - u_2 & if\ (x_F = Z_F) \\ 0 & otherwise \end{cases} \tag{4.9}$$

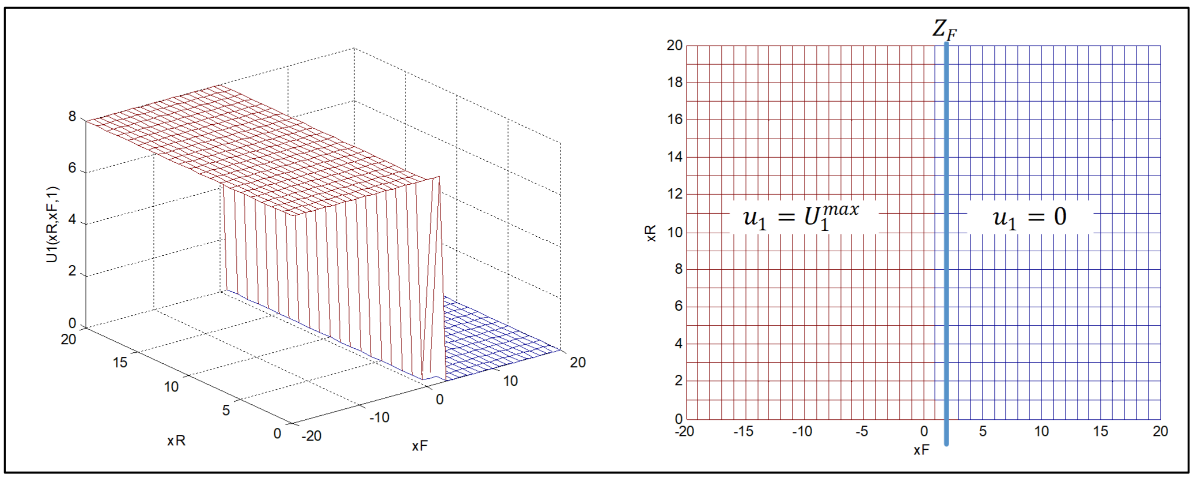

Figure 4.2. Facility $\boldsymbol{F_1}$ production rates in state 1

Figure 4.3 and Figure 4.4 show the production policy of the facility F_2 in mode 1 (manufacturing) and mode 2 (remanufacturing). This policy is governed by a setup policy to switch production from one mode to another. As shown in Figure 4.3, the production rate in the mode remanufacturing should be at its maximum rate when stock of returns is available and given that the threshold level $\mathrm{Z_F}$ of finished products is not exceeded. The setup for mode manufacturing (Figure 4.4) takes place when the stock of finished products reaches a critical level $\mathrm{a_F}$. If exceeded setup for remanufacturing mode can take place again.

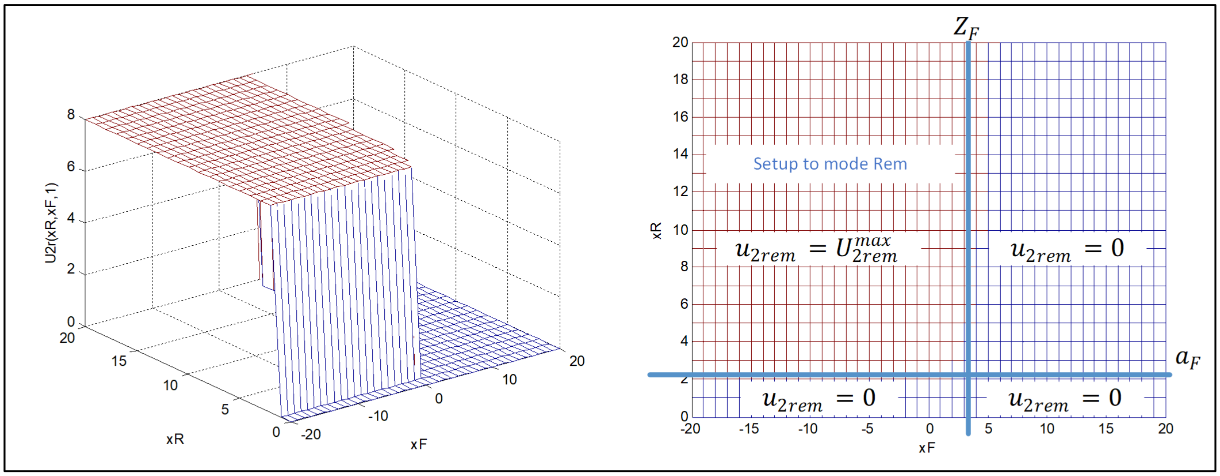

Figure 4.3. Facility $\boldsymbol{F_2}$ setup to the mode remanufacturing and its production rate in state 1

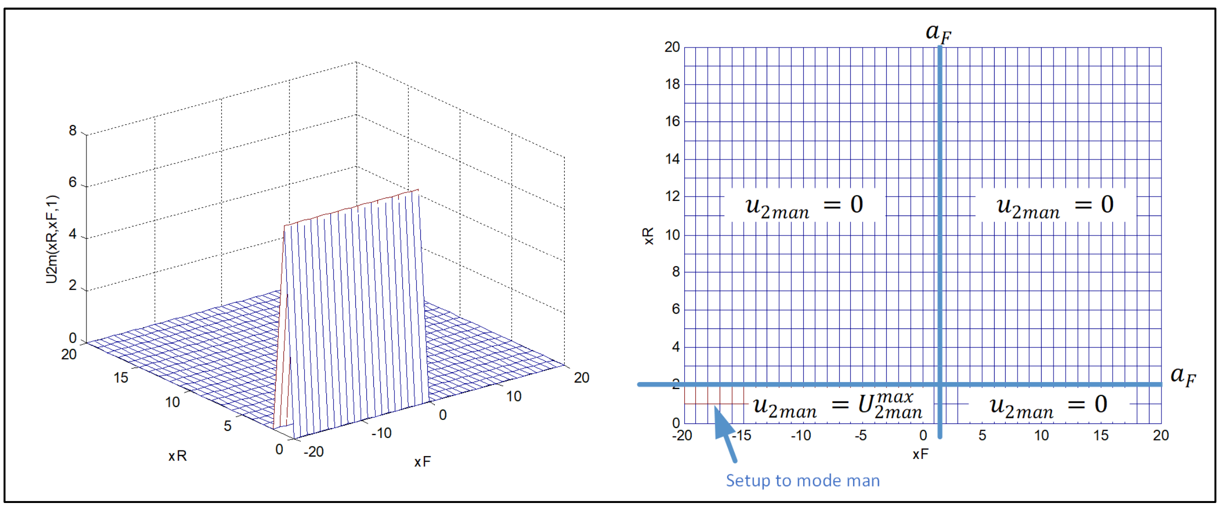

Figure 4.4. Facility $\boldsymbol{F_2}$ setup to the mode manufacturing and its production rate in state 1

The following equations (4.10) to (4.12) describe facility F_2 production policy and its setup strategy from mode 1 to mode 2 and vice versa.

$$u_2 = \begin{cases} U_{rem}^{max}.I\{S_{22} = 1\} & if\ (x_R > 0) \\ u_R.I\{S_{22} = 1\} & if\ (x_R = 0) \\ U_{man}^{max}.I\{S_{11} = 1\} & if\ (x_F < Z_F) \\ 0 & otherwise \end{cases} \tag{4.10}$$

$$S_{12} = \begin{cases} 1 & if\ (x_F \geq a_F) \\ 0 & otherwise \end{cases} \tag{4.11}$$

$$S_{21} = \begin{cases} 1 & if\ (x_F < a_F) \\ 0 & otherwise \end{cases} \tag{4.12}$$

Where $\mathrm{I}(\omega) = 1$ if ω is true while $\mathrm{I}(\omega) = 0$ if not. S_{ij}, $i, j \in \{1,2\}$, $i \neq j$ is used to define the setup operations as defined by equation (4.2).

Figure 4.5 describes the disposal policy in the stock space. The obtained results show that if the stock of returns exceeds Z_R all returned products should be disposed. This result is expected given that the capacity of transformation in the remanufacturing mode is limited to the maximal remanufacturing rate. Indeed, if we keep all returned products, especially during long repairs after the failure of the facility F_2, the system accumulates holding costs and may be economically inefficient. For the same reasons, this disposal policy will be applied to the control policies adapted to our context. The following equation (4.13) describes the disposal policy.

$$u_{dis} = \begin{cases} u_R & if\ (x_R = Z_R) \\ 0 & otherwise \end{cases} \tag{4.13}$$

The obtained numerical results clearly show that the production, disposal and setup policies are described by three control parameters (Z_F, a_F, Z_R). Governed by equations (4.9) to (4.13), the described policies guarantee consistent control with a lower cost. To consolidate these observations a preliminary sensitivity analysis is conducted. The results show that when system parameters (see Table 4.2) change, the structure of the described policies (4.9) to (4.13) is maintained and is described by three control parameters.

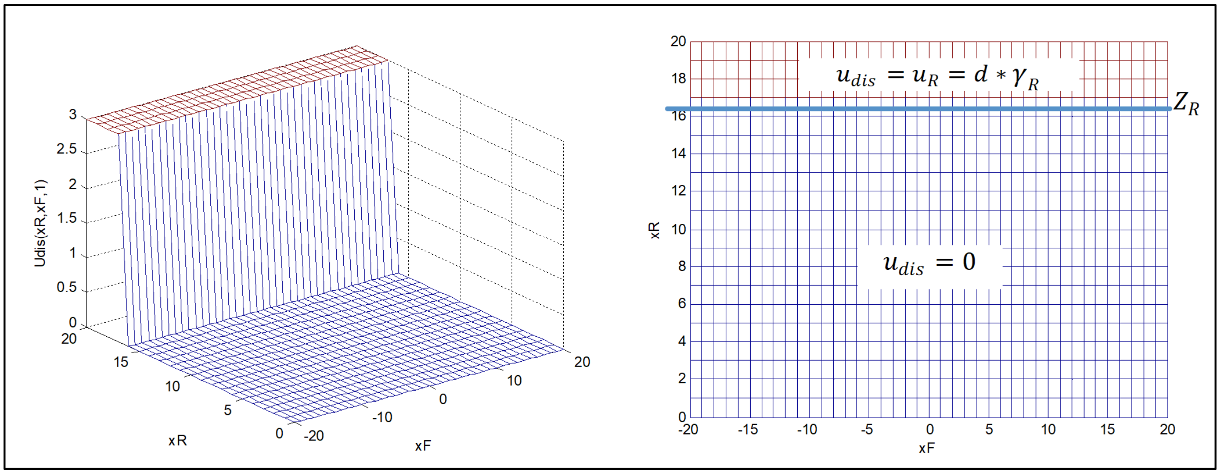

Figure 4.5 The disposal rates in state 1

4.5 Considered control policies for the different system configurations

As indicated earlier, our objective is to determine the joint control policy minimizing the expected total cost of unreliable HMRS composed of both dedicated and shared facilities. At this point, a parameterized control policy is developed based on the analysis of the numerical results (see Section 4.5.1.1). It will be compared (in Sections 4.6.6 and 0) to three other control policies adapted from the literature (see their description below). Two of those were developed for system configurations using only DF or SF in a dynamic and stochastic environment, while the third one is a control policy that we adapt to the system configuration consisting of MDSF. The goal is to confirm the economic advantage of combining both dedicated and shared facilities while managing the corresponding system by our proposed control policy (defined by (4.9)-(4.13)). In the following sections, the symbol "CP-SC" indicates the control policy CP which is applied to manage the system configuration SC.

4.5.1 Control policies for system configuration combining dedicated and shared facilities

In addition to the control policy obtained numerically, another one will be considered, based on literature, for the system configuration composed of MDSF. It is defined in Section 4.5.1.2.

4.5.1.1 The proposed control policy: (Proposed-MDSF)

Following the numerical results (see Section 4.4), equations (4.9)-(4.13) describe the proposed control policy, called Proposed-MDSF, which is of the hedging-point type. It acts as a feedback strategy to control the production rates and build a safety stock (of size Z_F) during periods of excess capacity with the aim to hedge against uncertainties related to failures. Specifically, it considers the production (manufacturing and remanufacturing) activities of the facility F_2 as priority by adapting the manufacturing rate of the facility F_1 to that of demand while taking into account the production rate of F_2 (see equation (4.9)). The priority assigned to F_2 is because it is the only one that integrates remanufacturing activities which cost less compared to manufacturing ones. In this sense, when F_2 is in remanufacturing mode (mode 2), it is always used at its maximum capacity if stored returns are available ($x_R > 0$) (see equation (4.10)). As regards setup operations, the Proposed-MDSF controls the transition of F_2 from one production mode to another based on the inventory level of finished products (x_F) through the parameter a_F ($a_F < Z_F$). Thus, if the stock of finished products is maintained at comfortable levels ($x_F \geq a_F$), F_2 is used in remanufacturing mode which costs less (see equation (4.11)). However, in the case of high risk of shortages ($x_F < a_F$), F_2 switches to manufacturing mode to benefit from unlimited raw materials (see equation (4.12)). The Proposed-MDSF performs disposal operations only when the storage space of returns is full ($x_R = Z_R$) (see equation (4.13)). The Proposed-MDSF is characterized by three control parameters: Z_F, a_F and Z_R.

4.5.1.2 The state dependent transition control policy: (SDT-MDSF)

The second control policy considered in this work is the state-dependent transition control policy, called SDT-MDSF. It switches between production modes based on the state of F_1, as shown by equations (4.14)-(4.15). It is inspired by the concept of reserve production capacity using standby machines (represented by F_2) as the provision of support when the central machine (represented by F_1) breaks down and until reparation ends (Freiheit et al., 2004). Thus, under SDT-MDSF, F_2 is used in the manufacturing mode (mode 1) only when F_1 is under repair. The objective is to make better use of the production capacity of F_2 affected by a limited rate of returns. This control policy is practical to implement and to manage in an industrial environment and is characterized by two control parameters: Z_F and Z_R. It is represented by equations (4.9)-(4.10) and (4.13) to manage production and disposal activities and by equations (4.14)-(4.15) for the setup sequence operations.

$$S_{12} = \begin{cases} 1 & if\ (\alpha_1 = 1) \\ 0 & otherwise \end{cases} \tag{4.14}$$

$$S_{21} = \begin{cases} 1 & if\ (\alpha_1 = 0) \\ 0 & otherwise \end{cases} \tag{4.15}$$

4.5.2 Control policy for system configurations composed of dedicated facilities: (CP#3-DF)

Based on most works dealing with PPC for HMRS, the third control policy adopted for the comparative study considers that both facilities are dedicated and operate in a different production mode. F_1 only transforms raw materials to finished products (see equation (4.16)) while F_2 only remanufactures returned products (see equation (4.17)). This control policy, called CP#3-DF, is an adaptation of that developed by (Kenné et al., 2012 ; Ouaret et al., 2018b ; Polotski et al., 2018). It is also of hedging-point type. Regarding the disposal policy, the CP#3-DF will conduct the disposal operations when the storage space of returns is full ($x_R = Z_R$) (see equation (4.13)). It is characterized by two control parameters: Z_F and Z_R.

$$u_1 = \begin{cases} U_1^{max} & if\ (x_F < Z_F) \\ d - u_2 & if\ (x_F = Z_F) \\ 0 & otherwise \end{cases} \tag{4.16}$$

$$u_2 = \begin{cases} U_{rem}^{max}.I\{S_{22} = 1\} & if\ (x_R > 0) \\ u_R.I\{S_{22} = 1\} & if\ (x_R = 0) \\ 0 & otherwise \end{cases} \tag{4.17}$$

4.5.3 Control policy for system configurations composed of a shared facility: (CP#4-SF)

The control policy CP#4-SF is based on (Assid et al., 2019). It will be considered to represent the case of HMRS consisting of a single shared facility F_S (instead of two facilities F_1 and F_2). In such case, setup operations become unavoidable to switch from one production mode to another in order to minimize the expected total cost while filling the customer demand. The considered facility F_S has the same production capacity as the combination of F_1 and F_2 shown in Figure 4.1. It is represented by new parameters u_{SF}, U_{SFman}^{max} and U_{SFrem}^{max}, which describe respectively the production rate of F_S and its maximum manufacturing and remanufacturing rates. The manufacturing and remanufacturing cost are respectively defined by c_{SFman} and c_{SFrem}. As previously noted, the disposal policy is based on the inventory level of returns (see equation (4.13)). Equations (4.13) and (4.18)-(4.20) describe the structure of the CP#4-SF.

$$u_{SF} = \begin{cases} U_{SFrem}^{max}.I\{S_{22} = 1\} & if\ (x_R > 0) \\ u_R.I\{S_{22} = 1\} & if\ (x_R = 0) \\ U_{SFman}^{max}.I\{S_{11} = 1\} & if\ (x_F < Z_F) \\ d.I\{S_{11} = 1\} & if\ (x_F = Z_F) \\ 0 & otherwise \end{cases} \tag{4.18}$$

$$S_{12} = \begin{cases} 1 & if\ (x_F \geq a_F) \\ 0 & otherwise \end{cases} \tag{4.19}$$

$$S_{21} = \begin{cases} 1 & if\ (x_F = d.D_S^{21}) \\ 0 & otherwise \end{cases} \tag{4.20}$$

Where, $a_F < Z_F$. As for previous control policies, the CP#4-SF combines maximal manufacturing and remanufacturing rates with both on-demand manufacturing and on-return remanufacturing rates (see equation (4.18)). The stored returns are transformed at the maximum remanufacturing rate (U_{SFrem}^{max}), but when the inventory of returns (x_R) empties the remanufacturing rate is adapted to that of returns (u_R). In the manufacturing mode, the system uses the maximum manufacturing rate (U_{man}^{max}) to build the stock of finished products and adapts its manufacturing rate to the customer demand when this stock is full. Regarding the setup policy, rules are established based on the inventory level of finished products (x_F). When

x_F increases and exceeds the threshold a_F, the system switches to the remanufacturing mode since it has a comfortable level of stored finished products. On the other hand, when it decreases and reaches $d.D_S^{21}$, which represents the inventory level needed to perform a setup operation before shortages, the system switches to the manufacturing mode. The CP#4-SF is characterized by three control parameters: Z_F, a_F and Z_R. It has been shown in (Assid et al., 2019) that this control policy gives the best results in terms of costs compared to those that exist in the literature for failure prone HMRS composed of a shared facility.

In summary, this section presents the considered control policies and their corresponding system configurations. The next sections aim to determine the best system configuration and its appropriate control policy in terms of costs.

4.6 Solution approach

This section presents the solution approach used to optimize the control parameters minimizing the expected total cost for each considered control policy when the latter is applied to its system configuration. Using numerical approaches is subject to several implementation difficulties. In fact, irregularities in the boundary of the numerical results make the approximation of the control parameters challenging, as discussed in (Berthaut et al., 2010). In addition, the optimization would be too time-consuming to be applicable at the operational level. This is principally due to the accuracy of the numerical results which depends on the size of discrete grid steps h_{x_R} and h_{x_F} (see Appendix III). In the same sense, the comparative study will require testing a wide range of system parameters. For these reasons, we privilege the simulation-based optimization approach because of its capacity to accurately capture the complexity of the interaction among activities within HMRS. It has been a successful alternative to determine an optimal solution for complex systems as suggested in (Gosavi, 2015 ; Myers, Montgomery, & Anderson-Cook, 2016) and has been applied to various PPC problems as in (Assid et al., 2019 ; Berthaut et al., 2010). This approach consists of combining the simulation tool with optimization techniques such as the design of experiments and the response surface methodology. The goal is to replace the complex total cost function (6) with an approximated total cost that can be expressed in terms of the control parameters and optimized through non-linear optimization techniques. A block-diagram representation of the adopted approach is depicted in Figure 4.6. The main steps of this approach are described as follows:

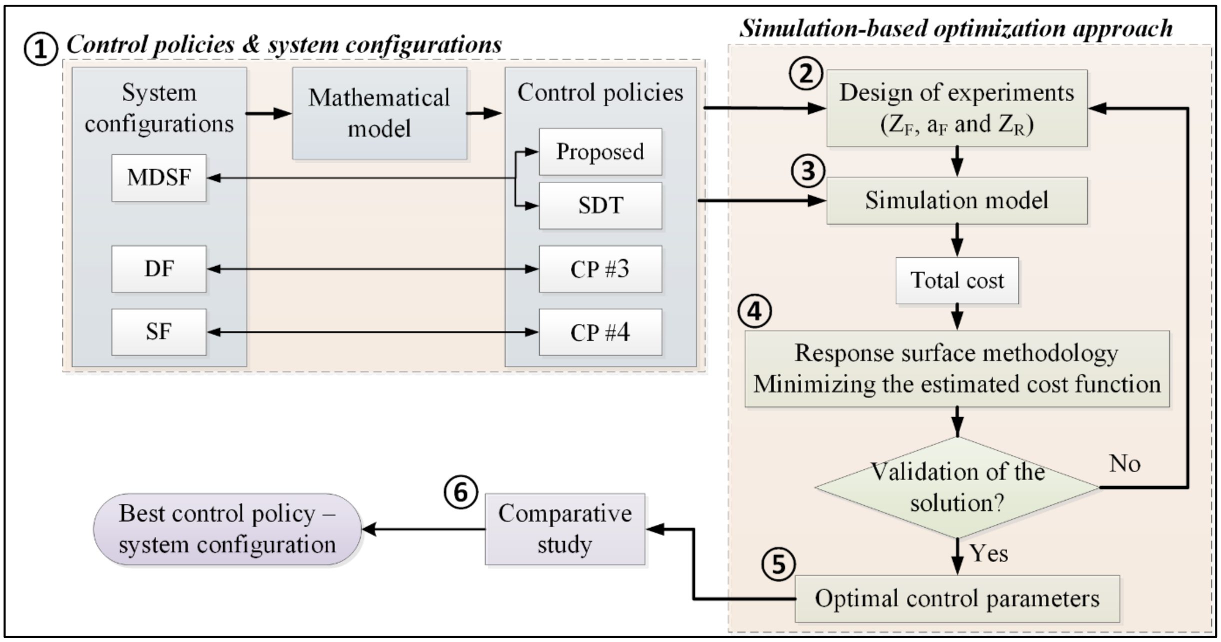

Figure 4.6 Block diagram of the solution approach

4.6.1 Step 1: Control policies and their corresponding system configurations

This step presents the derived structure of the optimal control policy for the proposed system configuration (Proposed-MDSF) using a numerical approach as well as three adapted control policies developed in the literature in different contexts (see 4.5). Two of those were adapted to our context using only DF or SF for their corresponding system configuration, while the third one is adapted to the system configuration consisting of MDSF. Such control policies will govern the decisions and the interaction between the elements of the simulation model. The control parameters are the inputs of the simulation model.

4.6.2 Step 2: Design of experiments

The design of experiments step defines how the control parameters (Z_F, a_F and Z_R), called also the design factors should be varied with a minimal set of simulation experiments. The objective is to obtain the effects of these control parameters, their interactions and their quadratic effects through the analysis of variance (ANOVA) on the resulting expected total cost. This will be considered in a further step (see Section 4.6.4) in order to fit an estimated relationship between the expected total cost and the control parameters for each considered control policy. The sequential procedure of the design of experiments and the optimization should be performed in an appropriate range for the control parameters to explore the entire admissible control domain and determine a close approximation of the optimal solution. A full-factorial design at three levels each $3^k, k \in N^*$ is selected depending on the number of control parameters k of the considered control policy. Such design evaluates all the possible combinations of the settings giving more accurate results (Montgomery, 2012). It is often used for models that assign a small number of parameters ($k \leq 4$). Using five replications for each combination of factors, a total of 45 (for both SDT-MDSF and CP#3-DF where $k = 2$) and 135 (for both Proposed-MDSF and CP#4-SF where $k = 3$) simulation runs are required.

4.6.3 Step 3: Simulation model

For each considered control policy–system configuration, the simulation model allows assessment of the system behaviour and its corresponding expected total cost (considered as the output of such a model) for given combinations of the design factors (considered as its inputs). Using the SIMAN language and executed through the Arena Simulation software, it transforms system components into combined discrete-continuous events. It aims to faithfully represent the system operation described in Section 4.3.2 and to determine its performance metrics (the expected total cost). Several networks are developed using synchronously both discrete and continuous components to represent the continuity of the workflow and the discrete nature of the system dynamics (see Figure 4.7). For example, the calculation of the instantaneous inventories level is covered by continuous components while the setup operations and the repair interventions of the facilities are modelled by discrete ones. The duration of simulation runs is set such as to reach the steady state. Each run is conducted for 500.000 units of time and takes only 5 seconds on average for each run on a computer with a 3.30 GHz CPU. At the end of each simulation run, data are collected in order to calculate the value of the expected total cost.

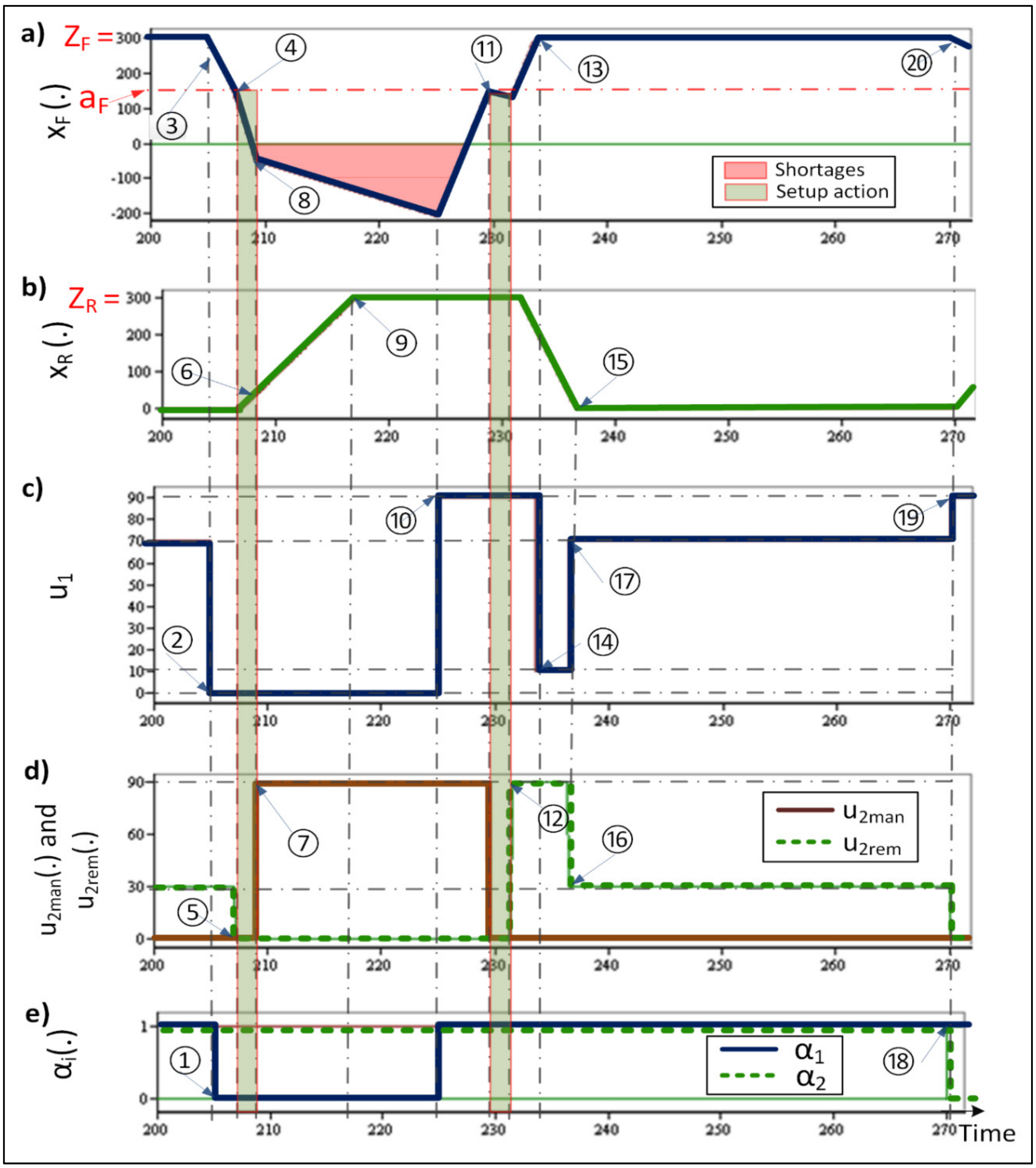

Figure 4.7 Dynamics of the simulation model when the Proposed-MDSF is used

Several steps are required to assess and validate the accuracy of the simulation model. This includes monitoring the model operation, testing its data, displaying animations and using debug features of the simulation software. Figure 4.7 presents a simulation sample of the dynamics of system operations when the Proposed-MDSF is used. It is displayed as a subfigures form in order to facilitate the validation of a proper behaviour of the developed simulation model. This sample represents the case where the Proposed-MDSF (see Section 4.5.1.1) is applied. It is performed for $U_1^{max} = 90$, $U_{2man}^{max} = U_{2rem}^{max} = 90$, $\gamma_R = 0.3$, $d = 100$, $\mathrm{Z_F} = 300$, $\mathrm{a_F} = 150$ and $\mathrm{Z_R} = 300$. We use the symbol "Arrow X.Z" to emphasize the phenomenon pointed by the arrow number X and illustrated in the subfigure 4.7.Z.

From Figure 4.7, we track the evolution of several system indicators at the same time. For example, it shows that when the manufacturing facility (F_1) is down ($\alpha_1(t) = 0$; arrow 1.e), $u_1 = 0$ (arrow 2.c), thereby triggering the decrease of the inventory level of finished products (x_F) at the rate of $dx_F/dt = u_{2rem} - d = 30 - 100 = -70$ (arrow 3.a). A setup action is executed as soon as the threshold a_F is reached (arrow 4.a) allowing the production facility F_2 to switch from mode 2 (remanufacturing) to the mode 1 (manufacturing) (see equation (4.12). During the setup action, the production rates of F_2 are zero (arrow 5.d). As a result, x_F decreases at the rate of demand. In addition, the interruption of the F_2 activities means that the returned products are not remanufactured any more, they are instead stored, hence the increase of their inventory level (x_R) (arrow 6.b). Once the setup action comes to its end, F_2 runs at maximum capacity in mode 1: $u_2 = U_{2man}^{max} = 90$ (arrow 7.d). The variation rate of x_F changes to $U_{2man}^{max} - d = -10$ (arrow 8.a). The increase of x_R stops when the storage space of returns is full ($x_R = Z_R$) (arrow 9.b) and disposals are then activated. When F_1 is repaired, its production activity resumes at maximum capacity (arrow 10.c), which generates an increase of x_F at the rate of $U_1^{max} + U_{2man}^{max} - d = 80$. When x_F reaches the threshold a_F, a setup action is then triggered for F_2, but this time to switch to the remanufacturing mode 2 (arrow 11.a). At the end of this setup action, F_2 takes advantage of the availability of the returns in stock and runs at maximum capacity (arrow 12.d). This stops the disposal activity. When $x_F = Z_F$ (arrow 13.a), F_1 adapts its production rate to that of demand, thus $u_1 = d -$

$u_2 = 10$ (arrow ⑭.c). When the stock of returns is consumed in its entirety ($x_R = 0$; arrow ⑮.b), the remanufacturing rate is adapted to that of returns ($u_{2rem} = u_R = \gamma_R.d = 30$; arrow ⑯.d). Consequently, F_1 has to adapt its production rate to the demand rate again (arrow ⑰.c). Figure 4.7 also shows the case where F_2 is down (arrow ⑱.e): F_1 should operate at its maximum capacity (arrow ⑲.c) but implies the decrease of x_F (arrow ⑳.a) since $U_1^{max} < d$.

4.6.4 Step 4: Response surface methodology

This step is based on data collected from simulation models. The system data in Table 4.3 represent the numerical example used to illustrate the system under study (see Figure 4.1). They are based on the literature of optimal control and inventory management. The cost parameters were chosen so that: $c_F^+ < c_F^-$, $c_{2rem} < c_1 < c_{2man}$, $U_{1man}^{max} < d$, $U_{2man}^{max} < d$ and $U_{2rem}^{max} < d$. As indicated in Section 4.5.3, if one shared facility F_S is used instead of F_1 and F_2 to study the performance of the CP#4-SF, the data related to F_S are chosen, such that the production capacities of both system configurations are equivalent. In this sense, we choose $U_{SFman}^{max} = U_1^{max} + U_{2man}^{max} = 180$ and $U_{SFrem}^{max} = 180$ to ensure the same basis of comparison. Similarly, $\mathrm{c_{SFman}} = \mathrm{u_{2man}}$ and $\mathrm{c_{SFrem}} = \mathrm{c_{2rem}}$. A new variable β ($0 \leq \beta < 1$, $a_F = \beta.Z_F$) is introduced to ensure that $a_F < Z_F$ when the Proposed-MDSF or the CP#4-SF is applied. It will then replace a_F.

Table 4.3 System data for the base case

Parameters	c_F^+	c_F^-	c_R^+	c_1	c_{2man}	c_{2rem}	c_{dis}	T_{f_1}	T_{f_2}
Values	3	150	0.3	30	40	5	500	Log-N(60,6)	Log-N(65,6)
Parameters	c_S^{ij}	D_S^{ij}	U_1^{max}	U_{2man}^{max}	U_{2rem}^{max}	d	γ_R	T_{r_1}	T_{r_2}
Values	2500	2	90	90	90	100	0.3	Log-N(10,5)	Log-N(12,5)

With T_{f_i}, $i \in \{1,2\}$ and T_{r_i} denote the time to failure and repair duration of the facility F_i respectively. Note that they could follow any probability distributions.

Using data collected by the simulation tool for the considered design factors, the main factors (Z_F, β and Z_R), their interactions and their quadratic effects, as well as the adjusted value of the R-squared for each control policy-system configuration, are presented in Figure 4.8. It shows that except both Z_F and β for the Proposed-MDSF, the interaction $Z_F.Z_R$ for the SDT-MDSF and interactions $Z_F.\beta$ and $\beta.Z_R$ for the CP#4-SF, all factors, interactions and quadratic effects are significant. It also shows that the obtained models explain more than 94% of the variability observed in the expected total costs (Montgomery, 2012). The residuals are also checked for uniformity, serial correlation or other indications of model's weakness.

Once significant factors are identified, they are considered as input of a response surface methodology in order to fit a second-order regression model relating the approximated total cost function φ to these factors. For each considered control policy, φ takes the following form:

$$\varphi \cong \beta_0 + \beta_1 Z_F + \beta_2 a_F + \beta_3 Z_R + \beta_{12} Z_F a_F + \beta_{13} Z_F Z_R + \beta_{23} a_F Z_R + \beta_{11} Z_F^2 + \beta_{22} a_F^2 + \beta_{33} Z_R^2 + \varepsilon \quad (4.21)$$

With, β_0, β_i and β_{ij} $(i, j \in \{1,2\})$ are the unknown coefficients to be estimated from the collected simulation data and ε presents the error component that incorporates all other sources of variability including uncontrolled factors and background noise. The reader is referred to (Montgomery, 2012) for more details on the statistical analysis.

For the base case (see Table 4.3), the response surface functions of the approximated total cost are given by equations (4.22)-(4.25) using Statgraphics software.

$$C_{Proposed-MDSF} = 17943.3 - 11.7716\,.Z_F - 3352.41\,.\beta - 9.815\,.Z_R + 3.078\,.Z_F.\beta + 2.01.\ 10^{-3}\,.Z_F.Z_R - 1.866\,.\beta.Z_R + 5.06.\ 10^{-3}.Z_F^2 + 2248.82\,.\beta^2 + 7.23.10^{-3}.Z_R^2 \quad (4.22)$$

$$C_{SDT-MDSF} = 16049.7 - 11.15\,.Z_F - 5.649\,.Z_R + 1.186.10^{-3}\,.Z_F.Z_R + 7.402\,.10^{-3}.Z_F^2 + 3.242.10^{-3}.Z_R^2 \quad (4.23)$$

$$C_{CP\#3-DF} = 26035.3 - 17.56\,.Z_F - 6.083\,.Z_R + 1.435.10^{-3}\,.Z_F.Z_R + 5.514.10^{-3}.Z_F^2 + 3.33.10^{-3}.Z_R^2 \tag{4.24}$$

$$C_{CP\#4-SF} = 23756{,}5 - 10{,}73\,.Z_F - 4761{,}11\,.\beta - 5{,}11\,.Z_R + 1.004\,.Z_F.\beta + 7.73.10^{-4}\,.Z_F.Z_R - 0.234\,.\beta.Z_R + 4.795.\;10^{-3}.Z_F^2 + 3959.31\,.\beta^2 + 1.366.10^{-3}.Z_R^2 \tag{4.25}$$

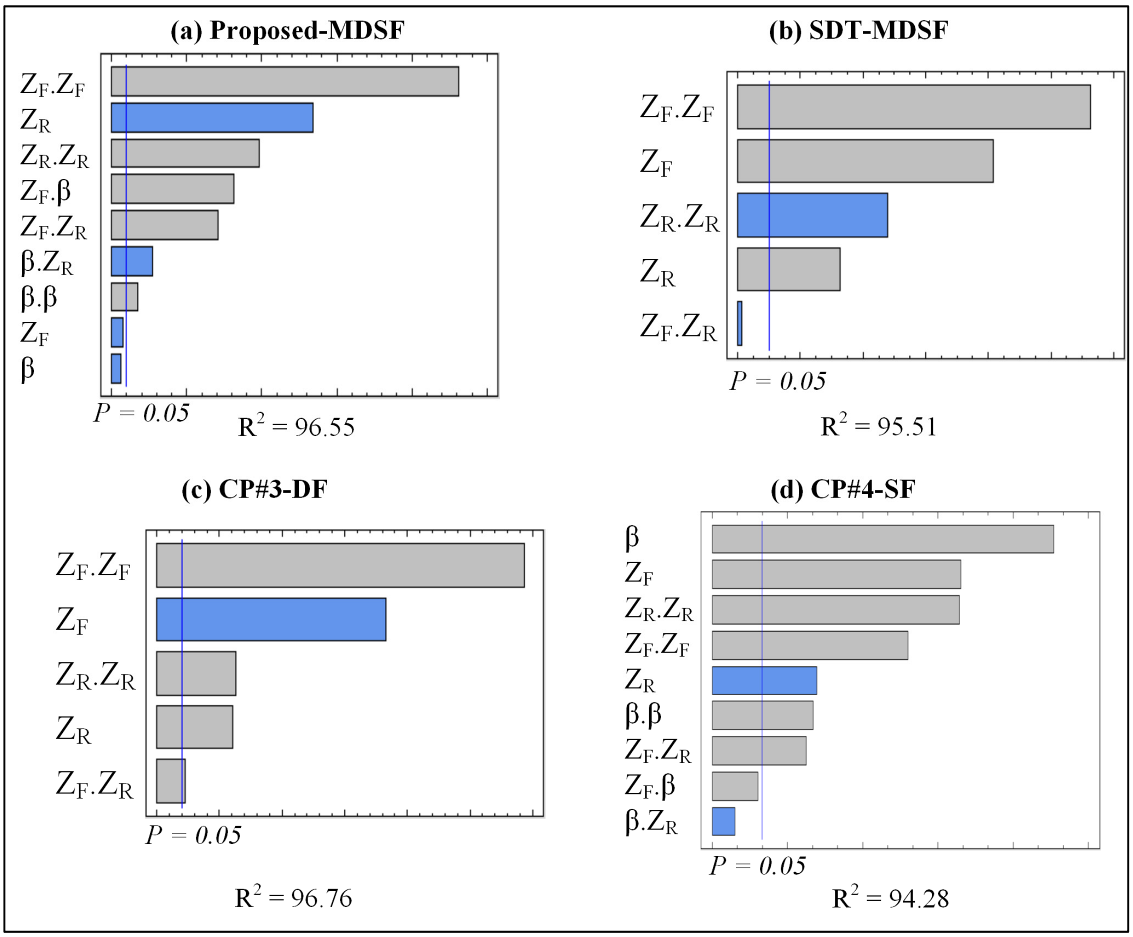

Figure 4.8 Pareto charts under the considered policies-system configurations

4.6.5 Step 5: Optimal control parameters

In this step, the obtained cost functions (14)-(17) are minimized using non-linear programming. The optimal results of the considered control policies-system configurations are presented in Table 4.4.

Table 4.4 Optimization results for the base case

Control policy – system configuration	Optimal Control parameters			Other system parameters							Optimal total cost	Confidence interval (set at 95%)
	Z_F^*	a_F^*	Z_R^*	S_N (c)	B_{FP} (d)	Dis_R (e)	U_{F_1} (f)	U_{F_2} (f)	$U_{F_2}^{m1}$ (g)	$U_{F_2}^{m2}$ (g)		
Proposed-MDSF	939	327	592	15216	3.88%	1.59%	66.40%	33.60%	4.08%	29.52%	8,923.57	[8,904.99 ; 8,926.66]
SDT-MDSF	693	-	744	57042	8.73%	0.77%	61.41%	38.60%	8.84%	29.76%	10,081.20	[9,938.49 ; 10,103.10]
CP#3-DF	1516	-	586	0	9.03%	0.32%	70.10%	29.90%	0.00%	29.90%	10,932.50	[10,867.06 ; 10,973.22]
CP#4-SF	930	495	1653	26376	15.61%	2.81%	-	100.00%	70.84%	29.16%	13,265.40	[13,255.68 ; 13,279.91]

(c) Number of setup operations performed during the simulation run. (d) Average percentage of shortage of all demand. (e) Average percentage of disposal of all returns. (f) U_{F_i}, $i = \{1,2\}$ denotes the capacity utilization of the facility F_i compared to demand. (g) $U_{F_2}^{mj}$, $j = \{1,2\}$ denotes the capacity utilization of the facility F_2 in mode j compared to demand.

The results show that the Proposed-MDSF gives the best result in terms of costs. The minimum total cost is 8,923.57 and is located at $Z_F^* = 939$, $a_F^* = 327$ ($\beta^* = 0.3483$) and $Z_R^* = 592$. This cost is respectively 11.48%, 18.38% and 32.73% lower than that of SDT-MDSF, CP#3-DF and CP#4-SF. The solution is validated by verifying that the estimated total cost for the considered control policies (Table 4.4) falls in the 95% confidence interval obtained with 40 more replications of the simulation model with the obtained solutio as input parameters (Banks, Carson, Nelson, & Nicol, 2005). This confidence interval is given by: $\overline{T.C.} \pm t_{1-(\alpha/2)}^{n-1}\sqrt{S^2/n}$, where $\overline{\mathrm{T.C.}}$ is the average optimal cost, n is the number of replications (set at 40), S is the sample standard deviation and $\mathrm{t}_{1-(\frac{\alpha}{2})}^{\mathrm{n}-1}$ is the Student coefficient function. It is also verified to ensure that the solution lies within the domain fixed at the step defined in Section 4.6.2. The quadratic approximation of the response surface represented by equations (4.22)-(4.25) can only be accurate if the domain specified at that step is appropriate. Adjustment of the domain is thus necessary in order to address this issue. This might require multiple offline simulation experiments.

Analyzing the values of optimal control parameters (Z_F^*, a_F^* and Z_R^*) presented in Table 4.4 can explain the difference in performance of the considered control policies. For example, the total cost of the CP#3-DF is mainly due to inventory costs of finished products (a high storage capacity Z_F^*) and shortages (B_{FP}) since the facility F_2 is dedicated only to limited returns even when the facility F_1 breaks down. Regarding the CP#4-SF, it generates a very high cost of shortages showing the disadvantage of using a single facility subject to breakdowns and random repairs. Its production also costs more since it has only one mode of manufacturing, the most expensive. For the SDT-MDSF, F_2 switches between the two production modes, but every time F_1 is down including when the repairs actions are brief. Compared to the Proposed-MDSF, significant costs of setup operations and manufacturing using F_2 ($U_{F_2}^{m1}$) are generated. This is expected since the Proposed-MDSF is based on the inventory level of finished products (x_F) to make the transition decisions between the two production modes which significantly reduces the number of setup operations (requiring production activities to stop). In this context, less switching between the production modes involves longer periods in remanufacturing mode allowing the system to reduce the storage capacity of returns (Z_R^*) compared to those of the SDT-MDSF, thereby saving considerable inventory costs, but ultimately generating more disposals (Dis_R) and fewer remanufactured products (U_{F_2}). In the same sense and because of limited returns, the Proposed-MDSF increases the value of Z_F^* in order to reduce the risk of shortages (B_{FP}) as well as the manufacturing activity of F_2 ($U_{F_2}^{m1}$) which comes at a greater cost.

4.6.6 Step 6: Comparative Study

The same simulation-based optimization approach (see the steps defined from Section 4.6.2 to Section 4.6.5) is used to analyze and compare the considered control policies and their corresponding system configurations for a wide range of system parameters. More thorough examination of the effect of system parameters on the total cost of the considered control policies is then conducted to verify how they evolve in relation to one another and to check whether the previous conclusions are always valid. Figure 4.9 summarizes the obtained results. The effect of the backlog, the manufacturing, the disposal and the setup costs, on the expected total cost of the considered control policies-system configurations are depicted in the subfigures 4.9.a, 4.9.b, 4.9.c and 4.9.d respectively. Similarly, subfigures 4.9.e, 4.9.f and 4.9.g respectively present the effect of the setup time, the rate of returns and the production capacity of the system (PC), which is expressed by: $PC = \left(U_1^{max} . \frac{MTTF_{F_1}}{MTTF_{F_1}+MTTR_{F_1}}\right) + \left(U_{2man}^{max} . \frac{MTTF_{F_2}}{MTTF_{F_2}+MTTR_{F_2}}\right)$, where $MTTF_{F_i}$ and $MTTR_{F_i}$ ($i \in \{1,2\}$) respectively denote the mean times to failure and to repair of the facility F_i. All other system parameters remain fixed at values given in the base case (Table 4.3).

Keeping in mind that remanufacturing becomes less attractive when the rate of returns decreases, the CP#3-DF, whose facility F_2 is always in remanufacturing mode, sees its unused production capacity increasing rapidly and its expected total cost becomes higher than that of the CP#4-SF when $u_R \leq 27$ (see Figure 4.9.f). The same reasoning explains why in the case of a higher rate of returns ($u_R \geq 33$), we notice more economic value to the CP#3-DF than the

SDT-MDSF (which undergoes many setup operations) since its expected total cost becomes lower. This coincides with some insights stating that it may be preferable to conduct remanufacturing operations on a dedicated facility in high returns rates situations (Teunter et al., 2008). Indeed, the setup operations have an associated cost and generate the unavailability of the production activity of F_2, so at some point, the gains made by the CP#3-DF become more important than those of the SDT-MDSF. The same phenomenon is observed when the setup cost (c_S^{ij}) exceeds the value 400 (Figure 4.9.d) or when the setup time (D_S^{ij}) exceeds the value 2.5 (Figure 4.9.e). For the last two scenarios, the cost and the unavailability of production facilities due to the increase of the impact of setup operations become much more important. Consequently, the economic benefit of the switching decisions between the production modes as used by the SDT-MDSF is not always interesting. We observe this phenomenon more clearly at $D_S^{ij} \geq 3.1$ when its total cost exceeds that of the CP#4-SF, because F_2 has to change its production mode with each change of F_1 state. Indeed, switching to the manufacturing mode when F_1 breaks down and then returning to remanufacturing mode when it is repaired significantly reduce the system availability and can lead to higher risk of shortages. In fact, there is no need for setup operations when the repair times are short or when the inventory of finished products is high. In the same sense, the Figure 4.9.a shows that the total cost difference between the CP#3-DF and the SDT-MDSF decreases when the backlog cost (c_F^-) increases. This is to be expected since the system responds by increasing the stock size of finished products to ensure a better protection against shortages. Therefore, there is less need for setup operations to increase this protection. The decrease of the importance of setup operations also explains the reduction of the total cost difference between the CP#3-DF and the SDT-MDSF when the production capacity (PC) increases (see Figure 4.9.g). Indeed, when the system has a greater production capacity, it restores its stock of finished products faster without the help of setup operations.

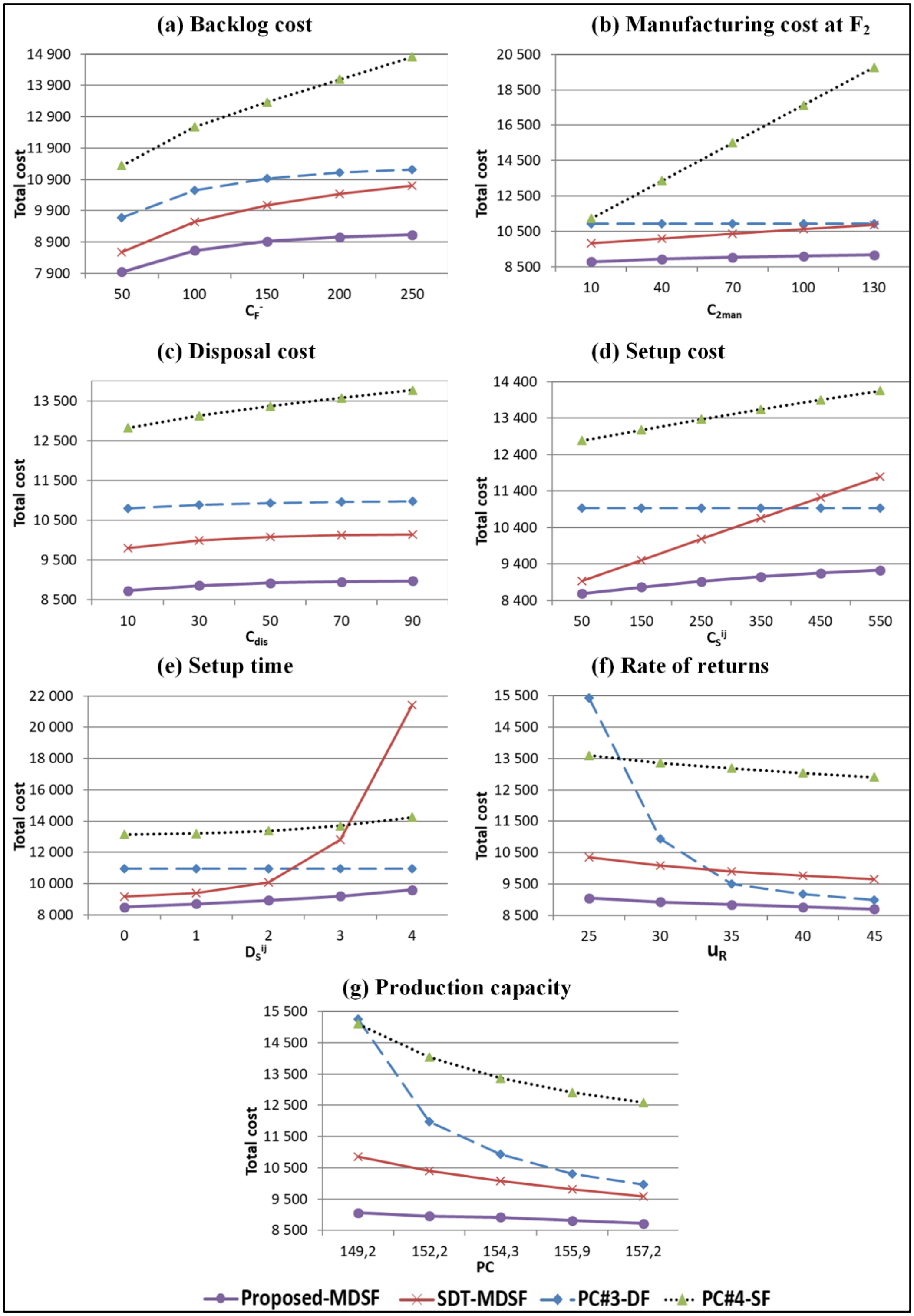

Figure 4.9 Influence of system parameters on the total cost of the considered policies-system configurations

In summary, the results show the Proposed-MDSF gives the best total cost compared to the considered control policies-system configurations for all studied scenarios. This is basically due to its capacity to streamline setup interventions in order to reduce the risk of shortages and to increase the overall system availability while avoiding unnecessary costs. Indeed, the switching of F_2 from one production mode to another causes the stoppage of production activities, but when it is performed only when there is a risk of shortages ($x_F < a_F$) more significant cost savings are obtained.

4.7 Extension to random demand and delivery lead-time of returns

As described in the previous sections, the delivery lead-time of these returns is assumed negligible and both customer demand and rate of returns are considered constant. However, these situations do not usually reflect the industrial reality. The purpose of this follow-up study is to illustrate the robustness of the proposed solution approach and to compare the considered control policies-system configurations in terms of costs for extended situations closer to reality. It addresses without the loss of generality questions such as: Is the economic advantage of the Proposed-MDSF maintained if the customer demand becomes random? How does a random rate of returns affect the optimal control parameters? What happens if the delivery lead-time of returns becomes non-negligible? In this sense, the simulation-based optimization approach described in Sections 4.6.2-4.6.5 is once again adopted. The objective is to determine the optimal control parameters and the associated total cost of each control policy-system configuration when the demand, the rate and the delivery lead-time of returns are random. They are assumed to follow a normal distribution $N(\mu_d, \sigma_d)$ with mean μ_d and standard deviation σ_d.

The optimization results are summarized in Table 4.5 and 4.6. They confirm the above-mentioned conclusions by showing that the Proposed-MDSF gives the best result in terms of costs in all the studied cases. Table 4.5 shows that considering random demand significantly increases the optimal control parameters Z_F^* and Z_R^* and, accordingly, the expected total cost increases too. This is because the system needs higher storage capacities to deal with the demand variability, which causes increased risk of shortages. Similarly, the higher the standard deviation, the more Z_F^* and Z_R^* increase.

Table 4.5 Optimization results considering random customer demand

Control policies	**Demand**	$\boldsymbol{Z_F^*}$	$\boldsymbol{a_F^*}$	$\boldsymbol{Z_R^*}$	**Optimal total cost ($)**
Proposed-MDSF	100	939	327	592	8,923.57
	N(100,5)	956	318	611	8,945.09
	N(100,10)	975	298	623	8,970.44
SDT-MDSF	100	693	-	744	10,081.20
	N(100,5)	701	-	784	10,141.20
	N(100,10)	745	-	802	10,263.80
CP#3-DF	100	1516	-	586	10,932.50
	N(100,5)	1562	-	601	11,143.20
	N(100,10)	1690	-	642	11,705.50
CP#4-SF	100	930	495	1653	13,265.40
	N(100,5)	958	538	1670	13,307.10
	N(100,10)	991	588	1682	13,429.80

The obtained results agree with those of previous works showing that the control policy structure with variable and random demand is also of hedging-point type (Presman & Sethi, 2006). Table 4.6 shows that when considering a random rate of returns (using a random proportion of demand $\gamma_R(.)$), the system increases their storage capacity of returned products (Z_R^* increases). This allows preserving as much as possible of these returns since their quantities are variable. In this context, the total cost increases mainly because of higher inventory costs of returns, but fewer disposals and more remanufactured products are generated. Therefore, the system decreases Z_F^* to achieve savings in storing finished products. This section also presents the impact of integrating a random delivery lead-time of returns $dl_R(.)$ in the considered system. Thus, if a quantity d_s is sold to customers at the time t_d, then the quantity returned after $dl_R(t_d)$ is equal to $u_R(t_d + dl_R(t_d)) = \gamma_R(t_d).d_s$, with, $u_R(t_0) = u_R^0, \forall t_0 \leq$

dl_R^0 is the initial rate of returns from $t = 0$ to $t = dl_R^0$ which represents the delivery lead-time before receiving the first returned products. Table 4.6 shows that considering a random $dl_R(.)$, has no significant influence on the control parameters. This is due to the continuous flow of returns, which already depend on random rates of returns $u_R(.)$ (both $\gamma_R(.)$ and d are random). Thus, varying dl_R only affects the curve form of $u_R(.)$, but the total quantity of returns is the same regardless of its value.

Table 4.6 Optimization results considering both random delivery lead-time and rate of returns

Control policies	**Demand**	$\boldsymbol{\gamma_R(.)}$	$\boldsymbol{dl_R(.)}$	$\boldsymbol{Z_F^*}$	$\boldsymbol{a_F^*}$	$\boldsymbol{Z_R^*}$	**Optimal total cost ($)**
Proposed-MDSF	N(100,5)	0.3	0	956	318	611	8,945.09
		N(0.3,0.05)		943	339	625	8,956.55
			N (5,0.5)	945	348	628	8,964.36
SDT-MDSF		0.3	0	701	-	784	10,141.20
		N(0.3,0.05)		668	-	806	10,150.20
			N (5,0.5)	668	-	808	10,154.89
CP#3-DF		0.3	0	1562	-	601	11,143.20
		N(0.3,0.05)		1555	-	614	11,162.50
			N (5,0.5)	1557	-	612	11,166.94
CP#4-SF		0.3	0	958	538	1670	13,307.10
		N(0.3,0.05)		950	537	1693	13,330.80
			N (5,0.5)	951	526	1695	13,336.59

With $\gamma_R(t)$ and $dl_R(t)$ respectively denote the proportion of the demand rate at time t to be returned to the system and the delivery lead-time of returns at time t.

4.8 Conclusion

This paper addresses the production planning and control problem for unreliable hybrid manufacturing–remanufacturing systems (HMRS) composed of mixed dedicated and shared facilities (MDSF). In addition to capturing the benefits of each setting (dedicated facilities (DF) and/or shared facilities (SF)), it is motivated by the need to equip practitioners with better coordination between interrelated manufacturing and remanufacturing activities, becoming critical for an efficient production process.

By controlling manufacturing, remanufacturing and disposal rates as well as the sequence of setups, we use optimal control theory to develop an optimal control policy of the system through numerical techniques yielding straightforward decision rules. This policy structure consists of a combination of hedging point policies to control production and disposal activities and a stock-based setup strategy, under which switching is based on finished products stock according to threshold rules. In addition to the developed policies, three other control policies adapted from the literature in a dynamic and stochastic environment are analyzed and compared to the proposal. Two of those were developed for system configurations using only DF or SF, while the third one is adapted to the system configuration consisting of MDSF. A comparative study is performed to investigate the impact of a wide range of system parameters on each considered control policy used to manage the corresponding system configuration (DF, SF or MDSF). This is achieved using a simulation-based optimization approach. Our results suggest that the use of MDSF managed by the proposed control policy gives the best performance in terms of costs compared to existing control policies when they are applied to their corresponding system configurations. They also generate valuable insights to the related production managers into how interrelated decisions of setups, manufacturing of new products and remanufacturing or disposal of returns can effectively be coordinated.

Future research directions include situations of sustainability where the rate of returned products can be controlled by compensations given to customers to stimulate the return of a used product. Another direction for future research is to include an investigation of cases of variable and uncertain procurement of both raw materials and returns and to study their influence on the optimal control parameters. It can also incorporate uncertainty in setup times and quality of returns.

CHAPITRE 5

PRODUCTION PLANNING AND CONTROL OF UNRELIABLE HYBRID MANUFACTURING-REMANUFACTURING SYSTEMS WITH QUALITY-BASED CATEGORIZATION OF RETURNS

Morad Assid [a], Ali Gharbi [b], Adnène Hajji [c],

[a, b] Department of Systems Engineering, École de Technologie Supérieure, 1100 Notre-Dame Ouest, Montréal (QC), Canada H3C 1K3

[c] Department of Operations and Decision Systems & CIRRELT. Laval University, 2325, rue de la Terrasse Québec (QC), Canada G1V 0A6

Paper submitted for publication, August 2020.

Résumé

En raison des avantages environnementaux et économiques, la refabrication fait partie intégrante de nombreuses entreprises manufacturières. Cette nouvelle réalité les contraint à se focaliser sur la planification et le contrôle de la production en termes de minimisation des coûts et de réduction de l'impact environnemental en diminuant la production des déchets et la consommation des ressources. Ce travail traite un problème du contrôle au sein d'un système hybride de fabrication-refabrication évoluant dans un environnement dynamique et stochastique. Le problème considère trois décisions centrales de manière intégrée afin d'optimiser le coût total encouru. L'objectif principal est de trouver à la fois les taux de fabrication et de refabrication ainsi que la séquence appropriée de setup pour basculer entre les modes de refabrication des retours qui diffèrent en matière de qualité. La caractérisation des politiques de commande sous-optimales est effectuée à l'aide d'une méthode numérique. Ces politiques sont une combinaison de politiques à seuils critiques et une stratégie de setup, en vertu de laquelle les opérations de setup sont effectuées si le niveau de stock des produits finis atteint un niveau adéquat. D'autres politiques de commande trouvées dans la littérature sont également prises en compte et comparées aux propositions. Pour un système aussi complexe, une approche d'optimisation basée sur la simulation est alors privilégiée pour déterminer les paramètres de commande optimaux caractérisant chacune des politiques étudiées. Des exemples illustratifs et une analyse comparative sont également fournis mettant en évidence les aspects pratiques des politiques de commande et l'interdépendance entre le niveau de qualité des retours et les paramètres de commande de la production. Ils apportent également des solutions pour aider les gestionnaires à contrôler efficacement et simultanément les opérations de refabrication, de fabrication et de setup pour une meilleure gestion des stocks, de la productivité de l'utilisation des ressources.

Mots-clés : planification de la production, commande optimale, refabrication, niveau de qualité, optimisation, simulation.

Abstract

Because of environmental and economic benefits, remanufacturing has become an integral part of a large number of manufacturing companies. This new reality forces them to focus on production planning and control (PPC) to minimize costs and reduce the environmental impact by decreasing waste and resource consumption. This paper deals with a PPC problem within a hybrid manufacturing-remanufacturing system (HMRS), which evolves in a constrained dynamic and stochastic context. The problem considers jointly three central decisions to optimize the long-term total cost. The main objective is to find both remanufacturing and manufacturing production rates as well as the policy used to switch between the remanufacturing modes of returns with different quality conditions. The optimal control policy characterization is performed combining optimal control theory and numerical techniques. Such policies consist of hedging point ones and stock-based switching decisions. Additional relevant control policies adapted from the literature are also considered and compared to the developed policies through a combined simulation-optimization approach, which optimize the policies control parameters. Both illustrative examples and a comparative analysis bring out the practical aspects of the proposed control policies and the interdependence between the quality conditions of returns and the production control settings. They also bring effective solutions to assist decision makers controlling simultaneously remanufacturing, manufacturing

and switching operations for proper management of resource utilization, inventories and productivity.

Keywords: Production planning, optimal control, remanufacturing, quality condition, optimization, simulation.

5.1 Introduction

Hybrid manufacturing-remanufacturing systems (HMRSs) consist of two processes for simultaneously generating remanufactured and new products with the same quality standards (Behret & Korugan, 2009). They have become a key issue in the advanced manufacturing industry (Esmaeilian et al., 2016 ; Vogt Duberg, Johansson, Sundin, & Kurilova-Palisaitiene, 2020). This is due in part to attractive environmental and economic perspectives of the emerging business of remanufacturing extending the product's useful life and reducing both material and energy consumption (V. Daniel R. Guide Jr. & Wassenhove, 2006). Most of the time they are found in industry sectors with high added value such as aerospace, automotive, electrical and electronic equipment (EEE), mechanical engineering and medical equipment (Lange, 2017). However, unlike traditional production systems, production planning and control (PPC) within HMRSs is more complex. Such complexity is a consequence of the uncertainty surrounding the availability of production facilities as well as the quality, the quantity and the time of acquisition of returns, which feed the remanufacturing process (Goodall, Rosamond, & Harding, 2014). In addition, other stochastic events characterizing machine breakdowns and repairs may increase such complexity. This paper addresses these issues regarding unreliable HMRSs, which is to cost-effectively match demand and production while considering different quality conditions of returns. In practice, since these returns are collected from different sources (cancelled orders, customer and lease returns, discards by customers at the end of use, damaged products), their quality is highly variable (from minor cosmetic adjustments to defects requiring disposing) and thus, is a major factor for uncertainties (C. H. Yang, Ma, & Talluri, 2018). To manage this variability, a quality-based return categorization is often used to assign the quality condition (high or low) to returns on the basis of their functional and aesthetic conditions. This categorization of returns is valuable to provide advance information on input quality and has become an essential tool in current remanufacturing industry practices (Panagiotidou, Nenes, & Zikopoulos, 2013 ; Sonntag & Kiesmüller, 2017). Indeed, the variability in the quality of returned products is a serious issue for production planning since the appropriate remanufacturing effort (cost and lead-time of treatment) seriously depends on the condition of the returns. Differences in the quality condition of returned products lead to highly variable processing operations and lead-times (J. Zhou, Deng, & Li, 2018). Generally, higher quality returns require less processing time, and vice versa. This explains why the quality condition of returns significantly affects the production capacity. One example from the automotive industry is that the remanufacturing processing time and cost of an automotive engine block, which has been remanufactured in the past are often much higher since the remanufacturing should be done with tighter tolerances (Akçali & Çetinkaya, 2011). In the same way, the remanufacturing of a four-year-old transmission generally costs much more than that of a one-year-old because of the number of components to be replaced. In this regard, the consideration of such quality variability, particularly for the planning and control of production activities could improve efficiency and generate savings.

The current paper is motivated by the necessity for efficient production control policies that are applicable to real-life unreliable HMRSs in order to support managers in moving toward economic and environmental objectives (Govindan & Soleimani, 2017). Our main purpose is to develop feedback production control policies, which minimize the total incurred cost for unreliable HMRSs that evolve in a stochastic and dynamic context while considering various quality conditions of returns. The optimal control policy is not known yet for this kind of system. Challenges remain in integrating the remanufacturing process to determine how to select the right quality-based category of returns, when to switch between the different categories with the aim to support the manufacturing facility and how to calculate optimal control parameters and to make proper adjustments to cope with their changes.

The remaining of this paper is as follows; we present the literature review related to this research in Section 5.2. Section 5.3 formulates the optimal control problem. Section 5.4 describes the optimal structure of control policies for an HMRS with multiple quality conditions of returns. Section 5.5 summarizes the obtained control policies in addition to those found in the literature after adapting them to our context. A combined simulation-optimization approach is then used to determine their optimal control parameters. This approach is presented in Section 5.6. A numerical example including a comparative study is detailed in Section 5.7. In Section 5.8, we show how to implement the proposed integrated control policies in real contexts. Finally, the paper is concluded Section 5.9.

5.2 Literature review

This research is related to the PPC problem within HMRSs. This class of problems deals with productivity, inventory management and resource utilization with the aim to coordinate the remanufacturing of returns and the manufacturing of new products. Some comprehensive reviews of the related problem are provided in (Akçali & Çetinkaya, 2011 ; V.D.R. Guide Jr., 2000 ; Lage & Godinho Filho, 2016). More specifically, our paper is linked to the literature considering integrated manufacturing and remanufacturing activities in a stochastic and dynamic context (dynamic and random failures of production facilities) with return categorization. For the remainder of this section, we will focus on references more aligned with our work in order to point out our contributions. These references are divided into two major classes based on whether production facilities are unreliable (they may randomly fail) or not (see Table 5.1). In addition, since most existing models integrating the quality-based variability of returns in the literature belong to the first class where the production facilities are assumed reliable, this class is separated into two groups. The first one consists of HMRSs without quality-based categorization of returns, while the second group aims for HMRSs with quality-based categorization of returns. In addition, to properly position this research, the reviewed literature is categorized according to different comparison criteria which are reported in the first line of Table 5.1. This includes the consideration of integrated manufacturing-remanufacturing process, stochastic production lead-time, failure-prone production facilities and switching option, which consists of specific actions to start a new remanufacturing cycle based on the quality condition of returns (remanufacturing using high quality of returns or remanufacturing using low quality of returns). The selected works are also compared by highlighting if they propose new control policies, if they optimize the control parameters of used policies, and if they consider the impact of both quality-based categorization and variation on the remanufacturing lead-time.

In diverse industries, in which produced units are transported to an outer storage space before satisfying the customer demand, production systems are usually controlled by batch production policies (the well known (s, Q) policy, which is used by most of the selected works in Class I, Table 1). Generally, companies with limited product variety or when quick response time is required traditionally employ make-to-stock or push production systems (Talay & Özdemir-Akyıldırım, 2019). However, make-to-order or pull type systems are commonly used when the start of production is only driven by demand (Kaminsky & Kaya, 2009). In the same context, we present the works of Group 1 (see Table 1), which considers production systems simultaneously integrating the manufacturing and remanufacturing processes. Van Der Laan et al. (1999a) made a comparison analysis between the two push and pull policies for an HMRS with random demand and lead-times. They explained that although these policies are non-optimal, they are easy to implement in practice. Kiesmüller (2003) showed that using two different variables related to manufacturing and remanufacturing processing lead-times allows a more effective control of the finished product inventory and a significant saving especially for large differences between these lead-times. Van der Laan and Teunter (2006) studied some extensions of (s, Q) policy and presented simple closed form expressions for calculating near-optimal policy parameters. Corum et al. (2014) have compared the traditional inventory-based production systems with hybrid push–pull ones. Using continuous review policies, various scenarios are simulated and then evaluated in terms of production lead-time variance and total inventory cost. Dev et al. (2017) extended the previous work comparing a periodic-review policies system with the continuous-review policies one for additional scenarios. They concluded that the letter gives the best result from the so-called bullwhip effect perspective, which refers to phenomena by which even minor variations (demand, quality of returns, etc.) could cause high alterations (processing lead-time of manufacturing remanufacturing). Further inventory control policies have been considered and analyzed using discrete event simulation by Zanoni et al. (2006) for hybrid systems where processing lead times and both return and demand rates are stochastic. Considering joint acquisition, inventory and production decisions with identical remanufacturing and manufacturing lead-times, Zhou and Yu (2011) concluded that the optimal control policy is characterized by a simple linear structure. More recently, Liu et al. (2019) developed a mathematical model for designing a hybrid manufacturing-remanufacturing system with a downward demand substitution. One of their major findings is that with the increase of the return rate, the system total cost decreases drastically until a threshold is reached.

Unlike above-mentioned references, several other researchers and practitioners addressing the important topic of HMRSs did consider the quality-based categorization of returns (see (Aras et al., 2004 ; Cai, Lai, Li, Li, & Wu, 2014) and the reference therein). However, most of their works continue to ignore the variability of the remanufacturing lead-times, despite being one of the direct consequences of the variability in the quality of returns (Dominguez et al., 2019). In this context, where the planning of production activities (manufacturing, remanufacturing using high or low quality of returns) must be determined regarding upon the system state, the interdependence between the quality condition of returns and their processing lead-time and cost creates a major challenge for decision makers. Among selected research papers in the Group 2 (see Table 1), Aras et al. (2004) explained that in order to cope with the variability in the quality of returns, categorizing them before the remanufacturing process could significantly reduce operating costs. The work of Behret and Korugan (2009) pointed in the same direction analyzing remanufacturing activities from a quality level of returns perspective. By considering three quality-based categories of returns (good, average and bad which requires different remanufacturing efforts), they showed that the categorization leads to significant savings. In another related work, Cai et al. (2014) considered two quality conditions when acquiring returns. They explained how both remanufacturing decisions and acquisition cost are significantly related to the difference in remanufacturing costs between the two considered quality conditions of returns. Dominguez et al. (2019) studied the operational performance and the dynamic behavior of closed-loop supply chains (CLSC) where the remanufacturing lead-times are variable. They investigated the impact of this variability in CLSC and observed the necessity for integrating this characteristic into the modelling assumptions" in order to better represent the dynamics of such systems.

Besides batch production systems (adopted by studied papers in Class I, Table 1) which consider reliable production facilities with fixed manufacturing and remanufacturing rates during production cycles, another class of works addresses continuous production problems while integrating elements representing the stochastic dynamics of production facilities (see selected papers in Class II, Table 1). For traditional manufacturing systems (without remanufacturing), the feedback control policies have demonstrated their efficiency regarding lots of stochastic phenomena such as quality deterioration, imperfect production, failures and repairs (Gershwin, 1994). Akella and Kumar (1986) analytically proved that the well-known hedging point policy (HPP) is optimal for continuous-time unreliable one-machine production systems. It controls production rates as a function of the machine operational state and maintains an optimal stock level during periods of system availability with the aim to cope with future shortages caused by machine failures. Several research works have extended the principle of HPP to other contexts such as preventive maintenance, subcontracting, multi-state machines, environmental control regulation, greenhouse gas emissions under carbon tax regulation and setup, which is used to change the production of one type of finished product to another (Afshar-Bakeshloo, Bozorgi-Amiri, Sajadi, & Jolai, 2018 ; M. Assid et al., 2014 ; M. Assid, Gharbi, & Hajji, 2015 ; Entezaminia et al., 2020 ; Magnanini & Tolio, 2020). For HMRSs, Kenné et al. (2012) investigated the stochastic dynamics of failure-prone facilities and determined the near-optimal production control policy minimizing the total cost. Kouedeu et al. (2014) used the same numerical approach to propose a stochastic optimization model when production machines failures depend on the production rates. Their model has been applied in the industry of printer cartridges. Polotski et al. (2018) extended the previous methodology by developing new control policies for unreliable HMRSs with variable return and demand rates. Integrating environmental aspects of unreliable hybrid systems producing harmful carbon emissions, Turki et al. (2018) addressed the issues of integrated remanufacturing, manufacturing, and warehousing decisions in line with carbon emission regulations and industrial perspectives. In the same context, Ndhaief et al. (2019) proposed a compromise between ecological and economic maintenance and production planning based on subcontractor solutions with the aim to avoid emission excesses and to satisfy the demand under a high service level. Assid et al. (2020) developed a new production control policy for unreliable HMRSs with dedicated and shared facilities. The considered setup decisions are related to the switch between both remanufacturing and manufacturing operations of the shared facility. Unlike previous works in Class II, only a few papers integrated the quality variation of returns and its impact on the failure process of facilities and hence on the production capacity of the system. For instance, Korugan et al. (2013) studied the impact of the quality variation of returns on remanufacturing process when the facility can be stopped either due to an operational failure or due to the production of bad quality units. Ouaret et al. (2018) considered that the deterioration of the manufacturing facility affects the quality of produced units, which in turn affects the failure process of the remanufacturing facility during its production operation. The authors demonstrated that the near-optimal joint replacement and production control policy is of hedging-point type. However, none of these works considers switching policies and the categorization of returns to manage their quality-based variation effectively.

Table 5.1 Summary of the related literature

Publications	Joint manufacturing-remanufacturing process	Stochastic production lead-times	quality-based categorization of returns	Quality variation impact on remanufacturing lead-time	Switching between quality-based conditions of returns	Proposal of new policies	Optimization of policies	Failure-prone facilities
Class I. Models not considering the unreliability of production facilities								
Group 1. HMRSs without quality-based categorization of returns								
Van der Laan et al. (1999a)	×	×						
Kiesmuller (2003)	×					×		
Van der Laan and Teunter (2006)	×						×	
Zanoni et al. (2006)	×	×				×		
Zhou and Yu (2011)	×					×		
Corum et al. (2014)	×	×						
Dev et al. (2017)	×	×						
Liu et al. (2019)	×						×	
Group 2. HMRSs with quality-based categorization of returns								
Aras et al. (2004)	×	×	×	×			×	
Behret and Korugan (2009)	×	×	×	×				
Cai et al. (2014)	×		×			×	×	
Dominguez et al. (2019)	×	×	×	×				
Class II. Models considering unreliability of production facilities								
Kenné et al. (2012)	×	×				×	×	×
Korugan et al. (2013)	×	×		×				×
Kouedeu et al. (2014)	×	×				×	×	×
Polotski et al. (2018)	×	×				×		×
Ouaret et al. (2018)	×	×		×		×	×	×
Turki et al. (2018)	×	×				×		×
Ndhaief et al. (2019)	×	×						×
Assid et al. (2020)	×	×				×	×	×
Our proposal	×	×	×	×	×	×	×	×

As pointed out above, the variability in the quality of returned products has been considered in the literature by a wide variety of remanufacturing systems. However, to the best of our knowledge, most of these works focused on reliable systems with fixed and uncontrollable production rates while no one integrated switching decisions between the remanufacturing of different quality-based conditions of returns. This line of research addressing the optimal structure of production control policies that are adjusted to the quality of returns within unreliable HMRSs remains an open problem in the literature. We argue that it could bring to decision makers a better way to control this system category. Our main contribution is to fill this gap by considering an unreliable HMRS where the PPC activities depend on the system state (production facilities are subject to random failure and repair times) and are characterized by different costs and processing lead-times according to the quality condition of the selected returns. The current paper also investigates the complex relationships between studied decisions (manufacturing, remanufacturing and quality of returns) and the impact of some system's variables in the resulting control parameters (switching thresholds and inventory levels). It provides insights into when to manufacture using raw materials, what quality-based category of returns to choose for remanufacturing and when to switch between such categories. It therefore aims to characterize the structure of the optimal control policies by determining the switch sequence of the remanufacturing facility between various quality-based conditions of returns as well as remanufacturing and manufacturing rates which minimize the total cost. To achieve our goal, the optimal structure characterization of joint control policies is performed using optimal control theory and numerical methods. An approach combining simulation and optimization techniques is then applied to determine related control parameters that minimize the total cost and to compare several other policies adapted from literature for wide range configurations of the considered system.

5.3 Problem statement

The notations used in this paper are defined below. $\forall i = \{1,2\}$, $\forall j = \{1,2,3\}$:

ρ	: Discount rate
α_i	: State of facility F_i
c^+	: Finished products holding cost ($/time/unit)
c^-	: Finished product backlog cost ($/time/unit)
c^{man}	: Manufacturing cost at facility F_1 ($/unit)
c_{Ri}^{rem}	: Remanufacturing cost at facility F_2 using the returns type i ($/unit)
c^{def}	: Penalty cost for selling a defective product ($/unit)
d	: Finished product demand rate
M_i	: Mode of facility F_2 using the returns type i
p_0	: Proportion of defective raw materials
p_i	: Proportion of defective returns of type i
$u^{man}(t)$	: Manufacturing rate of facility F_1 at time t
$u^{rem}(t)$	: Remanufacturing rate of facility F_2 at time t
$u_{Ri}^{rem}(t)$	: Remanufacturing rate of facility F_2 using the returns type i at time t
U^{man}	: Maximum manufacturing rate of facility F_1
U_{Ri}^{rem}	: Maximum remanufacturing rate of facility F_2 using the returns type i
$x_F(t)$	: Inventory level (or backlog) of finished products at time t
Z_F	: Inventory threshold of finished products

5.3.1 System description

Figure 5.1 presents the studied system, which is composed of two failure-prone facilities capable of producing one finished product type. All finished products are placed in a remote storage area before being sold to customers. Facility F_1 is supplied by new raw materials and operates using only the manufacturing mode. The raw material may contain a proportion of defective parts p_0 that can be transferred after processing to the finished products. Facility F_2 is supplied by two categories of returns: the category 1 of returns are of higher quality and contains a smaller proportion of defective units compared to the category 2 ($p_1 < p_2$). That means that F_2 may operate at two different remanufacturing modes: mode 1 if F_2 is using the category 1 of returns and mode 2 if the category 2 is used. A setting operation is therefore needed to switch from one remanufacturing mode to another.

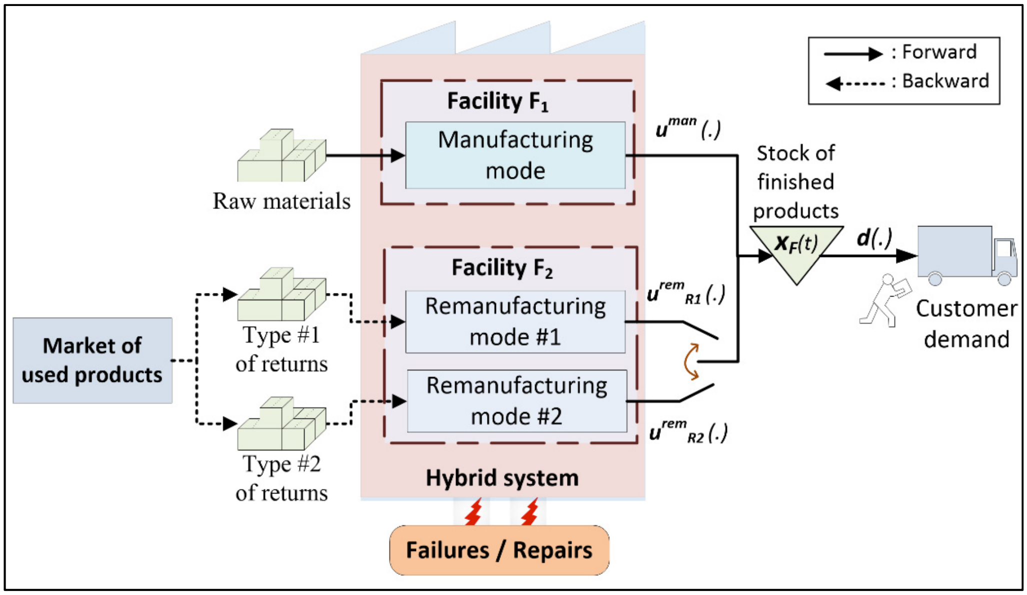

Figure 5.1 The unreliable hybrid manufacturing-remanufacturing system under study

Each defective unit (whether raw materials or returns) is transformed into a defective finished product and also sold to customers. In such a situation, customers are assumed to being capable of detecting the defective units and getting them replaced (a cost c^{def} is generated for each defective finished product). Given that the production rates and costs depend on the operated facility and the category of returns, the considered PPC problem consists in establishing how the two facilities should be operated in a dynamic and stochastic context while minimizing the total incurred cost. Our work is based on the following assumptions:

- the quality of both manufactured and remanufactured products is the same;
- the demand rate is constant;
- all returned products can be remanufactured;
- raw materials and returns are always available;
- switching time and cost between the remanufacturing modes are negligible;
- both remanufacturing and manufacturing facilities are necessary to fill all customer demand.

5.3.2 Problem formulation

Three elements are used to describe the system state at each time unit. The first one is the cumulative finished product level (calculated by $x_F(t)$), which is continuous. The second and third elements define the entire system state composed by both facilities (F_1 *and* F_2) using two random variables $\alpha_1(\mathrm{t})$ and $\alpha_2(\mathrm{t})$ with value in $M_1 = \{0,1\}$ and $M_2 = \{0,1\}$ as follows:

$$\alpha_1(\mathrm{t}) = \begin{cases} 1 & \mathrm{F_1 \text{ is available}} \\ 0 & \mathrm{F_1 \text{ is unavailable}} \end{cases}, \quad \alpha_2(\mathrm{t}) = \begin{cases} 1 & \mathrm{F_2 \text{ is available}} \\ 0 & \mathrm{F_2 \text{ is unavailable}} \end{cases}$$

Two transition rates matrix $T_i = \{q_{\gamma\vartheta}^i\}$, with $q_{\gamma\vartheta}^i \geq 0$ if $\gamma \neq \vartheta$ and $q_{\gamma\gamma}^i = -\sum_{\gamma\neq\vartheta} q_{\gamma\vartheta}^i$, where $\gamma, \vartheta \in M_i$ are used to define the stochastic processes related to the operational state of F_1 *and* F_2. The following expression define the transitions rates matrix $\mathrm{T_i}$:

$$T_i = \begin{vmatrix} -q_{12}^i & q_{12}^i \\ q_{21}^i & -q_{21}^i \end{vmatrix}$$

In addition, the operational state may be defined by a random vector $\alpha(\mathrm{t}) = (\alpha_1(\mathrm{t}), \alpha_2(\mathrm{t}))$, $\alpha(\mathrm{t}) \in M = \{1,2,3,4\}$:

$$\alpha(\mathrm{t}) = \begin{cases} 1 & \text{Both } \mathrm{F_1} \text{ and } \mathrm{F_2} \text{ are available } (1,1) \\ 2 & \mathrm{F_1} \text{ is available, } \mathrm{F_2} \text{ is unavailable } (1,0) \\ 3 & \mathrm{F_1} \text{ is unavailable, } \mathrm{F_2} \text{ is available } (0,1) \\ 4 & \text{Both } \mathrm{F_1} \text{ and } \mathrm{F_2} \text{ are unavailable } (0,0) \end{cases}$$

Based on T_i, $i \in \{1,2\}$, the stochastic process describing the operational state of the entire system is defined by:

$$\mathrm{T} = \begin{bmatrix} q_{11} & q_{12} & q_{13} & q_{14} \\ q_{21} & q_{22} & q_{23} & q_{24} \\ q_{31} & q_{32} & q_{33} & q_{34} \\ q_{41} & q_{42} & q_{43} & q_{44} \end{bmatrix} = \begin{bmatrix} -(\mathrm{q}_{12}^1 + \mathrm{q}_{12}^2) & \mathrm{q}_{12}^2 & \mathrm{q}_{12}^1 & 0 \\ \mathrm{q}_{21}^2 & -(\mathrm{q}_{12}^1 + \mathrm{q}_{21}^2) & 0 & \mathrm{q}_{12}^1 \\ \mathrm{q}_{21}^1 & 0 & -(\mathrm{q}_{21}^1 + \mathrm{q}_{12}^2) & \mathrm{q}_{12}^2 \\ 0 & \mathrm{q}_{21}^1 & \mathrm{q}_{21}^2 & -(\mathrm{q}_{21}^1 + \mathrm{q}_{21}^2) \end{bmatrix}$$

The state space of the studied system is given by (x_F, γ), $x_F \in R$ and $\gamma \in M$. Thus, the dynamics of the inventory level $x_F(t)$ is defined as follows:

$$\dot{x}_F(t) = u^{man}(t) + (u_{R1}^{rem}(t) \times I\{M_1 = 1\}) + (u_{R2}^{rem}(t) \times I\{M_2 = 1\}) - d, \;\; x_F(0) = x_F^0 \qquad (5.1)$$

Where x_F^0 is the initial inventory level and $\mathrm{I}\{\emptyset(.)\} = 1$ if $\emptyset(.)$ is true while $\mathrm{I}\{\emptyset(.)\} = 0$ otherwise. The decision variables of our problem are the production (manufacturing and remanufacturing) rates of F_1 and F_2: $u^{man}(t)$, $u_{R1}^{rem}(t)$, $u_{R2}^{rem}(t)$ and the remanufacturing modes of facility F_2. These remanufacturing modes may also be defined by the variable S_{ij}, $i, j \in \{1,2\}$ as follows:

$$\mathrm{S}_{11} = \begin{cases} 1 & \text{if } F_2 \text{ is in remanufacturing mode 1, using the returns category 1} \\ 0 & \text{Otherwise} \end{cases}$$
$$\mathrm{S}_{12} = \begin{cases} 1 & \text{if } F_2 \text{ switches from the remanufacturing mode 1 to the mode 2} \\ 0 & \text{Otherwise} \end{cases}$$
$$\mathrm{S}_{22} = \begin{cases} 1 & \text{if } F_2 \text{ is in remanufacturing mode 2, using the returns category 2} \\ 0 & \text{Otherwise} \end{cases}$$
$$\mathrm{S}_{21} = \begin{cases} 1 & \text{if } F_2 \text{ switches from mode 2 to the remanufacturing mode 1} \\ 0 & \text{Otherwise} \end{cases}$$

Recall that F_2 cannot be in both remanufacturing modes at the same time. Thus, the equation $\sum_{i,j} S_{ij} = 1$ must be true.

Note also that production rates must fulfill the production capacity constraints at any time:

$$\begin{cases} 0 \le u^{man}(t) \le U^{man} \\ 0 \le u_{R1}^{rem}(t) \le U_{R1}^{rem} \\ 0 \le u_{R2}^{rem}(t) \le U_{R2}^{rem} \end{cases} \qquad (5.2)$$

Let A describes the set of admissible decisions $\left(u^{man}(t), u_{R1}^{rem}(t), u_{R2}^{rem}(t)\right)$ such that:

$$\mathrm{A} = \left\{ \begin{matrix} p = \left(u^{man}(t), u_{R1}^{rem}(t), u_{R2}^{rem}(t)\right), 0 \leq u^{man}(t) \leq U^{man}, 0 \leq u_{R1}^{rem}(t) \leq U_{R1}^{rem}, \\ 0 \leq u_{R2}^{rem}(t) \leq U_{R2}^{rem}, \sum_i M_i = 1, \forall \mathrm{t} \geq 0, \mathrm{i} = \{1,2\} \end{matrix} \right\}$$

The selected performance measure of our system is the total cost rate function $g(.)$:

$$\begin{aligned} & g\left(x_F(t), u^{man}(t), u_{R1}^{rem}(t), u_{R2}^{rem}(t)\right) \\ & \qquad = c^+ \times x_F^+(t) + c^- \times x_F^-(t) + c^{man} \times u^{man}(t) + c_{R1}^{rem} \times u_{R1}^{rem}(t) \\ & \qquad + c_{R2}^{rem} \times u_{R2}^{rem}(t) + c_{def} \times \left(p_0 \times u^{man}(t) + p_1 \times u_{R1}^{rem}(t) + p_2 \times u_{R2}^{rem}(t)\right) \end{aligned} \tag{5.3}$$

Where, $x_F^+(t) = max\left(0, x_F(t)\right)$ and $x_F^-(t) = max(-x_F(t), 0)$.

We assume that $\mathrm{g}(.)$ is a nonnegative jointly convex function (in either w or q or both). For $\mathrm{q}, \mathrm{q}' \in \mathrm{A}$ and $\mathrm{w}, \mathrm{w}' \in \mathrm{R}$, constants C_0 and $\mathrm{K_g} \geq 0$ exist such that:

$$|g(w,q) - g(w',q')| \leq C_0 \lfloor (1 + |w|^{K_g} + |w'|^{K_g}).|w - w'| + |q - q'| \rfloor$$

The expected total cost J(.) is given by:

$$J(x_F, p, \alpha) = E_{x_F,\alpha}\left[\int_0^{\infty} e^{-\rho t}.g(x_F, p).dt\right] \tag{5.4}$$

$E_{x_F,\alpha}$ denotes the conditional expectation considering the condition (x_F, α) at $t = 0$.

Our control problem is to determine an admissible decision $p = \left(u^{man}(t), u_{R1}^{rem}(t), u_{R2}^{rem}(t)\right)$ minimizing $J(.)$, which is defined by (5.4) subject to (5.1) and (5.2). The following expression formulates the value function of our stochastic optimal control problem:

$$v(x_F, \alpha) = \min_{p \in A} J(x_F, p, \alpha) \tag{5.5}$$

This value function meets particular properties called optimality conditions. These consist of a set of PDEs (partial-derivatives-equations) known as Hamilton Jacobi Bellman (HJB) equations (see Appendix IV). We used a numerical approach to solve them (see Appendix V).

5.4 Numerical results

The numerical approach aims to determine the structure of the optimal production policies. Thus, an initial data set (see Table 5.2) is used in the numerical example to describe the optimal control policy of the entire system state. The result will be studied and compared (in Section 5.7) to several control policies found in literature. The considered values of the data presented in Table 2 are based on production-inventory control problems. The system data are adopted in a manner that: $c^+ < c^-$, $c_{Ri}^{rem} < c^{man}$, $i \in \{1,2\}$. In addition, by including the procurement cost of each returned item in its total cost of remanufacturing, the following applies: $c_{R2}^{rem} < c_{R1}^{rem}$. The average lead-time needed to remanufacture returns is also considered to be depending on their quality condition while assuming that: better quality leads to lower average remanufacturing lead time (Akçali & Çetinkaya, 2011 ; Masoudipour, Amirian, & Sahraeian, 2017). Thus, $U_{R2}^{rem} < U_{R1}^{rem}$. Note that it also makes sense when considering that remanufacturing processing time is less than manufacturing one, so: $U_{Ri}^{rem} < U^{man}$, $i \in \{1,2\}$ (Dominguez et al., 2019).

The state of both production facilities are modelled using: $\mathrm{T}_1 = \begin{bmatrix} -0.1 & 0.1 \\ 0.1 & -0.1 \end{bmatrix}$ and $\mathrm{T}_2 = \begin{bmatrix} -0.1 & 0.1 \\ 0.1 & -0.1 \end{bmatrix}$, which sets their availability to 50%. Thus, for the entire system:

$$T = \begin{bmatrix} -0.2 & 0.1 & 0.3 & 0 \\ 0.1 & -0.2 & 0 & 0.1 \\ 0.1 & 0 & -0.2 & 0.1 \\ 0 & 0.1 & 0.1 & -0.2 \end{bmatrix} \tag{5.6}$$

Table 5.2 Parameters for the numerical example

Parameters	c^+	c^-	U^{man}	U^{rem}_{R1}	U^{rem}_{R2}	d	h	ρ
Values	0.1	40	12	8.5	8	7	0.1	0.4
Parameters	c^{man}	c^{rem}_{R1}	c^{rem}_{R2}	c_{def}	p_0	p_1	p_2	
Values	3	1.2	1	3	0.01	0.15	0.2	

The numerical solution should reflect the relation between the system state and decision variables. Each one will be determined on the basis of the stochastic process T of the system and x_F. Figure 5.2 presents the obtained results when $\alpha(.) = 1$ (state 1: both production facilities are available). The results show that the resulting control policy, called control policy #1, splits the inventory space into distinct areas delimited by three thresholds:

- in areas I ($x_F < Z_1$): both F_1 and F_2 operate at the maximum rate. F_2 is used in the remanufacturing mode 1;
- in areas II ($Z_1 < x_F < Z_2$): F_2 is used at the maximum rate in the remanufacturing mode 1. The manufacturing rate is equal to zero;
- in areas III ($Z_1 < x_F < Z_2$): F_2 change its configuration for the remanufacturing mode 2. It is used at maximum rate. The manufacturing rate is equal to zero;
- in areas IV ($Z_3 < x_F$): both production rates are equal to zero.

The thresholds represent the security stock levels to cope with future unavailability of production facilities caused by failures. They also represent the need for a security stock before adopting the less expensive remanufacturing mode, which operates at a lower rate and may generate more defective products.

The same numerical technique is also performed to establish the optimal structure of production policies for two separate scenarios: when the facility F_2 is used only in mode 1 and when it is used only in mode 2. As expected, since no switching between remanufacturing modes is permitted, the respective production policies #2 and #3 split the inventory space into only three areas delimited by two thresholds (see Figure 5.3). In addition, the obtained results are consistent with those when F_2 operates in both remanufacturing modes such that each production mode (manufacturing, remanufacturing using high or low quality of returns) is characterized by a threshold level.

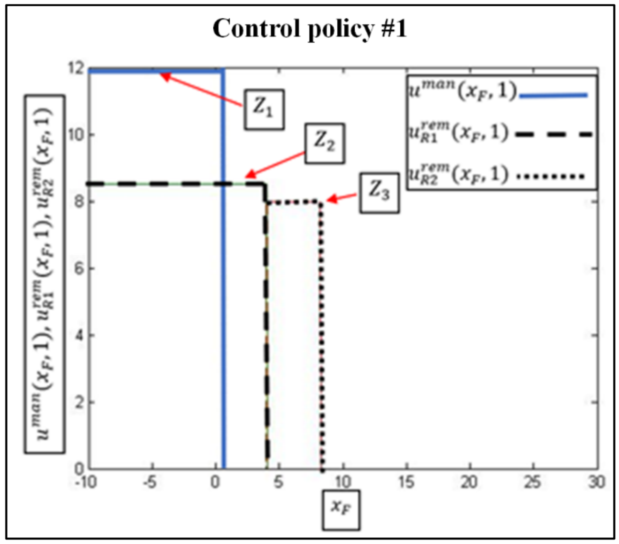

Figure 5.2 The production rates of the system in state 1

Table 5.3 presents the optimal values of control parameters and the total cost of the adopted numerical scenario. It shows that the threshold value related to manufacturing activity is less than those related to remanufacturing, so that $0 \leq Z_1^* < Z_2^* < Z_3^*$. This result is expected since it is more profitable to produce better quality finished products at a faster rate in situations of high risk of shortages. Otherwise, the system can use to remanufacture returned products while choosing the least expensive mode. Table 5.3 also shows that the policy #1 generates the lowest total cost precisely by taking advantage of its ability to use the proper production mode based on the evolution of system state (high risk of shortages, high proportion of defective finished products). However, we believe that an extended comparative study taking into account distinct production policies from the literature is essential to draw valuable conclusions about the performance of the considered control policies. These are defined in Section 5.5 while the comparative results are detailed in Sections 5.7.2 and 5.7.3.

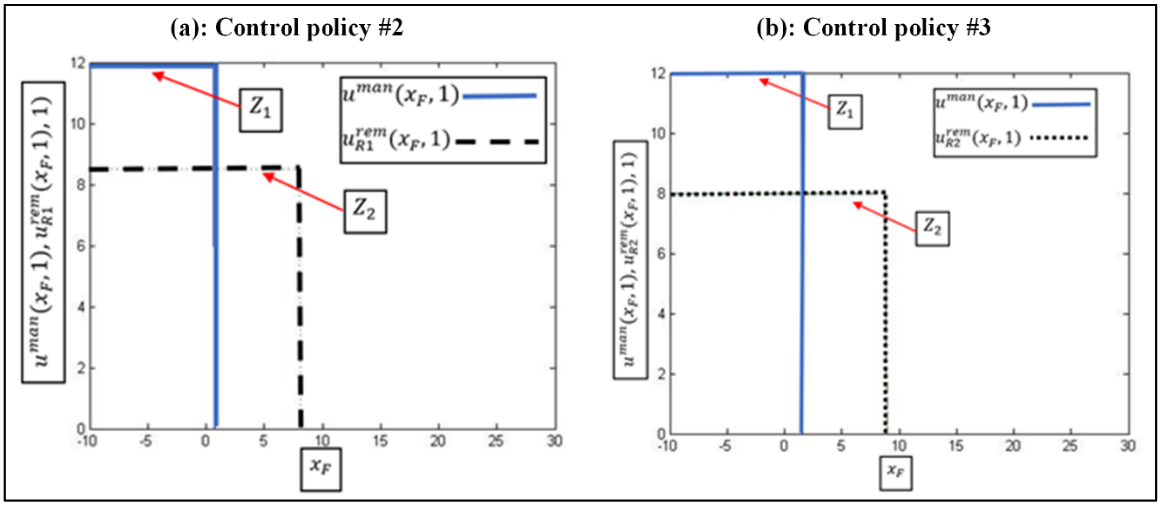

Figure 5.3 The production rates of the system in state 1 when F_2 is used only in one mode

Table 5.3 Optimal policies for the studied case

Control policies	Z_1^*	Z_2^*	Z_3^*	Total cost
#1	0.5	4.0	8.2	48.105
#2	0.6	8.0	-	49.203
#3	1.5	8.8	-	49.699

5.5 Control policies structure

As stated above, the main goal of our work is to characterize the optimal production control policy for the studied unreliable HMRS processing raw materials and returns that contain different proportions of defective parts. Based on the numerical results, three parameterized control policies are developed. The first one considers the facility F_2 with both remanufacturing modes (modes 1 and 2) using two different categories of returns (categorized by the proportion of defective units they may contain). The other control policies use F_2 in a single remanufacturing mode (mode 1 or mode 2). They will be compared one with another and with three distinct policies found in the literature (in Sections 5.7.2 and 5.7.3). Table 5.4 contains the list and the formulation of studied control policies while the following subsections describe their structure.

5.5.1 Control policy #1

The obtained numerical results show that the control policy #1 consists of a state-dependent multi-level base stock feedback policy. It is expressed by equations (5.7)-(7.9) (see Table 5.4). It aims to maintain the safety inventory level (Z_3) in order to cope with harmful stochastic events such as failures of production facilities. Using both categories of returns in addition to raw materials, it aims for a better synchronization of production activities and the best switching time between the remanufacturing modes. The control parameters of the control policy #1 are: Z_1 for the manufacturing, Z_2 for remanufacturing mode 1 including the switching policy and Z_3 for the remanufacturing mode 2, with $0 \leq Z_1 < Z_2 < Z_3$. Z_3 denotes also the size of the finished products stock.

Equation (5.7) shows that the facility F_1 should act as a standby facility transforming raw materials at maximum manufacturing rate as long as the inventory level of finished products (x_F) is below the threshold Z_1 ($x_F < Z_1$). The goal is to support the remanufacturing facility F_2 when the system faces a high risk of shortages. F_1 can also adapt its manufacturing rate to that of the demand, but only if $x_F = Z_1$ and F_2 cannot supply the stock of finished products because of failures. Indeed, the control policy #1 gives greater priority to the remanufacturing by processing the maximum possible number of returns since apart from being more environment-friendly they cost less compared to the manufacturing process. However, when F_2 is operational it is used at its maximum production rate to remanufacture the category 1 of returns (remanufacturing mode 1) as long as $x_F < Z_2$, which includes the case when $x_F < Z_1$ since $Z_1 < Z_2$ (see equation (5.8)). Then, when x_F reaches Z_2, F_2 adopts a lower-cost production mode by switching to the remanufacturing mode 2 (see equation (5.9)). Finally, when the stock of finished products is full ($x_F = Z_3$), F_2 adapts the remanufacturing rate to customer demand in order to maintain its inventory level.

5.5.2 Control policy #2

The control policy #2 is obtained when the numerical method is applied considering the remanufacturing mode 1 only (in addition to raw materials, only the category 1 of returns is considered). Based on the obtained numerical results; it is also of state-dependent multi-level base stock feedback policy and can be described by equations (5.7) and (5.10). Unlike the previous policy, two control parameters $Z_1\ and\ Z_2$ $(0 \leq Z_1 < Z_2)$ characterized it. They represent the manufacturing and the remanufacturing mode 1 respectively. Z_2 represents the size of the finished products stock.

5.5.3 Control policy #3

The difference between the control policies #2 and #3 is that the last one (#3) uses the category 2 of returns (instead of the category 1). The control policy #3 is described by equations (5.7) and (5.11). It is described by Z_1 and Z_2 $(0 \leq Z_1 < Z_2)$, which defines the size of the finished products stock.

5.5.4 Control policy #4

In addition to the obtained control policies, two others based on the literature are considered in our comparative study. They are an extended version of that proposed by (Polotski et al., 2019 and Ouaret et al., 2018). They are of hedging-point type with one control parameter Z_1. Using F_2 in the remanufacturing mode 1 only (only the category 1 of returns is considered), the control policy #4 prioritizes the remanufacturing process, so that when the stock of finished products is full (x_F reaches the threshold level Z_1), F_2 adapt its remanufacturing rate to that of demand while F_1 stops its production activities (since $U_{R1}^{rem} > d$). This control policy is formulated by the equations (5.7) and (5.12). Z_1 also defines the size of the finished products stock.

5.5.5 Control policy #5

Policy #5 differs from policy #4 by the fact that F_2 is used in the remanufacturing mode 2 as described by equations (5.7) and (5.13).

5.5.6 Control policy #6

The sixth control policy considered in this work is adapted from traditional production-inventory control policies such as (s, Q) for HMRSs (E. Van Der Laan, Salomon, Dekker, et al., 1999). It consists of a pull strategy monitoring the inventory level of finished products (x_F) and planning production activities in batches. So, as soon as x_F drops below a specific value S^{st}, the system actuates the production activities to produce a batch of size Q^{st}. The work-in-process batch is stored in a downstream space of facilities (F_1 and F_2) until the batch is fully produced, after which it is transported to the stock of finished products. When the batch arrives, x_F increases instantly with a finite jump equal to Q^{st}. Unlike policies presented above, which adapt their production rates according to the state of facilities, policy #6 only uses maximum production rates. The quantity Q^{st} comprises three components: the batch of Q^{man} made by the manufacturing facility F_1 using raw materials and two batches of Q_{R1}^{rem} and Q_{R2}^{rem} made by the remanufacturing facility F_2 using both categories 1 and 2 of returns respectively. Thus, $Q^{st} = Q^{man} + Q_{R1}^{rem} + Q_{R2}^{rem}$. The control policy #6 is characterized by four parameters: S^{st}, Q^{man}, Q_{R1}^{rem} and Q_{R2}^{rem}.

Table 5.4 Studied control policies

Policy	Manufacturing activity		Remanufacturing activities		Setup ($S_{ij}, i,j \in \{1,2\}, i \neq j$)	
#1	$\begin{cases} U^{man} & if\ (x_F < Z_1) \\ d & if\ (x_F = Z_1) and (\alpha_2 = 0) \\ 0 & otherwise \end{cases}$ (policies #1–#5)	(5.7)	$\begin{cases} d_{R2}{}^{(h)}.I\{S_{22}=1\} & if\ (x_F = Z_3) \\ U_{R2}^{rem}.I\{S_{22}=1\} & if\ (Z_2 \le x_F < Z_3) \\ U_{R1}^{rem}.I\{S_{11}=1\} & if\ (x_F < Z_2) \\ 0 & otherwise \end{cases}$	(5.8)	$\begin{cases} 1 & if\ (x_F = Z_2) \\ 0 & otherwise \end{cases}$	(5.9)
#2			$\begin{cases} U_{R1}^{rem}.I\{S_{11}=1\} & if\ (x_F < Z_2) \\ d & if\ (x_F = Z_2) \\ 0 & otherwise \end{cases}$	(5.10)	No setup actions (policies #2–#6)	
#3			$\begin{cases} U_{R2}^{rem}.I\{S_{22}=1\} & if\ (x_F < Z_2) \\ d & if\ (x_F = Z_2) \\ 0 & otherwise \end{cases}$	(5.11)		
#4			$\begin{cases} U_{R1}^{rem}.I\{S_{11}=1\} & if\ (x_F < Z_1) \\ d & if\ (x_F = Z_1) \\ 0 & otherwise \end{cases}$	(5.12)		
#5			$\begin{cases} U_{R2}^{rem}.I\{S_{22}=1\} & if\ (x_F < Z_1) \\ d & if\ (x_F = Z_1) \\ 0 & otherwise \end{cases}$	(5.13)		
#6	$\begin{cases} Q^{man} & if\ (x_F = S^{st}) \\ 0 & otherwise \end{cases}$	(5.14)	$\begin{cases} Q_{R1}^{rem} + Q_{R2}^{rem} & if\ (x_F = S^{st}) \\ 0 & otherwise \end{cases}$	(5.15)		

(h)With $\boldsymbol{d_{Ri}}$, $\boldsymbol{i} = \{\mathbf{1}, \mathbf{2}\}$ represents the remanufacturing rate when it is adapted to the demand one while using the type #i of returns.

5.6 Resolution approach

The numerical method presented in Section 4 (see also Appendix V) is part of a global resolution approach which also includes a combined simulation-optimization method while using the experimental design (DOE) and the response surface methodology (RSM). The combined simulation-optimization method is flexible and less time-consuming compared to the numerical one especially for comparative studies where several concurrent control policies should be tested in the same conditions. Berthaut et al. (2010) refer to many difficulties in the practical implementation of numerical methods such as the improprieties in result boundaries which makes "the estimation of control parameters much more time-consuming to be applicable at the operational level". The main reason is related to the accuracy of numerical results which depends on the dimension of the grid step h (see Appendix V). The proposed resolution approach provides a practical and implementable solution and has demonstrated success in the PPC area as in (Morad Assid et al., 2020). The proposed approach consists of the following steps (see Figure 5.5):

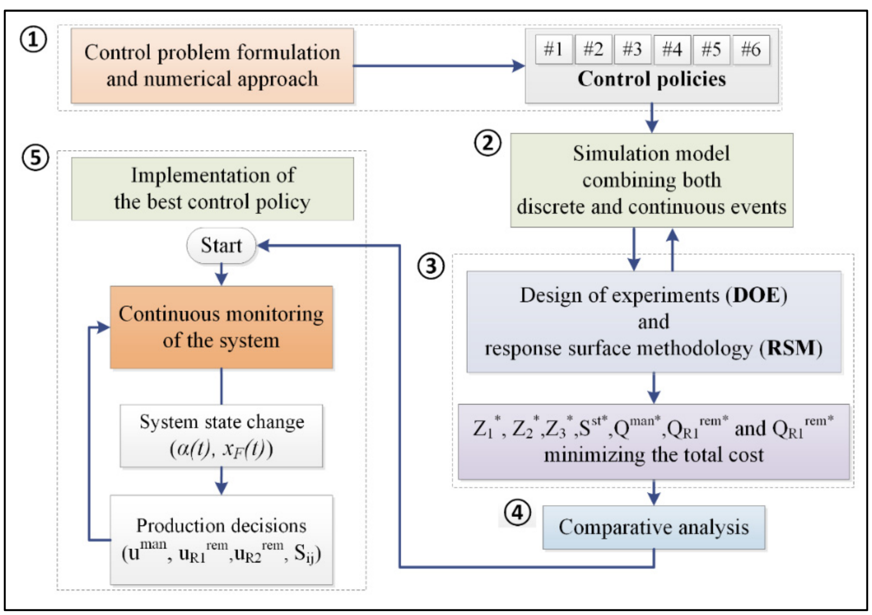

Figure 5.4 Combined simulation-optimization procedure

5.6.1 Control problem formulation and numerical method

This step describes the objective of finding the optimal control variables (production processes (p) and the sequence of setting activities used to switch between remanufacturing modes) which minimize the total cost (see Section 5.3.2). It also describes the obtained structure of three control policies using a numerical method (see Section 5.4) and three others that have been adapted from the literature to our context (see Section 5.5). The considered control policies are characterized by the control parameters (Z_1, Z_2 and Z_3) or (Z_1 and Z_2) or only Z_1 or (S^{st}, Q^{man}, Q_{R1}^{rem} and Q_{R2}^{rem}), and are considered as inputs in the simulation model.

5.6.2 Simulation model

For given combinations of control parameters, simulation models with discrete and continuous events are built to reproduce the system dynamics and the interactions between its components. Each model uses one policy in order to control the system's various operations and then to assess its economic performance. Section 5.7.1 details this step.

5.6.3 DOE and RSM

The control parameters optimization is performed thanks to the output data from the simulation with the aim to assess the economic performance (total cost) of studied policies and to compare them. The experimental design is used to establish the experimental space of these parameters defining the simulation set. For each of their configuration, the total incurred cost is calculated (simulation output) to establish the impact on the total cost of control parameters, their quadratic and their interactions. Thereafter, second order regression models are established relating the estimated total cost (CF) of each policy to its control parameters. For instance, when the policy #1 is applied, CF takes the following equation:

$$CF \cong \beta_0 + \beta_1 Z_1 + \beta_2 Z_2 + \beta_3 Z_3 + \beta_{12} Z_1 Z_2 + \beta_{13} Z_1 Z_3 + \beta_{23} Z_2 Z_3 + \beta_{11} Z_1^2 + \beta_{22} Z_2^2 + \beta_{33} Z_3^2 + \varepsilon \tag{5.7}$$

Where, ε denotes the error and β_0, β_i and β_{ij} are estimated coefficients using simulation results. Based on the CF of studied policies, the control parameters which minimize the estimated total cost are then calculated. Section 5.7.2 details this step.

5.6.4 Comparative analysis

The end of Section 5.7.2 presents the comparative results of our illustrative example considering the various control policies. An extended comparative study is also performed in Section 5.7.3 where some system parameters are varied one at a time in a wide range. The objective is to draw meaningful conclusions, to compare their economic performance and to determine the best control policy (the one with the lowest optimal cost).

5.6.5 Implementation of the best control policy

The implementation of the best policy is discussed in Section 5.8. It highlights the actions that should be taken by decision makers to effectively control the production processes. These actions shall relate to joint manufacturing, remanufacturing and switching decisions, which require complete information on the current state of production facilities, the quality levels of returns in stocks and the inventory level of finished products in comparison with optimal control parameters.

5.7 Numerical example

This section presents the numerical example considered for illustration purposes. Table 5.5 presents the adopted system's data.

A hypothetical example of the proposed model is provided for illustration. Table 5.5 presents the system's data for the base case where the considered values are based on the literature of optimal control and inventory management. The system parameters are adopted in a manner that: $c^{+} < c^{-}, c_{Ri}^{rem} < c^{man}, i \in \{1,2\}$. The average lead-time needed to remanufacture returns is also considered to be depending on their quality condition while assuming that better the quality, the lower the average lead time and the cost (Akçali & Çetinkaya, 2011 ; Masoudipour et al., 2017). Thus, $c_{R2}^{rem} < c_{R1}^{rem}$ and $U_{R2}^{rem} < U_{R1}^{rem}$. Note that it make sense that remanufacturing requires less processing time than manufacturing, so: $U_{Ri}^{rem} < U^{man}$, $i \in \{1,2\}$ (Dominguez et al., 2019).

Table 5.5 Adopted system's data

Variables	c^{-}	c^{+}	c^{def}	c^{man}	c_{R1}^{rem}	c_{R2}^{rem}	T_{Fail}	
Values	20	0.5	120	60	10	5	Log-N(50,10)	
Variables	p_0	p_1	p_2	U^{man}	U_{R1}^{rem}	U_{R2}^{rem}	d	T_{Rep}
Values	1%	5%	10%	120	115	105	100	Log-N(15,10)

T_{Fail} and T_{Rep} respectively define the time to failure and the repair time for both production facilities. We could used any other probability distributions.

5.7.1 Simulation model

The developed simulation models combine both continuous and discrete events using the SIMAN language, in the ARENA software. The combining of both continuous and discrete events modelling reduces the run time and accurately integrate continuous processes as that defining the dynamic of the finished product stock (see equation (5.1)) (Kelton, Sadowski, & Zupick, 2015). Figure 5.5 presents the block diagram defining the developed simulation model, where each module defines a specific task (breakdown, production, satisfying customer demand). It also highlights the important interactions that exist among the various modules, and updates the system variables at each time instant. The simulation runs duration is fixed at 1,000,000 time units to make sure that the system reaches steady state. The average time of a simulation run is five seconds (on a computer with a 3.50 GHz CPU). The expected total cost, consisting of inventory/backlog, manufacturing, remanufacturing and defective product costs is calculated for each simulation run.

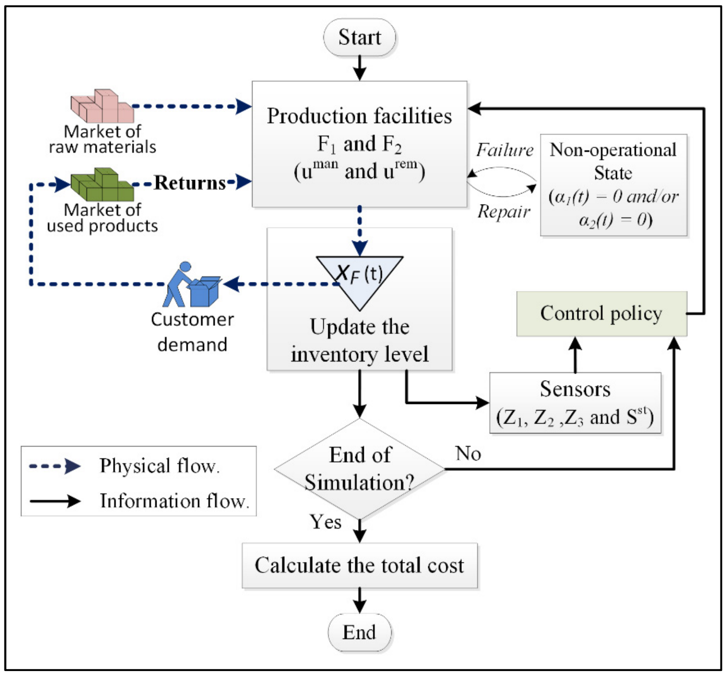

Figure 5.5 Simulation diagram

The developed simulation models are also verified and validated to ensure that they properly describe the dynamics of the system under study. Figure 5.6 illustrates an example of the evolution of a set of performance indicators (Figure 5.6.a-5.5.e) from the basic case when the control policy #1 is adopted. It shows that since $Z_2 \leq x_F < Z_3$ (see equation (5.8)), the production facility (F_2) remanufactures returns type 2 while increasing the inventory level of finished products (x_F) at the rate $U_{R2}^{rem} - d$ (Arrow 1, Figure 5.6.a). However, when x_F reaches Z_3 (Arrow 2, Figure 5.6.a), F_2 adapts its remanufacturing to the customer demand (Arrow 3, Figure 5.6.c) in order to keep the inventory level at the threshold Z_3, similar to the concept of

Hedging Point Policy. The breakdown of F_2 (Arrow 4, Figure 5.6.e) changes this situation since it can no longer transform the returns. So, x_F drops according to the rate of demand (Arrow 5, Figure 5.6.a). The manufacturing facility (F_1) takes over the production activities (see equation (5.7)) as soon as x_{F} reaches the threshold Z_1 (Arrow 6, Figure 5.6.a). It operates at the rate of demand (Arrow 7, Figure 5.6.b) to keep this inventory level.

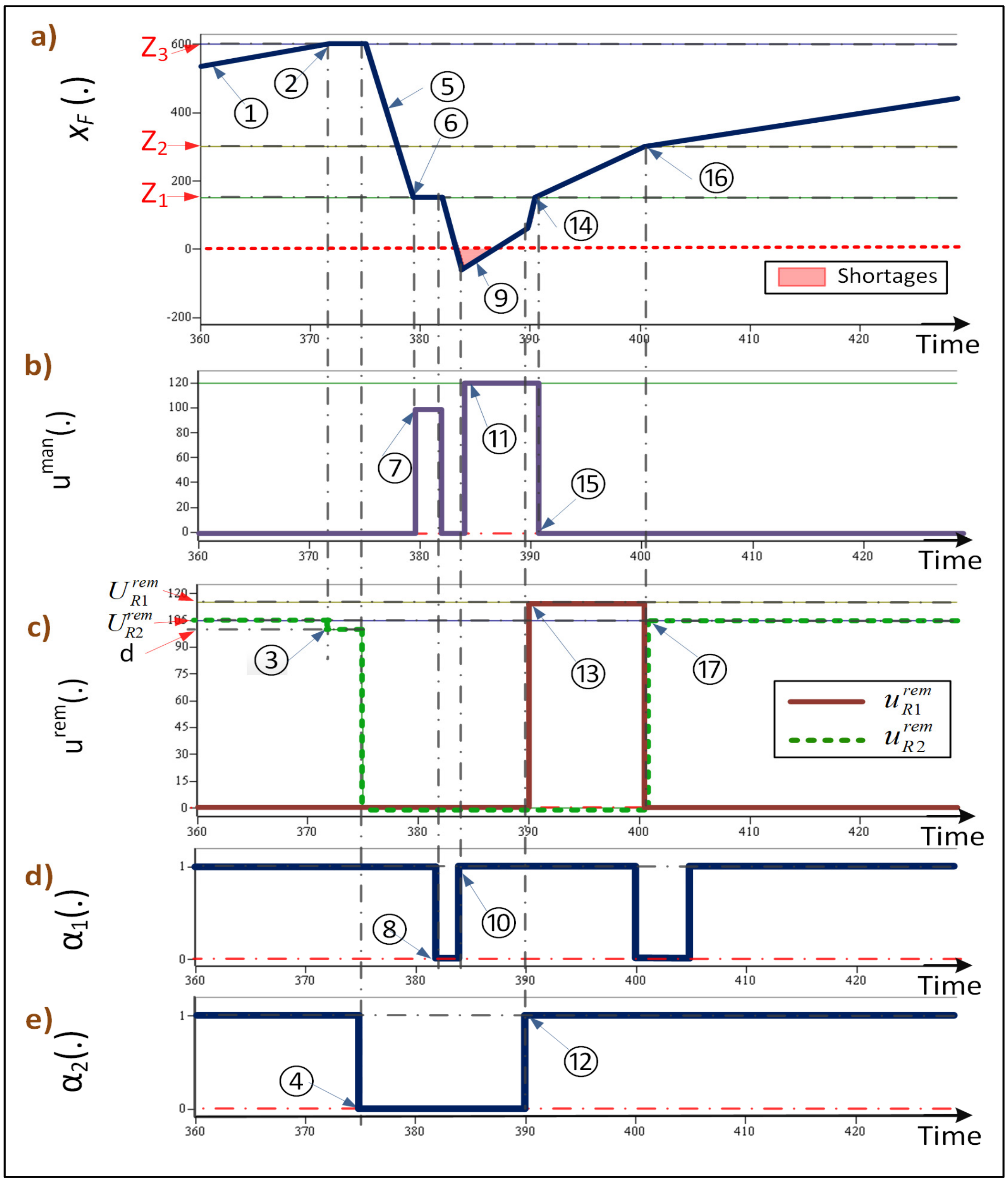

Figure 5.6 A sample of the system dynamics

In the current example, F_1 falls down (Arrow 8, Figure 5.6.d) while F_2 is also down, which stops the production activities and even generates shortages (Arrow 9, Figure 5.6.a). Figure 5.6 shows that F_1 is the first to be repaired (Arrow 10, Figure 5.6.d) and since $x_F < Z_1$, it operates at the maximum rate (Arrow 11, Figure 5.6.b), which increases x_F at the rate $U^{man} - d$. Similarly, the reparation of F_2 (Arrow 12, Figure 5.6.e) accelerate the increase of x_F at $U^{man} + U_{R1}^{rem} - d$. The use of returns type 1 at maximum remanufacturing rate (Arrow 13, Figure 5.6.c) is due to the condition $x_F < Z_2$ (see equation (5.9)). In this sense, when x_F reaches Z_1 (Arrow 14, Figure 5.6.a), F_1 is stopped (Arrow 15, Figure 5.6.b) while F_2 continues to remanufacture returns type 1. However, when x_F reaches Z_2 (Arrow 16, Figure 5.6.a), a setup operation is executed, which switches F_2 to the remanufacturing mode 2 (Arrow 17, Figure 5.6.c). A careful examination of Figure 5.6 allows concluding that the simulation model works as expected and accurately reflects the behavior of the studied system.

5.7.2 Results analysis

Simulation experiments are performed based on three levels full factorial designs. Such designs are often used for a small number of factors (control parameters) and provides more accurate results since interactions are estimated separately. The choice of design factor values is relevant for the accuracy of the solution and thus need an exploration of the admissible experimentation region. Five replications for each combination of control parameters: "Z_1, Z_2 and Z_3" for the control policy #1, "Z_1 and Z_2" for control policies #2 and #3 and "S^{st}, Q^{man}, Q_{R1}^{rem} and Q_{R2}^{rem}" for the control policy #6. This requires $3^m * 5$ simulation runs according to the number of control parameters m, so 135 for the control policy #1, 45 for both control policies #2 and #3 and 405 for the control policy #6. Regarding the control policies #4 and #5, a polynomial regression model is used to optimize their unique control parameter Z_1. The simulation outputs are processed by the software Statgraphics. It aims to perform the multi-factorial analysis of variance and to determine the regression models fitting equation (5.7). All factors, quadratic effects and interactions are statistically significant for the expected total cost of studied policies. This confirms the relevance of finding a trade-off solution between the interconnected remanufacturing, manufacturing and switching processes. Figure 5.7 presents the standardized Pareto chart (Figure 5.7(a)) and the response surface contour plot (Figure 5.7(b)) for the expected total cost when the control policy #1 is applied. The adjusted R-squared is greater than 0.95, which indicates that more than 95% of the variability observed at the cost function is explained by our regression models (Montgomery, 2012).

Once significant main and quadratic effects as well as interactions of the control parameters are identified, second-order regression models are calculated for the expected total cost CF. These models are given by the following equations (5.8)-(5.13), making reference to policies #1,…,#6 respectively. Note that the new parameters σ_1 and σ_2 are used to replace the control parameters Z_1 and Z_2, with $\sigma_1, \sigma_2 \in [0,1[$, $Z_1 = \sigma_1 . Z_2$ and $Z_2 = \sigma_2 . Z_3$. Therefore, the constraint $Z_1 < Z_2 < Z_3$ is fulfilled.

$$CF_{\#1} = 5059.67 - 1377.92\,.\,\sigma_1 - 2588.44\,.\,\sigma_2 - 0.717\,.\,Z_3 + 339.48\,.\,\sigma_1.\sigma_2 + 5.53.\ 10^{-2}\,.\,\sigma_1.Z_3 + 0.298\,.\,\sigma_2.Z_3 + 1206.87.\sigma_1^2 + 1033.1\,.\,\sigma_2^2 + 7.82.10^{-5}.Z_3^2 \tag{5.8}$$

$$CF_{\#2} = 3647.92 - 2267.51\,.\,\sigma_1 - 0.384\,.\,Z_2 + 0.327\,.\,\sigma_1.Z_2 + 2320.79.\sigma_1^2 + 6.895.10^{-5}.Z_2^2 \tag{5.9}$$

$$CF_{\#3} = 4882.3 - 4232.67\,.\,\sigma_1 - 0.537\,.\,Z_2 + 0.608\,.\,\sigma_1.Z_2 + 2966.99.\sigma_1^2 + 6.341.10^{-5}.Z_2^2 \tag{5.10}$$

$$CF_{\#4} = 3940.82 - 1.144\ .Z_1 + 5.33.10^{-4}.Z_1^2 \tag{5.11}$$

$$CF_{\#5} = 4165.31 - 1.276\ .Z_1 + 5.729.10^{-4}.Z_1^2 \tag{5.12}$$

$$CF_{\#6} = 17803.6 - 1.745\,.\,S^{st} - 4.581\,.\,Q^{man} + 1.844\,.\,Q_{R1}^{rem} + 3.037\,.\,Q_{R2}^{rem} + 2.3\,.\,10^{-4}.S^{st}.Q^{man} - 2.28.10^{-4}.S^{st}.Q_{R1}^{rem} - 2.9.10^{-4}.S^{st}.Q_{R2}^{rem} - 5.27.10^{-4}.Q^{man}.Q_{R1}^{rem} - 8.03.10^{-4}.Q^{man}.Q_{R2}^{rem} + 5.22.10^{-4}.Q_{R1}^{rem}.Q_{R2}^{rem} + 1.05.10^{-4}.{S^{st}}^2 + 7.22.10^{-4}.{Q^{man}}^2 + 2.23.10^{-4}.{Q_{R1}^{rem}}^2 + 4.06.10^{-4}.{Q_{R2}^{rem}}^2 \tag{5.13}$$

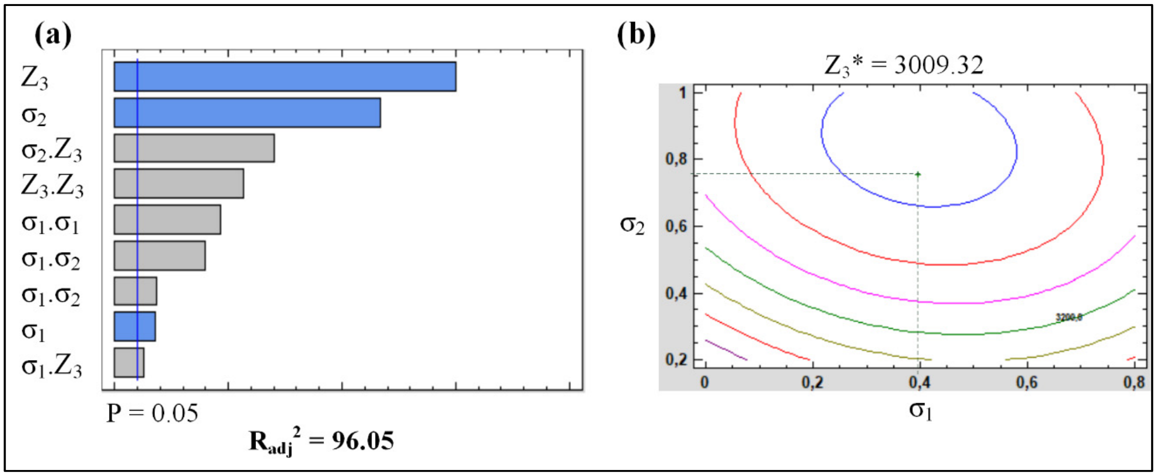

Figure 5.7 Pareto charts and response surface contour plot for the control policy #1

Table 5.6 summarizes the solution obtained by minimizing equations (5.8)-(5.13). The solution represents the optimal control parameters minimizing the total cost. In addition, a cross-check validation of the model based on 50 additional simulation runs is conducted to determine the confidence interval given by: $\overline{CF} \pm t_{1-(\pi/2)}^{n-1}\sqrt{S^2/n}$, where $\overline{\mathrm{CF}}$ denotes the average expected total cost, n represents the number of extra-simulation runs, $\mathrm{t}_{1-(\frac{\pi}{2})}^{\mathrm{n}-1}$ is the student coefficient function and S is the sample standard deviation (Banks et al., 2005). For all considered control policies, the results confirm that the optimal approximated total cost falls within their related 95% confidence interval (see Table 5.6).

The results show the advantage of the developed policy #1, which integrates the dynamic aspect of production facilities and combines different quality-based conditions of returns for the remanufacturing process. Its economic improvements compared to the control policies #2, #3, #4, #5 and #6 are respectively 4.93%, 16.94%, 17.85%, 20.89% and 55.32%. As well as being simple to implement in an industrial context (see Section 5.8), the proposal gives the system the possibility to use the right production modes according to the system evolution (high risk of shortages needs maximum production capacity). Table 5.6 also shows that the control policy structures with one threshold for each production mode (policies #2 and #3 are characterized by Z_1 for the manufacturing and Z_2 for the remanufacturing) are more cost-effective than those with one global threshold (policies #4 and #5). The control policy #6 generates the highest total cost. This because it does not consider the dynamic aspect of production facilities, which implies producing high quantities of finished products even when these installations are not down for long periods. In the same sense, by using only maximum production rates, the control policy #6 does not adapt its rate of production according to the variation of x_F, which implies larger quantities of these products in stock. The numerical example also shows the effectiveness of the combined simulation-optimization method, which provides an efficient tool to optimize the parameters of control policies, minimizing the total incurred cost. Additional experiments are needed to confirm the economic benefit of the policy #1 and to study important aspects in relation to interrelations involving switching and production control settings (see Section 5.7.3).

Table 5.6 Comparison results of the studied control policies

Control policies	$\mathbf{Z_1^*}$	$\mathbf{Z_2^*}$		$\mathbf{Z_3^*}$	**Total cost**	**Confidence interval (set at 95%)**
#1	897.46	2266.20		3009.32	2732.37	[2729.28 ; 2738.71]
#2	686.11	1958.10		-	2874.07	[2867.08 ; 2876.08]
#3	881.36	1606.89		-	3289.46	[3286.68 ; 3302.27]
#4	1073.83	-		-	3326.18	[3321.67 ; 3330.47]
#5	1114.30	-		-	3453.89	[3446.03 ; 3455.39]
	$\boldsymbol{S^{st*}}$	$\boldsymbol{Q^{man*}}$	$\boldsymbol{Q_{R1}^{rem*}}$	$\boldsymbol{Q_{R2}^{rem*}}$	**Total cost**	**Confidence interval (set at 95%)**
#6	9582,57	3321,29	4234,7	248,646	6115,03	[6094,56 ; 6127,43]

5.7.3 Comparative study and analysis

Other experiments are performed to compare the optimal total costs of the control policies, considering a wide range of system parameters derived from the basic case (Table 5.5). The comparative analysis aims to confirm the results obtained in Section 5.7.2 and to analyze how the total cost of these policies changes in relation to one another. The studied scenarios include the variation of inventory, manufacturing, remanufacturing and defective product costs as well as the proportion of defective returns of the category 1. The comparison results are summarized in Figure 5.8. It consolidates the previous results showing that the developed control policy #1 outperforms the rest of considered policies in terms of their optimal costs across a wide range of system parameters. It benefits from its capacity to take into account the dynamic of production facilities and to monitor the inventory level of finished products instantaneously in order to make better decisions related to manufacturing, remanufacturing both categories of returns and switching activities at each instant of time (see Section 5.5.1). Figure 5.8 also shows that the control policy #6 is the least economic solution. This is mainly due to the fact that this policy does not adapt its production rates to the stock-level variation and does not take into account the dynamic aspect of both facilities. Indeed, whether the downtime period of these facilities is short or long, the system will make the same production decision by producing at maximum production rates the calculated optimal quantities of finished products Q^{man*}, Q_{R1}^{rem*} and Q_{R2}^{rem*} (using raw materials and both categories 1 and 2 of returns) each time their stock reaches the level S^{st^*} (see Section 5.5.6). This implies a much more significant average level of stock than that when one of the considered policies is applied. The great impact of c^+ on the optimal total cost of the policy #6 is expected and confirmed in Figure 5.8.a., so that when c^+ drops to the level 0.1, its total cost becomes lower than that of policies #3, #4 and #5. The reason is the ability of the policy #6 to use both categories of returns (instead of one category) in order to support production activities.

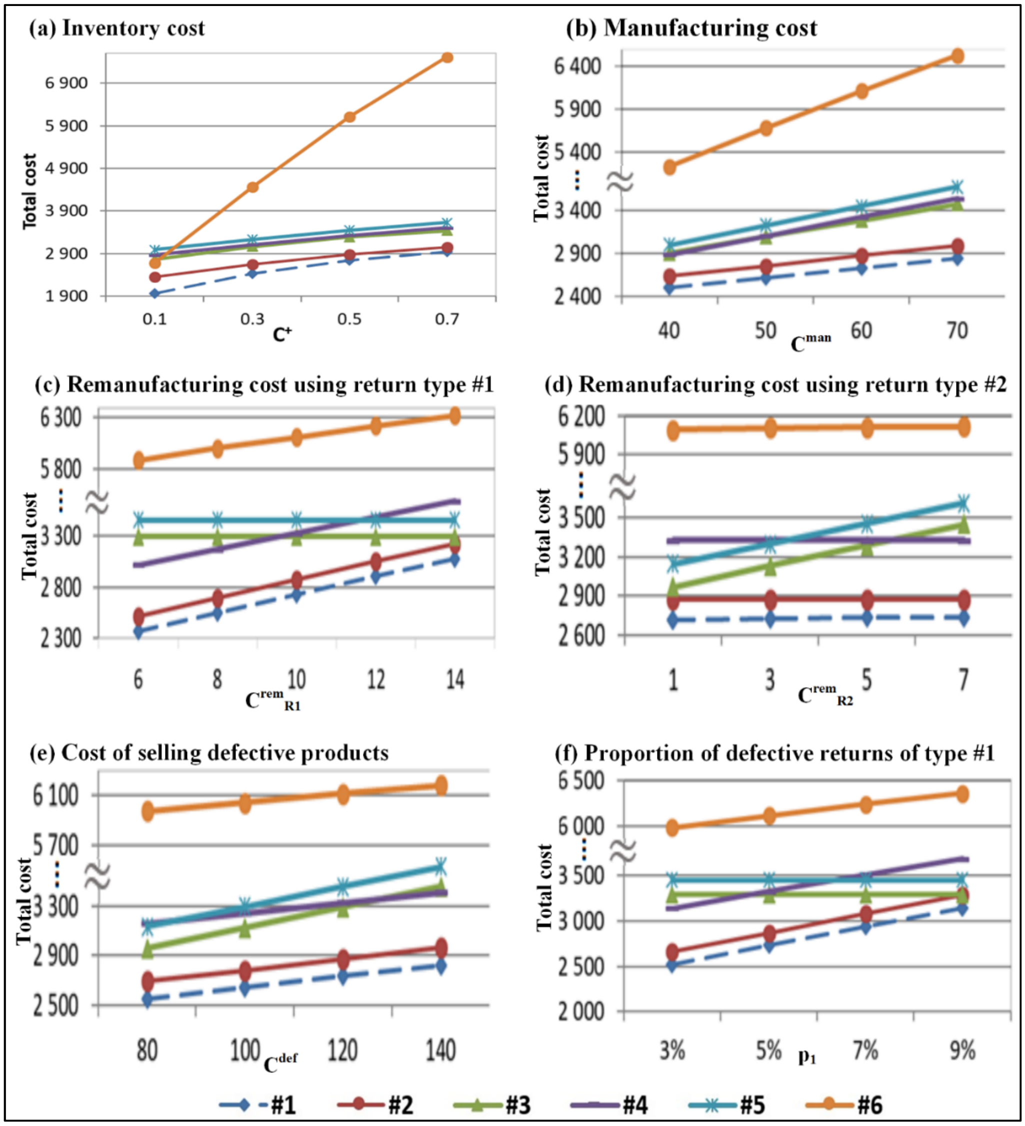

Figure 5.8 Optimal total cost comparison with different system parameters

The economic choice between control policies #2, #3, #4 and #5 will depend on the configuration of the system as shown in Figure 5.8 (b)-(f). For instance, as the manufacturing cost (c^{man}) decreases (see Figure 5.8.b), the manufacturing becomes more attractive. For both control policies #2 and #3, this is reflected in a lower value of Z_2^* in order to reduce the proportion devoted to remanufacturing activities compared to manufacturing ones (see equations (5.7), (5.10) and (5.11)). On the other hand, for control policies #4 and #5 which simultaneously use both manufacturing and remanufacturing modes to restore the finished product stock to the unique control parameter Z_1 (see equations (5.7), (5.12) and (5.13)), the variation of the latter does not affect the contribution of each mode to the total demand. Consequently, these control policies do not benefit from the advantages of operating exclusively in remanufacturing modes. This is why the differences between the total cost of control policy #2 (#3) and policy #4 (#5), which uses the same category of returns, decrease. The difference keeps decreasing following the decrease of Z_2^* until $Z_2^* = Z_1^*$, which represents the equivalence of the two policies (in this case, they have the same structure). For control policies having the same structure and using a single but different category of returns (policies #2 and #3 versus policies #4 and #5), the comparative analysis shows that the use of better-quality returns leads to better economic result. Indeed, even if lower quality returns cost less, the remanufacturing of better-quality returns is very competitive since it lasts less time (increases remanufacturing capacity), reduces the risk of producing defective units and remains less expensive compared to the manufacturing process. This explains why the total cost of policy #4 (which uses a higher quality category 1 of returns) becomes lower than that of policy #3 (which uses a category 2 of returns) when $c^{man} \leq 40$. However, it is obvious that when the cost of remanufacturing using the category 1 of returns (c_{R1}^{rem}) increases or when their quality (p_1) deteriorate, policies #2 and #4, which only use this category of returns become less and less attractive in terms of costs. Figure 5.8.c shows that when $c_{Ri}^{rem} \geq 12$, the total cost of the policy #4 exceeds that of the policy #5, but when $c_{Ri}^{rem} \leq 9$, it is lower than that of the policy #3, benefiting from lower cost of remanufacturing, higher production capacity and better quality of returns. The same phenomenon is observed during the variation of p_1 presented in Figure 5.8.f. Similarly, the increased cost of the remanufacturing using the category 2 of returns (c_{R2}^{rem}) (see Figure 5.8.d) or the defective products (c^{def}) B (see Figure 5.8.e) penalizes policies #3 and #5 which are supplied only by category 2 of returns, but the decrease of these two system parameters makes them more advantageous in terms of costs.

5.8 Managerial insight and practical implementation

This section provides guidance in the implementation of the proposed policy #1 which can be suitable for many companies using both manufacturing and remanufacturing processes, and characterized by a variable quality-based condition of returns that has significant effects on the remanufacturing lead-times and the quality of parts produced. The proposed control policy has direct managerial implications, namely, to control production processes and to improve the system performance. These managerial implications require complete information on key elements of the system like its state, the change in the stock level and the availability and quality of returns in stocks. To this end, existing technologies including those related to the Industry 4.0 can be adopted to obtain required data automatically and instantly, thereby exploiting tools for the transmission, integration and storage of massive data (Yin, Stecke, & Li, 2018). The objective is to continuously monitor real-time data on the quality level of returns (high or low), the system state (in operation or down) and the reaching of defined thresholds (control parameters) in order to generate alerts of critical events.

Figure 5.9 presents an example in the form of a decision model illustrating the actions that should be taken for an effective dynamic production-inventory control. It shows that the implementation of both developed control policies and the proposed simulation-based optimization in an industrial context can use data collection and transmission technologies to continuously monitor and update changes in the inventory of finished products and the state of the system. This allows adjusting system operations. Joint manufacturing, remanufacturing and switching decisions are made according to the current state of production facilities and the stock level x_{F} in comparison with the optimal control parameters Z_1^*, Z_2^* and Z_3^* (see Section 5.5.1). The dotted line denotes the link between remanufacturing and manufacturing processes especially in the area of high risk of shortages ($x_{\mathrm{F}} \leq Z_1^*$, with $Z_1^* = 897$). Thus, when the facility F_2 is down, the manufacturing one F_1, which costs more, reduces its production rate by adapting it to the demand rate (see equation (5.7)). Likewise, the remanufacturing facility F_2 operates in this area at maximum rate using higher quality returns (category 1) but needs less time of treatment. Thereafter, it switches to lower quality returns (category 2) when the system considers that the inventory level x_{F} is high enough.

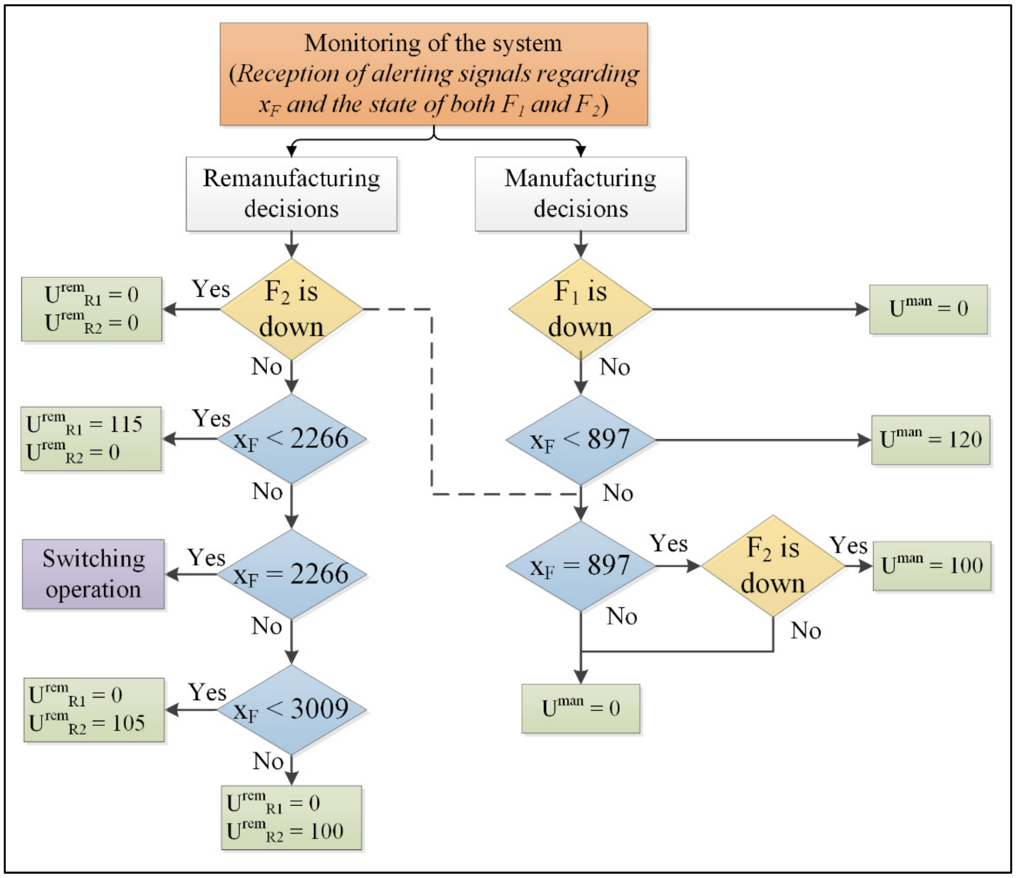

Figure 5.9 Implementation logic chart of the control policy #1

The proposed resolution approach also provides practical solutions to make any necessary adjustments improve both economic and environmental performances. As an illustration, five key system parameters are used to confirm the important aspect related to the interrelations between manufacturing and remanufacturing of different quality-based conditions of returns, and to show how decision makers could improve the system performances. These parameters are the proportion of defective returns (p_i, $i = \{1,2\}$), the maximum remanufacturing rates (U_{Ri}^{rem}) and the mean time to failure of the remanufacturing facility ($\mu_{T_{Fail}}$). Table 5.7

summarizes the results. Complementary performance indices are also calculated to help analyze and explain the obtained results. These indices are defined as a percentage of the customer demand and represent the proportion of the manufacturing (P^{man}), the remanufacturing that uses returns category 1 (P_{R1}^{rem}) and the remanufacturing that uses returns category 2 (P_{R2}^{rem}).

Table 5.7 Effect of some system parameters on production activities

Parameter	**Value**	**Parameters of the control policy #1**				**Remark**
		$\mathbf{P^{man}}$	$\mathbf{P_{R1}^{rem}}$	$\mathbf{P_{R2}^{rem}}$	**Total cost**	
		21.55	**63.03**	**15.43**	**2732.37**	**Basic case**
$\boldsymbol{p_1}$	0.03	20.826	64.192	14.988	2517.50	$P^{man}\downarrow, P_{R1}^{rem}\uparrow, P_{R2}^{rem}\downarrow$
	0.07	22.367	61.581	16.058	2941.56	$P^{man}\uparrow, P_{R1}^{rem}\downarrow, P_{R2}^{rem}\uparrow$
$\boldsymbol{p_2}$	0.08	21.517	62.814	15.675	2727.64	$P^{man}\downarrow, P_{R1}^{rem}\downarrow, P_{R2}^{rem}\uparrow$
	0.12	21.630	63.440	14.937	2736.40	$P^{man}\uparrow, P_{R1}^{rem}\uparrow, P_{R2}^{rem}\downarrow$
$\boldsymbol{U_{R1}^{rem}}$	105	23.925	59.631	16.451	3036,42	$P^{man}\uparrow, P_{R1}^{rem}\downarrow, P_{R2}^{rem}\uparrow$
	125	19.772	67.265	12.967	2473,15	$P^{man}\downarrow, P_{R1}^{rem}\uparrow, P_{R2}^{rem}\downarrow$
$\boldsymbol{U_{R2}^{rem}}$	100	22,500	62,368	15,139	2741,52	$P^{man}\uparrow, P_{R1}^{rem}\downarrow, P_{R2}^{rem}\downarrow$
	110	20,180	64,174	15,648	2717,30	$P^{man}\downarrow, P_{R1}^{rem}\uparrow, P_{R2}^{rem}\uparrow$
$\boldsymbol{\mu_{T_{Fail}}}$	45	29.033	55.805	15.168	2833,20	$P^{man}\uparrow, P_{R1}^{rem}\downarrow, P_{R2}^{rem}\downarrow$
	55	16.138	66.645	17.224	2631,85	$P^{man}\downarrow, P_{R1}^{rem}\uparrow, P_{R2}^{rem}\uparrow$

As illustrated in Table 5.7, when the proportion of defective returns (p_i) decreases, the system turns more towards the remanufacturing (P_{Ri}^{rem} increases since a higher number of returns are used for remanufacturing) and reduces the amount of manufactured products (P^{man} decreases). This is consistent with the increase of the maximum remanufacturing rate (U_{Ri}^{rem}). Indeed, when U_{Ri}^{rem} increases, it is logical to expect that the system will be in line with both economic (the total cost decreases) and environmental (P_{Ri}^{rem} increases) objectives by dedicating more production capacity to remanufacture the return category i. From a practitioner's point of view, managers could coordinate and harmonize production activities with the quality control which should allow receiving better quality of returns (Hlioui, Gharbi, & Hajji, 2015 ; Sonntag & Kiesmüller, 2017). Table 5.7 also shows that when $\mu_{T_{Fail}}$ increases, the system benefits from higher availability of the remanufacturing facility (F_2) in order to increase the number of remanufactured products (P_{R1}^{rem} and P_{R2}^{rem} increase), to reduce the risk of shortages of finished products and then reduce the total cost. This could be obtained through integrating preventive maintenance, which prevents failures and contributes to the maintaining of the remanufacturing facility in operation (H. Wang & Pham, 2006), in order to enhance economic and environmental performance levels.

In summary, such study shows that production managers can further enhance economic and environmental performances of the proposed policy by establishing a quality control plan of returns and implementing a preventive maintenance program for the remanufacturing facility.

5.9 Conclusion

Quality variability of returns and its effects on PPC have been one of the major concerns in the remanufacturing industry. The current paper addresses this issue of HMRSs where both returns and raw materials are used as inputs in a production process evolving dynamically in a stochastic context. The production facilities are capacitated and subject to random failures and repairs. Returns are categorized into two categories according to their quality condition and the time of treatment (the remanufacturing rate) of each category is random. A stochastic optimization model is developed while considering manufacturing, remanufacturing and switching decisions. In spite of the optimality condition complexity, the problem remains tractable and an efficient resolution approach coupling optimal control theory, numerical methods, simulation and statistics, is used to determine the optimal structure of the integrated policies as well as to optimize their control parameters by minimizing the total incurred cost. Such structure is a derivation of hedging point policy with stock-based switching decisions. In addition, other relevant control policies from the literature are also considered for comparative purposes. Both the efficiency of the adopted resolution approach and the economic performance of the considered control policies are illustrated through numerical examples and comparative studies. Our study reveals strong interactions between the production, the quality of returns and the quantity of finished products to keep in stock. Valuable insights are also generated for the coordination of manufacturing, remanufacturing and switching decisions for unreliable HMRSs, where the inventory of finished products are restored through both raw materials or returned units with different quality-based conditions. The proposed control policy practical implementation is discussed in the way that companies could control production processes and adjust their control parameters to the system changes. The authors believe that an efficient PPC that exploit the full potential of remanufacturing companies require both integrated control policies and modern information technologies of industry 4.0.

Further issues may be studied to investigate more complex problems. In this paper, two quality categories of returns are used whenever needed. However, the rate of returns could be random and the yield (the probability of a returned item to be remanufacturable) changes with the procurement quantity. Questions may arise regarding the case of multiple categories of returns based on quality, where used products are not always available in the market due to limited proportion compared to customer demand. An interesting extension is to develop a formal formulation of our problem while integrating stocks of returns and disposal options. Another important element addressed in this work is the consideration of dynamic and stochastic aspects related to production facilities. It would be meaningful to see how preventive maintenance could help to maintain production facilities in service and to prevent failures. These production facilities may deteriorate as a result of a combination of factors, including wear, imperfect repair, human interventions, the return of heterogeneous used products, etc. In this sense, data collection and transmission technologies could be considered to extend the possibilities of monitoring the status of the system and use the collected data for useful information about developing innovative industrial services like predictive maintenance.

CONCLUSION GÉNÉRALE

Aujourd'hui, un nombre croissant d'entreprises industrielles dans presque tous les grands secteurs perçoivent la valeur commerciale potentielle de l'intégration du processus de refabrication dans leur système existant. Les travaux de recherche de cette thèse s'inscrivent dans ce contexte en considérant plusieurs configurations de systèmes hybrides mono-produits non fiables qui utilisent à la fois des matières premières (mode de fabrication) et des produits récupérés (mode de refabrication) dans leurs processus de production. Pour les questions de planification et de contrôle de la production (PCP), les modèles d'aide à la décision développés dans la littérature présentent certaines lacunes et continuent de négliger certains éléments, tels que l'approvisionnement en matières premières et en retours (produits récupérés), la dynamique de stock de ces derniers, les pannes et réparations des installations de production, la variabilité de la qualité des retours, etc. Ces éléments font partie intégrante de l'environnement de production. En étudiant l'influence de ces éléments sur le processus de production, cette thèse a eu pour objectif d'établir des structures plus efficientes, en matière de coûts, de politiques de commande de production pour cette classe de systèmes. La performance économique de ces structures obtenues est illustrée à travers d'exemples numériques et des analyses comparatives.

Dans le premier article présenté au chapitre n°2, nous avons traité le problème de PCP pour les systèmes hybrides non fiables composés d'installations séparées dissociant les activités de fabrication de celles de refabrication. Des éléments importants, comme la stratégie d'approvisionnement des matières premières et des retours, la stratégie de rejets de ces retours et le dimensionnement de l'espace de stockage des matières premières, des retours et des produits finis ont été intégrés simultanément dans notre étude. Ces éléments font partie de l'environnement des systèmes hybrides, mais ils sont négligés dans les modèles développés de la littérature. Pour résoudre le problème, des politiques de commande pertinentes développées dans d'autres contextes proches du nôtre ont été considérées et analysées. Une nouvelle structure des politiques de commande combinant simultanément les activités de fabrication, de refabrication, de rejet de certains retours et d'approvisionnement en matières premières et en retours a été ainsi établie. Ensuite, une approche d'optimisation basée sur la simulation a été appliquée afin d'optimiser ses paramètres de commande qui minimise le coût total. Elle a aussi permis de mener une analyse de sensibilité approfondie montrant le comportement robuste et l'utilité de notre proposition. Pour tous les scénarios testés, les résultats ont également montré que notre proposition conduit à des économies de coûts considérables par rapport aux politiques de commande de production adaptées à partir de la littérature.

Dans le deuxième article, nous avons considéré un système hybride non fiable où une installation de production, évoluant dans un environnement dynamique et stochastique, requiert des actions de setup chaque fois qu'il passe du mode de fabrication à celui de refabrication et vice versa. Le problème PPC a été traité en utilisant une approche de solution alternative, qui consiste à adapter trois politiques de commande de production et de setup trouvées dans la littérature à notre contexte en intégrant simultanément l'option de rejets et le dimensionnement des espaces de stockage. Une analyse approfondie a été ensuite réalisée pour déterminer les forces et les faiblesses de chacune des politiques de commande et améliorer leurs caractéristiques. Dans ce sens, une approche d'optimisation basée sur la simulation a été utilisée pour établir une meilleure structure des politiques de commande en matière de coûts. Cette approche, qui offre une technique puissante pour contrôler de tels systèmes complexes, a permis d'analyser l'effet d'une large gamme de paramètres système sur les paramètres de commande optimaux. Elle a aussi mis en évidence les fortes interactions entre les processus de production, les décisions de rejet des retours, les conditions de setup et les coûts générés.

Dans le troisième article, nous avons abordé le problème de PCP pour les systèmes hybrides non fiables composés d'installations de production séparées et communes. Cette configuration de systèmes vise à offrir une meilleure coordination entre les activités interdépendantes de fabrication et de refabrication. En contrôlant les taux de fabrication, de refabrication et de rejet des retours ainsi que la séquence de setup, nous avons utilisé la théorie de commande optimale en utilisant des techniques numériques pour développer une structure sous-optimale de politiques de commande pour le système étudié. Cette structure implique des règles de décision simples. Elle consiste en une combinaison de politiques à seuils critiques (en anglais, *Hedging*

Point Policies) pour contrôler les activités de production et de rejet des retours et une stratégie de setup basée sur le niveau du stock de produits finis. Trois autres politiques de commande développées dans la littérature pour d'autres configurations de systèmes hybrides ont été adaptées dans notre contexte, puis analysées et comparées à notre proposition sur un large éventail de paramètres. Ceci a été réalisé en utilisant une approche d'optimisation basée sur la simulation. Nos résultats suggèrent qu'une configuration composée d'installations de production séparées et communes et soumise au contrôle de la politique de commande proposée donne de meilleures performances en matière de coûts. Ce travail a aussi permis d'apporter des informations précieuses sur la manière dont les décisions interdépendantes de setup, de fabrication de nouveaux produits et de refabrication ou de rejet des retours peuvent être efficacement coordonnées.

Dans le quatrième article, nous avons introduit la variabilité de la qualité des retours dans le problème de PPC d'un système hybride de fabrication-refabrication non fiable. Ce système utilise les retours et les matières premières comme intrants dans son processus de production, qui peut produire une proportion de produits finis non conformes aux exigences des clients. Cette proportion dépend de la qualité des unités utilisées de matières premières et de retours. Une classification des retours selon la qualité a été également considérée pour les classer en deux catégories distinctes selon le temps requis pour leur traitement ainsi que la proportion des unités défectueuses. Ainsi, des opérations de setup sont nécessaires lors d'un changement de catégories de retours pour le processus de refabrication. Un modèle d'optimisation stochastique a été développé en tenant compte des décisions de fabrication, de refabrication et de setup. Une approche de résolution combinant des méthodes numériques, la simulation et des analyses statistiques a été par la suite utilisée pour déterminer la structure optimale des politiques de commande intégrées et optimiser leurs paramètres qui minimisent le coût total. D'autres structures de politiques de commande trouvées dans la littérature ont été également considérées à des fins comparatives. La performance économique de la structure obtenue ainsi que l'utilité de l'approche adoptée ont été illustrées à travers un exemple numérique et une analyse comparative. Des propositions d'implantation et de mise en œuvre de la structure obtenue des politiques de commande intégrées ont été également discutées dans la manière dont les entreprises peuvent contrôler les processus de production et de setup et ajuster leurs paramètres aux changements du système.

Les travaux de recherche menés dans cette thèse nous ont permis d'atteindre nos objectifs et d'apporter des contributions scientifiques originales à la recherche sur la planification et le contrôle de production des systèmes hybrides de fabrication-refabrication. Les structures de politiques de commande développées répondent mieux aux préoccupations des gestionnaires de production en permettant une gestion efficace du flux des retours et des matières premières ainsi que celle du stock des produits finis. Ce travail a montré que la prise en compte de certains éléments clés qui reflètent la réalité manufacturière (par exemple, l'approvisionnement en matières premières, la variabilité en qualité des retours, la dynamique des stocks) dans une perspective de contrôle intégré conduit à de meilleures performances. Il confirme également l'importance de combiner ces politiques de commande à des configurations de systèmes flexibles qui représente leurs caractéristiques (par exemple, taux de retours faible ou élevé). Les travaux de cette thèse forment une base solide pour des travaux futurs.

TRAVAUX FUTURS

Les travaux de cette thèse ouvrent plusieurs axes de recherche. Parmi ceux-ci, les orientations suivantes :

- les structures de politiques de commande obtenue dans nos travaux peuvent être étendues à des systèmes plus complexes, impliquant plusieurs produits finis et plusieurs installations de production séparées et communes. En plus de la taille des systèmes, l'incertitude est l'un des attributs de la complexité comme nous l'avons montré dans cette thèse. Cependant, plusieurs autres sources d'incertitude peuvent être prises en compte, notamment celles relatives à la demande des clients, le délai de setup, le temps d'acquisition des retours, le taux de production, etc. Une étude de leur impact sur les paramètres de commande est nécessaire. Il s'agit d'une importante direction de recherche vers une application à des industries sujettes à des aléas qui affectent la performance économique, un domaine vaste avec des sujets qui nécessitent des études plus approfondies. Des collaborations industrielles peuvent être développées pour travailler sur des cas réels. Dans ces cas, l'approche d'optimisation basée sur la simulation constitue un atout considérable qui offre un outil puissant pour contrôler de tels systèmes complexes.

- à l'exception du premier article (présenté dans le chapitre nº2), nos travaux de recherche considèrent un flux de retours continu et déterministe. Cependant, la situation est très différente dans la pratique. Des études ont montré que la quantité d'acquisitions des produits d'occasion (quantité des produits récupérés) est stochastique et sensible au prix d'acquisition (Bakal & Akcali, 2006 ; X. Li, Li, & Saghafian, 2013 ; Zouadi, Yalaoui, & Reghioui, 2018). Ils ont également défini plusieurs paramètres du système qui influencent les prix d'acquisition, et donc la quantité des produits récupérés et refabriqués. Dans ce sens, les travaux futurs peuvent étudier plusieurs politiques d'acquisition de retours ainsi que leur intégration dans la planification et le contrôle de la production. Ils peuvent considérer des politiques contrôlées par des compensations accordées aux clients afin de stimuler le taux de retour et le niveau de qualité des produits d'occasion et analyser leur impact sur la performance économique obtenue. Finalement, plusieurs structures de collecte des produits d'occasion peuvent être aussi explorées (par exemple, interne ou sous-traitance de ce processus à des collecteurs tiers indépendants).

- le système adopté dans le quatrième article (présenté dans le chapitre n°5) considère deux catégories de retours basées sur leur niveau de qualité et la proportion des unités défectueuses. Cependant, plusieurs autres questions, du côté pratique et théorique (formulation analytique), peuvent être traitées pour explorer ce problème d'incertitude relative à la qualité des retours au sein des systèmes hybrides de fabrication-refabrication. Parmi lesquelles figurent le nombre de catégories à adopter et le temps de traitement de chacune. Une catégorie de retours à rejeter devrait également étudier en incluant un coût d'opportunité, car les produits rejetés pourraient perdre l'opportunité d'être une valeur de réutilisation plus élevée pour le fabricant. En fait, le processus de classification des retours en entier peut être étudié, incluant le test à 100% et d'autres méthodes de tri (par exemple, l'inspection par échantillonnage). En réalité, les procédures de classification exhaustives sont considérablement affectées par le coût de la méthode de tri et il n'est pas toujours possible d'appliquer une technique suffisamment précise à faible coût (Panagiotidou et al., 2013). Une extension intéressante de nos travaux est la considération d'une pratique de contrôle de la qualité plus élargie intégrant la matière première, les retours ou les produits finis.

- un autre élément important abordé dans ce travail est la prise en compte des aspects dynamiques et stochastiques liés aux installations de production. Il serait intéressant de voir comment la maintenance préventive pourrait contribuer à la prévention des pannes et au maintien en service des installations de production. Ces installations peuvent également se détériorer en raison d'une combinaison de facteurs, notamment l'usure, les réparations imparfaites, les interventions humaines, etc. Dans ce sens, des technologies de collecte et de transmission de données pourraient être envisagées pour étendre les possibilités de surveillance de l'état du système et utiliser les données collectées pour obtenir des informations utiles sur le développement de techniques industrielles innovantes comme la maintenance prédictive. Cet aspect constitue aussi une avenue de recherche.

- les différents travaux de recherche de cette thèse utilisent le coût comme le seul critère de performance. Toutefois, les systèmes hybrides de fabrication-refabrication adoptés aident également à réduire le fardeau environnemental en réduisant les déchets et à récupérer les ressources et l'énergie déjà consommées dans la fabrication d'origine des produits. Il serait intéressant d'équilibrer le développement économique et la protection de l'environnement dans des travaux futurs. Ainsi, le problème de PCP des systèmes hybrides peut être étudié en vertu des réglementations de la taxe sur le carbone et des systèmes de plafonnement et d'échange (en anglais, Cap and Trade Systems). Les effets de ces réglementations sur les économies de coût et les émissions totales de carbone peuvent être analysés. Parmi les approches proposées figurent le contrôle réglementaire (en anglais, Regulatory Control Approach) utilisé dans (Jaber, Glock, & El Saadany, 2013) pour inciter les gestionnaires de production à respecter les normes et les règles qui stipulent que durant chaque période de contrôle, si la quantité d'émissions de gaz à effet de serre dépasse un seuil fixé par une réglementation, la quantité excédentaire est pénalisée avec un coût environnemental.

ANNEXE I

STATISTICAL ANALYSIS

A 3^4 response surface design is selected since we have four independent variables (Z_{FP}, δ, Q_{RM} and Z_R) at three levels each. Recall that the parameter δ replaces S_{RM} in the DOE. It is defined by: $S_{RM} = \delta . Q_{RM}$, $\delta \in [0,1[$. This design gives more accurate results since each interaction is estimated separately. Five replications are used for each combination of control factors. This leads to a total of 405 simulation runs. Each run is conducted for 500,000 units of time which ensure the steady state is met and it takes only 5 seconds on average for each on a computer with a 3.30 GHz CPU. Several preliminary runs made offline to set the levels of control factors representing the domain of interest. An add-in integrated in the Arena simulation software called OptQuest is also used to explore the area where the optimal solution can be found. This area will be refined using DOE combined with RSM to determine the optimal control parameters.

An analysis of variance (ANOVA) and other statistical analyses such as the response surface generation and the calculation of the regression coefficients are then conducted using the software Statgraphics and simulation results. A validation of the conformity of the regression model is also performed based on an analysis of the residual normality and of the homogeneity of variance. The adjusted correlation coefficient (R^2) values obtained show that our model explains more than 93.1% and 99.05% of the variability of the expected finished product function cost (C_{FP}) as well as that of raw materials and returns ($C_{RM\&R}$) respectively. For the total cost function (sum of C_{FP} and $C_{RM\&R}$), all the main factors (Z_{FP}, δ, Q_{RM} and Z_R), their interactions and their quadratic effects (Z_{FP}^2, δ^2, Q_{RM}^2 and Z_R^2) are significant at a 95% level of significance (see Figure-A I-1).

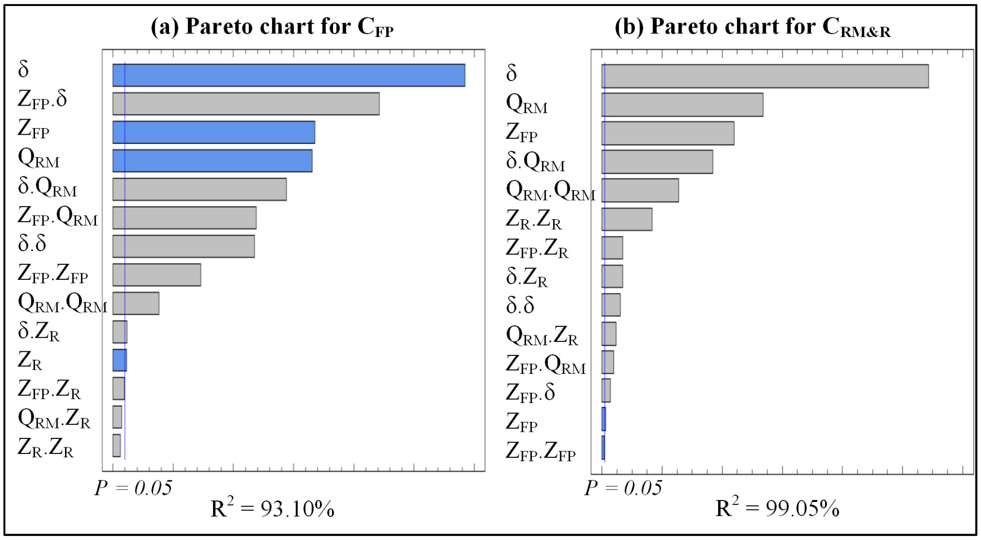

Figure-A I-1 Pareto Chart under the integrated control policies

ANNEXE II

PROPERTIES OF THE VALUE FUNCTION

Some properties of the value function are given below showing that it satisfies a set of coupled partial derivatives equations (HJB: Hamilton Jacobi Bellman) derived from the application of the dynamic programming principal. In our case, the presence of state constraints needs to be dealt with separately and it leads to some boundary conditions to be considered at inner points of S.

Proposition A.II.1

The value function given by (4.7) is convex and continuous on S^0, and satisfies the condition $|v(z,\alpha) - v(z',\alpha)| \leq C_1(1 + |z|^{K_g} + |z'|^{K_g}).|z - z'|$.

Proof: considering proposition (P4.1), the proof is very similar to (Lou, Sethi, & Zhang, 1994 ; Sethi & Zhang, 1994 ; Yong, 1989) given that we consider the interior of the state space S denoted by S^0.

Based on the dynamic programming principle and following (Sethi & Zhang, 1994), if we consider the interior of the state space S denoted by S^0, it can be shown that the value function is locally Lipschitz and is the unique viscosity solution of the resulting optimality conditions, which are formally given by:

$$min\left\{\begin{array}{l} \min\limits_{p\in A_p}\left\{\begin{array}{c}(u_R - u_{2rem} - u_{dis}).(v_i)_{x_R} + (u_1 + u_{2man} + u_{2rem} - d).(v_i)_{x_F} \\ +g(x_R, x_F, p) + \sum\limits_{\beta\neq\alpha} q_{\alpha\beta}\big((v_i)(x_R, x_F, \beta) - (v_i)(x_R, x_F, \alpha)\big)\end{array}\right\} - \rho.(v_i)(x_R, x_F, \alpha)\,; \\ \min\limits_{j\neq i}\left\{R_{ij}\big(x_R, x_F, p, D_s^{ij}\big) + e^{-\rho D_s^{ij}}(v_j)\begin{pmatrix} x_R + u_R D_s^{ij}, x_F \\ +(U_1^{max} - d)D_s^{ij}, 1\end{pmatrix}\right\} - (v_i)(x_R, x_F, \alpha)\end{array}\right\} = 0$$

(A II-1)

Where $v_x(.)$, denotes the gradient of $v_x(.)$ With respect to x.

Definition A.II.1

A function $\mathrm{v}(.) \in \mathrm{C}(\mathrm{S}) \equiv \{\text{set of continuous function on S}\}$ is called a viscosity sub-solution (super-solution) of (A II-1), if for any $\varphi(.) \in C^1(S)$ with $v(.) - \varphi(.)$ attaining a local maximum (minimum) at $z \in S$, then:

$$\rho.(v_i)(x_R, x_F, \alpha) - \min_{p \in A_p} \left\{ \begin{gathered} (u_R - u_{2rem} - u_{dis}).(v_i)_{x_R} \\ +(u_1 + u_{2man} + u_{2rem} - d).(v_i)_{x_F} \\ +g(x_R, x_F, p) + \sum_{\beta \neq \alpha} q_{\alpha\beta}\big((v_i)(x_R, x_F, \beta) - (v_i)(x_R, x_F, \alpha)\big) \end{gathered} \right\} \\ \leq 0 (\geq 0)$$

Or

$$(v_i)(x_R, x_F, \alpha) - \min_{j \neq i} \left\{ R_{ij}\left(x_R, x_F, p, D_s^{ij}\right) + e^{-\rho T_s^{ij}} (v_j) \begin{pmatrix} x_R + u_R D_s^{ij}, x_F \\ +(U_1^{max} - d)\, D_s^{ij}, 1 \end{pmatrix} \right\} \leq 0\ (\geq 0)$$

Definition A.II.2

A function $\mathrm{v}(.) \in \mathrm{C}(\mathrm{S}) \equiv \{\text{set of continuous function on S}\}$, is called a viscosity solution if it is both a sub-solution and super-solution.

Theorem A.II.1

The value function $\mathrm{v}(\mathrm{x_R}, \mathrm{x_F}, \alpha)$ is a viscosity solution (see definition A.II.2) of the HJB equations (A II-1) on S^0.

Proof:

The proof can be developed, as in (Sethi & Thompson, 2000), by considering the proposition A.II.1 and the dynamic programming principle.

Because we are faced with a state-constrained problem, we need to shape the value function on the boundary of S. To state these boundary conditions, we follow the same theory introduced in (Capuzzo-Dolcetta & Lions, 1990). In their work they have shown that, for state constrained problems, we have to consider the solution of the HJB equations as viscosity solution inside S and viscosity super-solution on the boundaries (, ∂S). The property that $v(x_R, x_F, \alpha)$ is a viscosity super-solution on ∂S plays the role of a boundary condition, which can be given by:

$$\rho.(v_i)(x_R, x_F, \alpha) - \min_{p \in A_p} \left\{ \begin{array}{c} (u_R - u_{2rem} - u_{dis}).(v_i)_{x_R} \\ +(u_1 + u_{2man} + u_{2rem} - d).(v_i)_{x_F} + g(x_R, x_F, p) \\ + \sum_{\beta \neq \alpha} q_{\alpha\beta}\big((v_i)(x_R, x_F, \beta) - (v_i)(x_R, x_F, \alpha)\big) \end{array} \right\} \geq 0, \text{on } \partial S \quad \text{(A II-2)}$$

Or

$$(v_i)(x_R, x_F, \alpha) - \min_{j \neq i} \left\{ R_{ij}\big(x_R, x_F, p, D_s^{ij}\big) + e^{-\rho D_s^{ij}} (v_j)\big(x_R + u_R D_s^{ij}, x_F + (U_1^{max} - d) D_s^{ij}, 1\big) \right\} \geq 0, \text{ on } \partial S$$

ANNEXE III

NUMERICAL RESOLUTION

The optimality conditions are a set of coupled partial derivatives equations (HJB) very difficult to solve analytically. Following the development of (Kushner & Dupuis, 1992), the solution of the numerical approximation of the optimality conditions (A II-1) may be obtained by either successive approximation or policy improvement techniques.

Let h_{x_R} and h_{x_F} denote the lengths of the finite difference interval of the variable x_R and x_F, respectively. Using the finite difference approximation, $v_i(x_R, x_F, \alpha)$ could be given by $(v_i)^{h_{x_R}}(x_R, x_F, \alpha)$, $(v_i)^{h_{x_F}}(x_R, x_F, \alpha)$ and the gradients $(v_i)_{x_R}(x_R, x_F, \alpha)$ and $(v_i)_{x_F}(x_R, x_F, \alpha)$ by:

$$(v_i)_{x_R}(x_R, x_F, \alpha) = \begin{cases} \frac{1}{h_{x_R}}\left((v_i)^{h_{x_R}}\left(x_R + h_{x_R}, x_F, \alpha\right) - (v_i)^{h_{x_R}}(x_R, x_F, \alpha)\right) & if\ u_R - u_{2rem} - u_{dis} \geq 0 \\ \frac{1}{h_{x_R}}\left((v_i)^{h_{x_R}}(x_R, x_F, \alpha) - (v_i)^{h_{x_R}}\left(x_R - h_{x_R}, x_F, \alpha\right)\right) & if\ u_R - u_{2rem} - u_{dis} < 0 \end{cases}$$

$$(v_i)_{x_F}(x_R, x_F, \alpha) = \begin{cases} \frac{1}{h_{x_F}}\left((v_i)^{h_{x_F}}\left(x_R, x_F + h_{x_F}, \alpha\right) - (v_i)^{h_{x_F}}(x_R, x_F, \alpha)\right) & if\ u_1 + u_{2man} + u_{2rem} - d \geq 0 \\ \frac{1}{h_{x_F}}\left((v_i)^{h_{x_F}}(x_R, x_F, \alpha) - (v_i)^{h_{x_F}}\left(x_R, x_F - h_{x_F}, \alpha\right)\right) & if\ u_1 + u_{2man} + u_{2rem} - d < 0 \end{cases}$$

Let: $\psi^h(p_1, p_2, \alpha, \rho) = \rho + |q_{\alpha\alpha}| + \frac{|p_1|}{h_{x_R}} + \frac{|p_2|}{h_{x_F}}$, With, $p_1 = u_R - u_{2rem} - u_{dis}$ and $p_2 = u_1 + u_{2rem} + u_{2man} - d$.

$$(\Gamma_i)^{x_R}\left(h_{x_R}, x_R, x_F, p_1, \alpha\right) = \frac{|p_1|}{h_{x_R}}\begin{pmatrix} (v_i)^{h_{x_R}}\left(x_R + h_{x_R}, x_F, \alpha\right) I(p_1 \geq 0) \\ +(v_i)^{h_{x_R}}\left(x_R - h_{x_R}, x_F, \alpha\right) I(p_1 < 0) \end{pmatrix}$$

$$(\Gamma_i)^{x_F}\left(h_{x_F}, x_R, x_F, p_2, \alpha\right) = \frac{|p_2|}{h_{x_F}}\begin{pmatrix} (v_i)^{h_{x_F}}\left(x_R, x_F + h_{x_F}, \alpha\right) I(p_2 \geq 0) \\ +(v_i)^{h_{x_F}}\left(x_R, x_F - h_{x_F}, \alpha\right) I(p_2 < 0) \end{pmatrix}$$

For convenience in notation, let $h_{x_R} = h_{x_F} = h$. With this approximation, the HJB equations (A.1) are expressed in terms of $(v_i)^h(x_R, x_F, \alpha)$ as follows:

$$(v_i)^h(x_R, x_F, \alpha)$$
$$= min\left\{\begin{array}{l} \underset{p \in A_p}{min}\left\{\left(\psi^h(p_1, p_2, \alpha, \rho)\right)^{-1} \times \begin{pmatrix} (\Gamma_i)^{x_R}\left(h_{x_R}, x_R, x_F, p_1, \alpha\right) + (\Gamma_i)^{x_F}\left(h_{x_F}, x_R, x_F, p_2, \alpha\right) \\ +g(x_R, x_F, p) + \sum_{\beta \neq \alpha} q_{\alpha\beta}\left((v_i)^h(x_R, x_F, \beta)\right) \end{pmatrix}\right\}; \\ \underset{j \neq i}{min}\left\{R_{ij}\left(x_R, x_F, p, D_s^{ij}\right) + e^{-\rho D_s^{ij}}\left(v_j\right)^h\left(x_R + u_R D_s^{ij}, x_F + (U_1^{max} - d) D_s^{ij}, 1\right)\right\} \end{array}\right\}$$

The implementation of the successive approximation technique needs the use of a finite grid denoted herein G_h, where h is the length of the finite difference interval of the variables x_R and x_F. Thus, we need to define some boundary conditions to describe the behaviour of the system at the borders of G_h. These boundary conditions are necessary but with a little influence since the value function is Lipschitz. In addition, if we consider that the optimal policy changes rarely if we go over the boundary of our grid, then the optimal solution will never be at the boundaries of the domain. The considered boundary conditions respect equation (A II-1) and the development of Appendix II.

The computation domain CD is defined as follows:

$$CD = \left\{(x_R, x_F): 0 \leq x_R \leq x_R^{sup}, -x_F^{sup} \leq x_F \leq x_F^{sup}\right\} \qquad \text{(A III-1)}$$

With x_R^{sup} and x_F^{sup} are given positive constants. The successive approximation algorithm is given by six steps for a given finite difference interval h and is implemented following the same details in (Hajji et al., 2004). This algorithm is applied to solve the optimality conditions for the considered system under study.

ANNEXE IV

PROPERTIES OF THE VALUE FUNCTION

To solve the optimal control problem, the value function of our problem need to be studied using the principle of dynamic programming. As in (Suresh P Sethi & Zhang, 1994), the value function can be shown locally Lipschitz and the unique solution of the following (HJB: Hamilton Jacobi Bellman) optimality equations.

$$\rho.(\mathrm{v})(x_F,\alpha) = \min_{p\in \mathrm{A}} \left\{ \begin{array}{c} (u^{man} + u_{R1}^{rem} + u_{R2}^{rem} - d).(\mathrm{v})_{x_F} \\ +g(x_F,p) + \sum_{\gamma\neq\vartheta} q_{\gamma\vartheta}\big((\mathrm{v})(x_F,\gamma) - (\mathrm{v})(x_F,\alpha)\big) \end{array} \right\} \tag{A IV-1}$$

Where $v_x(.)$, is the gradient of $v(.)$ Associated to x.

Definition A.IV.1

A given continuous function $\mathrm{v}(.)$ on S (set C(S)) is called a viscosity subsolution (respectively, supersolution) of (A IV-1), if for any $\varphi(.) \in C^1(S)$ with $v(.) - \varphi(.)$ attaining a local maximum (respectively, minimum) at $z \in S$, then,

$$\rho.(v)(x_F,\alpha) - \min_{p\in \mathrm{A}} \left\{ \begin{array}{c} (u^{man} + u_{R1}^{rem} + u_{R2}^{rem} - d).(\mathrm{v})_{x_F} \\ +g(x_F,p) + \sum_{\gamma\neq\vartheta} q_{\gamma\vartheta}\big((\mathrm{v})(x_F,\gamma) - (\mathrm{v})(x_F,\alpha)\big) \end{array} \right\} \leq 0 (\geq 0) \tag{A IV-2}$$

Definition A.IV.2

A given continuous function $\mathrm{v}(.)$ on S (set C(S)) is a “viscosity-solution” if it is both a subsolution and supersolution.

Theorem A.IV.1

Based on definitions A.IV.1 and A.IV.2, the value-function $\mathrm{v}(\mathrm{x_F},\alpha)$ is a “viscosity-solution” of the Hamilton Jacobi Bellman equations (A IV-1) in the state space.

Proof:

The theorem can be easily proven, based on proposition A.IV.1, and following (S. P. Sethi & Thompson, 2000).

ANNEXE V

NUMERICAL RESOLUTION

The Hamilton Jacobi Bellman equations define the optimality conditions of the problem. These equations are very difficult to solve analytically. Based on previous developments as in (Kushner & Dupuis, 1992), we can solve by approximation techniques the numerical form of the Hamilton Jacobi Bellman equations.

Let's define a difference interval h_{x_F} of the variable x_F. Using the finite difference approximation, $v(\mathrm{x_F}, \alpha)$ is approximated by $(v)^{h_{x_F}}(x_F, \alpha)$ and the gradient $(v)_{\mathrm{x_F}}(\mathrm{x_F}, \alpha)$ by:

$$(v)_{\mathrm{x_F}}(\mathrm{x_F}, \alpha) = \begin{cases} \dfrac{1}{\mathrm{h_{x_F}}}\left((v)^{\mathrm{h_{x_F}}}\left(\mathrm{x_F} + \mathrm{h_{x_F}}, \alpha\right) - (v)^{\mathrm{h_{x_F}}}(\mathrm{x_F}, \alpha)\right) & \text{if } u^{man} + u_{R1}^{rem} + u_{R2}^{rem} - d \geq 0 \\ \dfrac{1}{\mathrm{h_{x_F}}}\left((\mathrm{v})^{\mathrm{h_{x_F}}}(\mathrm{x_F}, \alpha) - (v)^{\mathrm{h_{x_F}}}\left(\mathrm{x_F} - \mathrm{h_{x_F}}, \alpha\right)\right) & \text{if } u^{man} + u_{R1}^{rem} + u_{R2}^{rem} - d < 0 \end{cases}$$

Let: $\psi^{\mathrm{h}}(\mathrm{p_2}, \alpha, \rho) = \rho + |\mathrm{q}_{\alpha\alpha}| + \frac{|\mathrm{p_2}|}{\mathrm{h_{x_F}}}$, With, $\mathrm{p_2} = u^{man} + u_{R1}^{rem} + u_{R2}^{rem} - d$.

$$(\Gamma)^{x_F}\left(h_{x_F}, x_F, p_2, \alpha\right) = \frac{|p_2|}{h_{x_F}} \begin{pmatrix} (v)^{h_{x_F}}\left(x_F + h_{x_F}, \alpha\right) Ind\{p_2 \geq 0\} \\ +(v_i)^{h_{x_F}}\left(x_F - h_{x_F}, \alpha\right) Ind\{p_2 < 0\} \end{pmatrix}$$

For convenience in notation, let $h_{x_F} = h$. The HJB equations (A IV-1) are then expressed as follows:

$$(v)^h(x_F, \alpha) = \min_{p \in A}\left\{\left(\psi^h(p_2, \alpha, \rho)\right)^{-1} \times \left((\Gamma)^{x_F}\left(h_{x_F}, x_F, p_2, \alpha\right) + g(x_F, p) + \sum_{\gamma \neq \vartheta} q_{\gamma\vartheta}\left((v)^h(x_F, \gamma)\right)\right)\right\}$$

To implement the numerical approximation technique, one need to define a finite grid (called G_h in the rest of the paper). Given that we approximated an infinite resolution domain by a finite one, some boundary conditions at the borders of G_h should be defined. In this paper, we considered some boundary conditions related to equation (A IV-1) and Appendix IV.

Let D, the considered resolution domain:

$$D = \{(x_F), -x_F^{inf} \leq x_F \leq x_F^{sup}\} \quad \text{(A V-1)}$$

With x_F^{inf} and x_F^{sup} consist of positive constants. The numerical approximation algorithm applied to solve the HJB equations of the studied system follows the details given in (Hajji et al., 2004).

ANNEXE VI

ARTICLES DE CONFÉRENCES

Assid, M., Gharbi, A., & Hajji, A. (2020). Commande optimale de systèmes hybrides de fabrication-refabrication utilisant des installations dédiée et flexible. *12th International Conference on Modeling, Optimization and Simulation, Agadir, Morocco, November 12-14, 2020*.

Assid, M., Gharbi, A., & Hajji, A. (2019). Contrôle de production, d'approvisionnement et de qualité pour un système manufacturier non fiable. *13th International Congress of Industrial Engineering and conference QUALITA, Montréal, QC, Canada, June 25-28, 2019*.

Assid, M., Gharbi, A., & Hajji, A. (2018). Planification simultanée de la production, de la refabrication et du setup pour un système hybride non fiable. *12th International Conference on Modeling, Optimization and Simulation, Toulouse, France, June 27-29, 2018*.

Assid, M., Gharbi, A., & Hajji, A. (2017). Planification simultanée de la production et de la sous-traitance de différents types de produits. *12th International Congress of Industrial Engineering, Compiègne, France, May 3-5, 2017*.

Assid, M., Gharbi, A., & Hajji, A. (2016). Planification de la production et de la maintenance préventive opportuniste pour un système manufacturier non fiable produisant deux types de produits. *11th International Conference on Modeling, Optimization and Simulation, Montreal, Canada, August 22-24, 2016*.

Assid, M., Gharbi, A., & Hajji, A. (2015). Étude de comparaison de politiques de commande pour un système manufacturier non fiable avec setup. *11th International Congress of Industrial Engineering, Québec, Canada, October 26-28, 2015*.

Assid, M., Gharbi, A., & Hajji, A. (2015). Production Planning and Opportunistic Preventive Maintenance for Unreliable One-Machine Two-Products Manufacturing Systems. *15th IFAC Symposium on Information Control Problems in Manufacturing, Ottawa, ON, 48 (3), 478-483*.

LISTE DE RÉFÉRENCES BIBLIOGRAPHIQUES

Afshar-Bakeshloo, M., Bozorgi-Amiri, A., Sajadi, S. M., & Jolai, F. (2018). A multi-objective Environmental Hedging Point Policy with customer satisfaction criteria. *Journal of Cleaner Production*, *179*, 478-494. https://doi.org/10.1016/j.jclepro.2018.01.041

Ahiska, S. S., Gocer, F., & King, R. E. (2017). Heuristic inventory policies for a hybrid manufacturing/remanufacturing system with product substitution. *Computers and Industrial Engineering*, *114*(April), 206-222. https://doi.org/10.1016/j.cie.2017.10.014

Akçali, E., & Çetinkaya, S. (2011). Quantitative models for inventory and production planning in closed-loop supply chains. *International Journal of Production Research*, *49*(8), 2373-2407. https://doi.org/10.1080/00207541003692021

Akella, R., & Kumar, P. (1986). Optimal control of production rate in a failure prone manufacturing system. *IEEE Transactions on Automatic control*, *31*(2), 116-126.

Alinovi, A., Bottani, E., & Montanari, R. (2012). Reverse Logistics: A stochastic EOQ-based inventory control model for mixed manufacturing/remanufacturing systems with return policies. *International Journal of Production Research*, *50*(5), 1243-1264.

Aras, N., Boyaci, T., & Verter, V. (2004). The effect of categorizing returned products in remanufacturing. *IIE Transactions*, *36*(4), 319-331.

Aras, N., Verter, V., & Boyaci, T. (2006). Coordination and Priority Decisions in Hybrid Manufacturing/Remanufacturing Systems. *Production and Operations Management*, *15*(4), 528-543. https://doi.org/10.1111/j.1937-5956.2006.tb00161.x

Assid, M., Gharbi, A., & Hajji, A. (2014). Joint production and setup control policies: An extensive study addressing implementation issues via quantitative and qualitative criteria. *International Journal of Advanced Manufacturing Technology*, *72*(5-8).

Assid, M., Gharbi, A., & Hajji, A. (2015). Joint production, setup and preventive maintenance policies of unreliable two-product manufacturing systems. *International Journal of Production Research*, *53*(15). https://doi.org/10.1080/00207543.2015.1030468

Assid, Morad, Gharbi, A., & Dhouib, K. (2015). Joint production and subcontracting planning of unreliable multi-facility multi-product production systems. *Omega International journal of management science*, *50*, 54-69. https://doi.org/10.1016/j.omega.2014.07.007

Assid, Morad, Gharbi, A., & Hajji, A. (2019). Production and setup control policy for unreliable hybrid manufacturing-remanufacturing systems. *Journal of Manufacturing Systems*, *50*(November 2018), 103-118. https://doi.org/10.1016/j.jmsy.2018.12.004

Assid, Morad, Gharbi, A., & Hajji, A. (2020). Production control of failure-prone manufacturing-remanufacturing systems using mixed dedicated and shared facilities. *International Journal of Production Economics*, *224*.

Atasu, A., Sarvary, M., & Van Wassenhove, L. N. (2008). Remanufacturing as a Marketing Strategy. *Management Science*, *54*(10), 1731-1746.

Atasu, A., & Van Wassenhove, L. N. (2010). Environmental legislation on product take-back and recovery. *Closed-Loop Supply Chains: New Developments to Improve the Sustainability of Business Practices*, 23-28.

Bakal, I. S., & Akcali, E. (2006). Effects of Random Yield in Remanufacturing with Price-Sensitive Supply and Demand. *Production and Operations Management*, *15*(3), 407-420.

Banks, J., Carson, J. S., Nelson, B. L., & Nicol, D. M. (2005). *Discrete-Event System Simulation* (Fourth Edi). Upper Saddle River, NJ : Pearson Education India.

Behret, H., & Korugan, A. (2009). Performance analysis of a hybrid system under quality impact of returns. *Computers and Industrial Engineering*, *56*(2), 507-520.

Berthaut, F., Gharbi, A., Kenné, J. P., & Boulet, J. F. (2010). Improved joint preventive maintenance and hedging point policy. *International Journal of Production Economics*, *127*(1), 60-72. https://doi.org/10.1016/j.ijpe.2010.04.030

Bulmuş, S. C., Zhu, S. X., & Teunter, R. (2013). Capacity and production decisions under a remanufacturing strategy. *International Journal of Production Economics*, *145*(1), 359-370. https://doi.org/10.1016/j.ijpe.2013.04.052

Cai, X., Lai, M., Li, X., Li, Y., & Wu, X. (2014). Optimal acquisition and production policy in a hybrid manufacturing/ remanufacturing system with core acquisition at different quality levels. *European Journal of Operational Research*, *233*(2), 374-382.

Capuzzo-Dolcetta, I., & Lions, P. L. (1990). Hamilton-Jacobi Equations With State Constraints. *Trans. Amer. Math. Soc.*, *318*(2), 643-683. https://doi.org/10.2307/2001324

Corum, A., Vayvay, Ö., & Bayraktar, E. (2014). The impact of remanufacturing on total inventory cost and order variance. *Journal of Cleaner Production*, *85*, 442-452.

Debo, L. G. ., Toktay, L. B. ., & Van Wassenhove, L. N. . (2006). Joint life-cycle dynamics of new and remanufactured products. *Production and Operations Management*, *15*(4), 498-513. https://doi.org/10.1111/j.1937-5956.2006.tb00159.x

Dev, N. K., Shankar, R., & Choudhary, A. (2017). Strategic design for inventory and production planning in closed-loop hybrid systems. *International Journal of Production Economics*, *183*, 345-353. https://doi.org/10.1016/j.ijpe.2016.06.017

Dobos, I. (2003). Optimal production-inventory strategies for a HMMS-type reverse logistics system. *International Journal of Production Economics*, *81-82*, 351-360.

Dominguez, R., Cannella, S., Ponte, B., & Framinan, J. M. (2019). On the dynamics of closed-loop supply chains under remanufacturing lead time variability. *Omega Int. J. Manag. Sci.*, 102106. https://doi.org/10.1016/j.omega.2019.102106

Driesch, H.-M., van Oyen, H. E., & Flapper, S. D. P. (2005). Recovery of car engines: the Mercedes-Benz case. Dans *Managing closed-loop supply chains* (pp. 157-166) : Springer.

El Saadany, A. M. A., & Jaber, M. Y. (2010). A production/remanufacturing inventory model with price and quality dependant return rate. *Computers and Industrial Engineering*, *58*(3), 352-362. https://doi.org/10.1016/j.cie.2009.01.017

Elhafsi, M., & Bai, S. X. (1996). Optimal production and setup control of a dynamic two-product manufacturing system: Analytical solution. *Mathematical and Computer Modelling*, *24*(3), 57-78. https://doi.org/10.1016/0895-7177(96)00100-8

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*.

Esmaeilian, B., Behdad, S., & Wang, B. (2016). The evolution and future of manufacturing: A review. *Journal of Manufacturing Systems*, *39*, 79-100.

Fang, C. C., Lai, M. H., & Huang, Y. S. (2017). Production planning of new and remanufacturing products in hybrid production systems. *Computers and Industrial Engineering*, *108*, 88-99. https://doi.org/10.1016/j.cie.2017.04.015

Fang, C., Liu, X., Pardalos, P. M., Long, J., Pei, J., & Zuo, C. (2017). A stochastic production planning problem in hybrid manufacturing and remanufacturing systems with resource capacity planning. *Journal of Global Optimization*, *68*(4), 851-878.

Feng, L., Zhang, J., & Tang, W. (2013). Optimal control of production and remanufacturing for a recovery system with perishable items. *International Journal of Production Research*, *51*(13), 3977-3994. https://doi.org/10.1080/00207543.2012.762133

Feng, L., Zhang, J., & Tang, W. (2016). Optimal Inventory Control and Pricing of Perishable Items Without Shortages. *IEEE Transactions on Automation Science and Engineering*, *13*(2), 918-931. https://doi.org/10.1109/TASE.2015.2425415

Ferguson, M. (2010). Strategic issues in closed-loop supply chains with remanufacturing. *Closed-loop supply chains: New developments to improve the sustainability of business practices*, 9-21.

Ferguson, M., & Toktay, L. B. (2006). The Effect of Competition on Recovery Strategies. *Production and Operations Management*, *15*(3), 351-368.

Flapper, S. D., Gayon, J. P., & Lim, L. L. (2014). On the optimal control of manufacturing and remanufacturing activities with a single shared server. *European Journal of Operational Research*, *234*(1), 86-98. https://doi.org/10.1016/j.ejor.2013.10.049

Fleischmann, M., Bloemhof-Ruwaard, J. M., Dekker, R., Van Der Laan, E., Van Nunen, J. A. E. E., & Van Wassenhove, L. N. (1997). Quantitative models for reverse logistics: A review. *European Journal of Operational Research*, *103*(1), 1-17.

Fleischmann, M., & Kuik, R. (2003). On optimal inventory control with independent stochastic item returns. *European Journal of Operational Research*, *151*(1), 25-37.

Francas, D., & Minner, S. (2009). Manufacturing network configuration in supply chains with product recovery. *Omega*, *37*(4), 757-769. https://doi.org/10.1016/j.omega.2008.07.007

Freiheit, T., Shpitalni, M., Huyz, S. J., & Korenyz, Y. (2004). Productivity of synchronized serial production lines with flexible reserve capacity. *International Journal of Production Research*, *42*(10), 2009-2027. https://doi.org/10.1081/00207540310001647596

Gayon, J. P., Vercraene, S., & Flapper, S. D. P. (2017). Optimal control of a production-inventory system with product returns and two disposal options. *European Journal of Operational Research*, *262*(2), 499-508. https://doi.org/10.1016/j.ejor.2017.03.018

Gershwin, S. B. (1994). *Manufacturing systems engineering*. Englewood Cliffs, NJ : PTR Prentice Hall.

Geyer, R., Van Wassenhove, L. N., & Atasu, A. (2007). The Economics of Remanufacturing Under Limited Component Durability and Finite Product Life Cycles. *Management Science*, *53*(1), 88-100. https://doi.org/10.1287/mnsc.1060.0600

Gharbi, A., Kenné, J. P., & Hajji, A. (2006). Operational level-based policies in production rate control of unreliable manufacturing systems with set-ups. *International Journal of Production Research*, *44*(3), 545-567. https://doi.org/10.1080/00207540500270364

Goodall, P., Rosamond, E., & Harding, J. (2014). A review of the state of the art in tools and techniques used to evaluate remanufacturing feasibility. *Journal of Cleaner Production*, *81*, 1-15. https://doi.org/10.1016/j.jclepro.2014.06.014

Gosavi, A. (2015). *Simulation-Based Optimization, parametric optimization techniques and reinforcement learning* (Second). New York, NY : Springer.

Govindan, K., & Soleimani, H. (2017). A review of reverse logistics and closed-loop supply chains: a Journal of Cleaner Production focus. *Journal of Cleaner Production*, *142*, 371-384. https://doi.org/10.1016/j.jclepro.2016.03.126

Govindan, K., Soleimani, H., & Kannan, D. (2015). Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future. *European Journal of Operational Research*, *240*(3), 603-626. https://doi.org/10.1016/j.ejor.2014.07.012

Guide Jr., V. Daniel R., Souza, G. C., Van Wassenhove, L. N., & Blackburn, J. D. (2006). Time value of commercial product returns. *Management Science*, *52*(8), 1200-1214.

Guide Jr., V. Daniel R., & Wassenhove, L. N. (2006). Closed-Loop Supply Chains: An Introduction to the Feature Issue (Part 1). *Production and Operations Management*, *15*(3), 345-350.

Guide Jr., V.D.R. (2000). Production planning and control for remanufacturing: Industry practice and research needs. *Journal of Operations Management*, *18*(4), 467-483.

Guide Jr, V. D. R., & Van Wassenhove, L. N. (2009). The Evolution of Closed Loop Supply Chain Research. *Operations Research*, *57*(1), 10-18.

Guide, V. D. R., Jayaraman, V., & Srivastava, R. (1999). Production planning and control for remanufacturing: a state-of-the-art survey. *Robotics and Computer-Integrated Manufacturing*, *15*(3), 221-230. https://doi.org/10.1016/S0736-5845(99)00020-4

Guo, J., & Ya, G. (2015). Optimal strategies for manufacturing/remanufacturing system with the consideration of recycled products. *Computers and Industrial Engineering*, *89*, 226-234. https://doi.org/10.1016/j.cie.2014.11.020

Hajji, A., Gharbi, A., & Kenne, J. P. (2004). Production and set-up control of a failure-prone manufacturing system. *International Journal of Production Research*, *42*(6), 1107-1130.

Hajji, A., Gharbi, A., & Kenne, J. P. (2009). Joint replenishment and manufacturing activities control in a two stage unreliable supply chain. *International Journal of Production Research*, *47*(12), 3231-3251. https://doi.org/10.1080/00207540701805612

Hlioui, R., Gharbi, A., & Hajji, A. (2015). Replenishment, production and quality control strategies in three-stage supply chain. *International Journal of Production Economics*, *166*, 90-102. https://doi.org/10.1016/j.ijpe.2015.04.015

Hlioui, R., Gharbi, A., & Hajji, A. (2017). Joint supplier selection, production and replenishment of an unreliable manufacturing-oriented supply chain. *International Journal of Production Economics*, *187*(November 2016), 53-67.

Ilgin, M. A., & Gupta, S. M. (2010). Environmentally conscious manufacturing and product recovery (ECMPRO): A review of the state of the art. *Journal of Environmental Management*, *91*(3), 563-591. https://doi.org/10.1016/j.jenvman.2009.09.037

Inderfurth, K. (1997). Simple optimal replenishment and disposal policies for a product recovery system with leadtimes. *OR Spectrum*, *19*(2), 111-122.

Inderfurth, K. (2004). Optimal policies in hybrid manufacturing/remanufacturing systems with product substitution. *International Journal of Production Economics*, *90*(3), 325-343.

Inderfurth, K., & Van Der Laan, E. (2001). Leadtime effects and policy improvement for stochastic inventory control with remanufacturing. *International Journal of Production Economics*, *71*(1-3), 381-390. https://doi.org/10.1016/S0925-5273(00)00135-3

Jaber, M. Y., Glock, C. H., & El Saadany, A. M. A. (2013). Supply chain coordination with emissions reduction incentives. *International Journal of Production Research*, *51*(1), 69-82. https://doi.org/10.1080/00207543.2011.651656

Kaminsky, P., & Kaya, O. (2009). Combined make-to-order / make-to-stock supply chains. *IIE Transactions*, *41*(2), 103-119. https://doi.org/10.1080/07408170801975065

Kelle, P., & Silver, E. A. (1989). Purchasing policy of new containers considering the random returns of previously issued containers. *IIE Transactions (Institute of Industrial Engineers)*, *21*(4), 349-354. https://doi.org/10.1080/07408178908966241

Kelton, W. D., Sadowski, R. P., & Zupick, N. B. (2015). Simulation with Arena. New York City. New York, NY : New York: McGraw-Hill Education.

Kenné, J. P., Dejax, P., & Gharbi, A. (2012). Production planning of a hybrid manufacturingremanufacturing system under uncertainty within a closed-loop supply chain. *International Journal of Production Economics*, *135*(1), 81-93.

Kenne, J. P., & Gharbi, A. (2000). Production planning problem in manufacturing systems with general failure and repair time distributions. *Production Planning and Control*, *11*(6), 581-588. https://doi.org/10.1080/095372800414142

Kiesmüller, G. P. (2003a). A new approach for controlling a hybrid stochastic manufacturing/remanufacturing system with inventories and different leadtimes. *European Journal of Operational Research*, *147*(1), 62-71.

Kiesmüller, G. P. (2003b). Optimal control of a one product recovery system with leadtimes. *International Journal of Production Economics*, *81-82*, 333-340.

Kiesmüller, Gudrun P., & Van der Laan, E. A. (2001). An inventory model with dependent product demands and returns. *International Journal of Production Economics*, *72*(1), 73-87. https://doi.org/10.1016/S0925-5273(00)00080-3

Kilic, O. A., Tunc, H., & Tarim, S. A. (2018). Heuristic policies for the stochastic economic lot sizing problem with remanufacturing under service level constraints. *European Journal of Operational Research*, *267*(3), 1102-1109.

Kim, E., Saghafian, S., & Van Oyen, M. P. (2013). Joint control of production, remanufacturing, and disposal activities in a hybrid manufacturing-remanufacturing system. *European Journal of Operational Research*, *231*(2), 337-348.

Kimemia, J. G., & Gershwin, S. B. (1983). An algorithm for the computer control of production in a flexible manufacturing system. *IIE Transactions*, *15*(4), 353-362.

King, A. M., Burgess, S. C., Ijomah, W., & Mcmahon, C. A. (2006). Reducing Waste: Repair, Recondition, Remanufacture or Recycle? *Sustainable Development*, *14*(December 2005), 257-267.

Kleijnen, J. P. C. (2015). Design and analysis of simulation experiments. Dans *International Workshop on Simulation* (pp. 3-22). New York, NY : Springer-Verlag.

Korugan, A., Dingeç, K. D., Önen, T., & Ateş, N. Y. (2013). On the quality variation impact of returns in remanufacturing. *Computers and Industrial Engineering*, *64*(4), 929-936.

Kouedeu, A. F., Kenné, J.-P., Dejax, P., Songmene, V., & Polotski, V. (2014). Production planning of a failure-prone manufacturing / remanufacturing system with production-dependent failure rates. *Applied Mathematics*, *5*(10), 1557-1572.

Kouedeu, A. F., Kenné, J.-P., Dejax, P., Victor, S., & Polotski, V. (2015). Stochastic models and numerical solutions for manufacturing/remanufacturing systems with applications to the printer cartridge industry. *Journal of Manufacturing Systems*, *37*, 662-671.

Kushner, H. J., & Dupuis, P. G. (1992). *Numerical Methods for Stochastic Control Problems in Continuous Time*. New York, NY : (s.n.).

Lage, M., & Godinho Filho, M. (2016). Production planning and control for remanufacturing: Exploring characteristics and difficulties with case studies. *Production Planning and Control*, *27*(3), 212-225. https://doi.org/10.1080/09537287.2015.1091954

Lange, U. (2017). *Resource efficiency through remanufacturing*. Berlin, Germany.

Lavoie, P., Gharbi, A., & Kenne, J.-P. (2010). A comparative study of pull control mechanisms for unreliable homogenous transfer lines. *International Journal of Production Economics*, *124*(1), 241-251.

Law, A. M., & Kelton, W. D. (1991). *Simulation modeling and analysis* (Vol. 2). New York, NY : McGraw-Hill New York.

Lee, C.-W., Doh, H.-H., & Lee, D.-H. (2015). Capacity and production planning for a hybrid system with manufacturing and remanufacturing facilities. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *229*(9), 1645-1653. https://doi.org/10.1177/0954405414539485

Li, S., Zhang, J., & Tang, W. (2015). Joint dynamic pricing and inventory control policy for a stochastic inventory system with perishable products. *International Journal of Production Research*, *53*(10), 2937-2950. https://doi.org/10.1080/00207543.2014.961206

Li, X., Li, Y., & Saghafian, S. (2013). A hybrid manufacturing/remanufacturing system with random remanufacturing yield and market-driven product acquisition. *IEEE Transactions on Engineering Management*, *60*(2), 424-437.

Liao, H., Deng, Q., & Wang, Y. (2017). Optimal acquisition and production policy for end-of-life engineering machinery recovering in a joint manufacturing/remanufacturing system under uncertainties in procurement and demand. *Sustainability (Switzerland)*, *9*(3), 1-19.

Liu, W., Ma, W., Hu, Y., Jin, M., Li, K., Chang, X., & Yu, X. (2019). Production planning for stochastic manufacturing/remanufacturing system with demand substitution using a hybrid ant colony system algorithm. *Journal of Cleaner Production*, *213*, 999-1010.

Lou, S., Sethi, S., & Zhang, Q. (1994). Optimal feedback production planning in a stochastic two-machine flowshop. *European Journal of Operational Research*, *73*(2), 331-345.

Lund. (1984). Remanufacturing. *Technology review*, *87*(2), 19–23.

Lund, R. T., & Hauser, W. (2003). *The remanufacturing industry: Anatomy of a giant*. *Department of Manufacturing Engineering, Boston …*. Boston, MA.

Macedo, P. B., Alem, D., Santos, M., Junior, M. L., & Moreno, A. (2016). Hybrid manufacturing and remanufacturing lot-sizing problem with stochastic demand, return, and setup costs. *International Journal of Advanced Manufacturing Technology*, *82*(5-8), 1241-1257. https://doi.org/10.1007/s00170-015-7445-z

Magnanini, M. C., & Tolio, T. (2020). Switching- and hedging- point policy for preventive maintenance with degrading machines: application to a two-machine line. *Flexible Services and Manufacturing Journal*, *32*(2), 241-271.

Marx-Gómez, J., Rautenstrauch, C., Nürnberger, A., & Kruse, R. (2002). Neuro-fuzzy approach to forecast returns of scrapped products to recycling and remanufacturing. *Knowledge-Based Systems*, *15*(1-2), 119-128.

Masoudipour, E., Amirian, H., & Sahraeian, R. (2017). A novel closed-loop supply chain based on the quality of returned products. *Journal of Cleaner Production*, *151*, 344-355.

Matsumoto, M., & Umeda, Y. (2011). An analysis of remanufacturing practices in Japan. *Journal of Remanufacturing*, *1*(1), 1-11. https://doi.org/10.1186/2210-4690-1-2

Mitra, S. (2016). Models to explore remanufacturing as a competitive strategy under duopoly. *Omega*, *59*, 215-227. https://doi.org/10.1016/j.omega.2015.06.009

Montgomery, D. C. (2012). *Design and analysis of experiments* (8th ed.). New York, NY : John Wiley & Sons.

Muckstadt, J. A., & Isaac, M. H. (1981). An analysis of single item inventory systems with returns. *Naval Research Logistics Quarterly*, *28*(2), 237-254.

Mukhopadhyay, S. K., & Ma, H. (2009). Joint procurement and production decisions in remanufacturing under quality and demand uncertainty. *International Journal of Production Economics*, *120*(1), 5-17.

Myers, R. H., Montgomery, D. C., & Anderson-Cook, C. M. (2016). *Response surface methodology: process and product optimization using designed experiments* (4th éd.). Hoboken, New Jersey : John Wiley & Sons.

Naeem, M. A., Dias, D. J., Tibrewal, R., Chang, P. C., & Tiwari, M. K. (2013). Production planning optimization for manufacturing and remanufacturing system in stochastic environment. *Journal of Intelligent Manufacturing*, *24*(4), 717-728.

Ndhaief, N., Nidhal, R., Hajji, A., & Bistorin, O. (2020). Environmental issue in an integrated production and maintenance control of unreliable manufacturing/remanufacturing systems. *International Journal of Production Research*, *58*(14), 4182-4200.

Ouaret, S., Kenné, J.-P., & Gharbi, A. (2018a). Stochastic optimal control of random quality deteriorating hybrid manufacturing/remanufacturing systems. *Journal of Manufacturing Systems*, *49*(September), 172-185. https://doi.org/10.1016/j.jmsy.2018.10.002

Ouaret, S., Kenné, J. P., & Gharbi, A. (2018b). Production and replacement policies for a deteriorating manufacturing system under random demand and quality. *European Journal of Operational Research*, *264*(2), 623-636. https://doi.org/10.1016/j.ejor.2017.06.062

Ouaret, S., Kenné, J. P., & Gharbi, A. (2019). Production and replacement planning of a deteriorating remanufacturing system in a closed-loop configuration. *Journal of Manufacturing Systems*, *53*(August), 234-248.

Ouaret, S., Polotski, V., Kenné, J., & Gharbi, A. (2013). Optimal Production Control of Hybrid Manufacturing / Remanufacturing Failure-Prone Systems under Diffusion-Type Demand. *Applied Mathematics*, *2013*(March), 550-559.

Ozcan, S., & Corum, A. (2019). A Scientometric Analysis of Remanufacturing by Mapping Scientific , Organizational , and National Concentration Zones. *IEEE Transactions on Engineering Management*. https://doi.org/10.1109/TEM.2019.2924199

Padmanabhan, V., & Png, I. P. L. (1995). Returns policies: make money by making good. *Sloan Management Review*, *37*(1), 65.

Panagiotidou, S., Nenes, G., & Zikopoulos, C. (2013). Optimal procurement and sampling decisions under stochastic yield of returns in reverse supply chains. *OR Spectrum*, *35*(1), 1-32.

Parkinson, H. J., & Thompson, G. (2003). Analysis and taxonomy of remanufacturing industry practice. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, *217*(3), 243-256.

Parsopoulos, K. E., Konstantaras, I., & Skouri, K. (2015). Metaheuristic optimization for the Single-Item Dynamic Lot Sizing problem with returns and remanufacturing. *Computers and Industrial Engineering*, *83*, 307-315. https://doi.org/10.1016/j.cie.2015.02.014

Polotski, Vladimir, Kenne, J.-P., & Gharbi, A. (2019). Joint production and maintenance optimization in flexible hybrid Manufacturing–Remanufacturing systems under age-dependent deterioration. *International Journal of Production Economics*, *216*(April), 239-254.

Polotski, Vladimir, Kenne, J. P., & Gharbi, A. (2015). Optimal production scheduling for hybrid manufacturing-remanufacturing systems with setups. *Journal of Manufacturing Systems*, *37*, 703-714. https://doi.org/10.1016/j.jmsy.2015.02.001

Polotski, Vladimir, Kenne, J. P., & Gharbi, A. (2017a). Production and setup policy optimization for hybrid manufacturing–remanufacturing systems. *International Journal of Production Economics*, *183*, 322-333. https://doi.org/10.1016/j.ijpe.2016.06.026

Polotski, Vladimir, Kenne, J. P., & Gharbi, A. (2017b). Set-up and production planning in hybrid manufacturing–remanufacturing systems with large returns. *International Journal of Production Research*, *55*(13), 3766-3787.

Polotski, Vladmir, Kenné, J.-P., & Gharbi, A. (2019). Production control of hybrid manufacturing–remanufacturing systems under demand and return variations. *International Journal of Production Research*, *57*(1), 100-123.

Presman, E., & Sethi, S. P. (2006). Inventory Models with Continuous and Poisson Demands and Discounted and Average Costs. *Production and Operations Management*, *15*(2), 279-293. https://doi.org/10.1111/j.1937-5956.2006.tb00245.x

Rezg, N., Dellagi, S., & Chelbi, A. (2008). Joint optimal inventory control and preventive maintenance policy. *International Journal of Production Research*, *46*(19), 5349-5365.

Rivera-Gómez, H., Gharbi, A., Kenné, J. P., Montaño-Arango, O., & Hernandez-Gress, E. S. (2016). Production control problem integrating overhaul and subcontracting strategies for a quality deteriorating manufacturing system. *International Journal of Production Economics*, *171*, 134-150.

Rivera-Gómez, H., Gharbi, A., Kenné, J. P., Montaño-Arango, O., & Hernández-Gress, E. S. (2018). Subcontracting strategies with production and maintenance policies for a manufacturing system subject to progressive deterioration. *International Journal of Production Economics*, *200*(January), 103-118.

Rogers, D. S., & Tibben-lembke, R. (2001). An examination of reverse logistics practices. *Journal of Business Logistics*, *22*(2), 129-148.

Ross, S. M. (2014). *Introduction to probability models* (Eleventh e). New York, NY : Academic press.

Sethi, S. P., & Thompson, G. L. (2000). *Optimal control theory: application to management science and economics*. *Kluwer Academic Publishers*. Boston, MA.

Sethi, Suresh P, & Zhang, Q. (1994). *Hierarchical Decision Making in Stochastic Manufacturing Systems*. Boston, MA : Birkhäuser Boston.

Sharifnia, A. (1988). Production control of a manufacturing system with multiple machine states. *IEEE Transactions on Automatic Control*, *33*(7), 620-625.

Sharifnia, Ali, Caramanis, M., & Gershwin, S. B. (1991). Dynamic setup scheduling and flow control in manufacturing systems. *Discrete Event Dynamic Systems: Theory and Applications*, *1*(2), 149-175.

Sonntag, D., & Kiesmüller, G. P. (2017). The Influence of Quality Inspections on the Optimal Safety Stock Level. *Production and Operations Management*, *26*(7), 1284-1298.

Souza, G. C. (2013). Closed-Loop Supply Chains: A Critical Review, and Future Research. *Decision Sciences*, *44*(1), 7-38. https://doi.org/10.1111/j.1540-5915.2012.00394.x

Srivastava, S. K. (2007). Green supply-chain management: A state-of-the-art literature review. *International Journal of Management Reviews*, *9*(1), 53-80.

Talay, I., & Özdemir-Akyıldırım, Ö. (2019). Optimal procurement and production planning for multi-product multi-stage production under yield uncertainty. *European Journal of Operational Research*, *275*(2), 536-551. https://doi.org/10.1016/j.ejor.2018.11.069

Tang, O., & Teunter, R. (2006). Economic Lot Scheduling Problem with Returns. *Production & Operations Management*, *15*(4), 488.

Teunter, R. H., Bayindir, Z. P., & Van Den Heuvel, W. (2006). Dynamic lot sizing with product returns and remanufacturing. *International Journal of Production Research*, *44*(20), 4377-4400.

Teunter, R., Kaparis, K., & Tang, O. (2008). Multi-product economic lot scheduling problem with separate production lines for manufacturing and remanufacturing. *European Journal of Operational Research*, *191*(3), 1241-1253. https://doi.org/10.1016/j.ejor.2007.08.003

Teunter, R., Tang, O., & Kaparis, K. (2009). Heuristics for the economic lot scheduling problem with returns. *International Journal of Production Economics*, *118*(1), 323-330.

Thierry, M., Salomon, M., Nunen, J. Van, & Wassenhove, L. Van. (1995). Strategic issues in product recovery management. *Long Range Planning*, *28*(3), 120.

Toktay, L. B., Wein, L. M., & Zenios, S. A. (2000). Inventory Management of Remanufacturable Products. *Management Science*, *46*(11), 1412-1426.

Tsiliyannis, C. A. (2018). Markov chain modeling and forecasting of product returns in remanufacturing based on stock mean-age. *European Journal of Operational Research*, *271*(2), 474-489.

Turki, S., & Rezg, N. (2016). Optimal production control of a manufacturing-remanufacturing system with delivery activity. Dans *IFAC-PapersOnLine* (Vol. 49, pp. 1233-1238). Troyes, France : Elsevier B.V.

Turki, S., Sauvey, C., & Rezg, N. (2018). Modelling and optimization of a manufacturing/remanufacturing system with storage facility under carbon cap and trade policy. *Journal of Cleaner Production*, *193*, 441-458.

Van der Laan, E. A., & Teunter, R. H. (2006). Simple heuristics for push and pull remanufacturing policies. *European Journal of Operational Research*, *175*(2), 1084-1102. https://doi.org/10.1016/j.ejor.2005.06.030

Van Der Laan, E., Dekker, R., Salomon, M., & Ridder, A. (1996). An (s , Q) inventory model with remanufacturing and disposal. *International Journal of Production Economics*, *47*, 339-350.

Van Der Laan, E., & Salomon, M. (1997). Production planning and inventory control with remanufacturing and disposal. *European Journal of Operational Research*, *102*(2), 264-278. https://doi.org/10.1016/S0377-2217(97)00108-2

Van Der Laan, E., Salomon, M., & Dekker, R. (1999). Investigation of lead-time effects in manufacturing/remanufacturing systems under simple PUSH and PULL control strategies. *European Journal of Operational Research*, *115*(1), 195-214.

Van Der Laan, E., Salomon, M., Dekker, R., & Wassenhove, L. Van. (1999). Inventory Control in Hybrid Systems with Remanufacturing. *Management Science*, *45*(5), 733-747.

Vercraene, S., Gayon, J. P., & Flapper, S. D. (2014). Coordination of manufacturing, remanufacturing and returns acceptance in hybrid manufacturing/remanufacturing systems. *International Journal of Production Economics*, *148*, 62-70.

Vogt Duberg, J., Johansson, G., Sundin, E., & Kurilova-Palisaitiene, J. (2020). Prerequisite factors for original equipment manufacturer remanufacturing. *Journal of Cleaner Production*, *270*, 122309. https://doi.org/10.1016/j.jclepro.2020.122309

Wang, H., & Pham, H. (2006). *Reliability and Optimal Maintenance*. *Springer*. (S.l.) : Springer London. https://doi.org/10.1007/b138077

Wang, J.-J., Chen, H., Rogers, D. S., Ellram, L. M., & Grawe, S. J. (2017). A bibliometric analysis of reverse logistics research (1992-2015) and opportunities for future research. *International Journal of Physical Distribution & Logistics Management*, *47*(8), 666-687.

Wu, C. H., & Wu, H. H. (2016). Competitive remanufacturing strategy and take-back decision with OEM remanufacturing. *Computers and Industrial Engineering*, *98*, 149-163.

Xie, J., Zhao, Z., Kong, L., & Chen, R. (2007). An affecting factors and optimizing model for the remanufacturing production planning. *Systems Engineering*, *25*, 53-59.

Yang, C.-H., Ma, X., & Talluri, S. (2019). Optimal acquisition decision in a remanufacturing system with partial random yield information. *International Journal of Production Research*, *57*(6), 1624-1644. https://doi.org/10.1080/00207543.2018.1494393

Yang, C. H., Ma, X., & Talluri, S. (2018). Optimal acquisition decision in a remanufacturing system with partial random yield information. *International Journal of Production Research*, *7543*, 1-21. https://doi.org/10.1080/00207543.2018.1494393

Yang, J., Yan, H., & Taksar, M. I. (2000). Optimal production and setup scheduling: A one-machine, two-product system. *Annals of Operations research*, *98*(1-4), 291-311.

Yin, Y., Stecke, K. E., & Li, D. (2018). The evolution of production systems from Industry 2.0 through Industry 4.0. *International Journal of Production Research*, *56*(1-2), 848-861.

Yong, J. (1989). Systems governed by ordinary differential equations with continuous, switching and impulse controls. *Applied Mathematics & Optimization*, *20*(1), 223-235.

Zanoni, S., Ferretti, I., & Tang, O. (2006). Cost performance and bullwhip effect in a hybrid manufacturing and remanufacturing system with different control policies. *International Journal of Production Research*, *44*(18-19), 3847-3862.

Zhang, J., Wang, Y., Lu, L., & Tang, W. (2015). Optimal dynamic pricing and replenishment cycle for non-instantaneous deterioration items with inventory-level-dependent demand. *International Journal of Production Economics*, *170*, 136-145.

Zhou, J., Deng, Q., & Li, T. (2018). Optimal acquisition and remanufacturing policies considering the effect of quality uncertainty on carbon emissions. *Journal of Cleaner Production*, *186*, 180-190. https://doi.org/10.1016/j.jclepro.2018.03.150

Zhou, S. X., Tao, Z. T., & Chao, X. C. (2011). Optimal control of inventory systems with multiple types of remanufacturable products. *Manufacturing and Service Operations Management*, *13*(1), 20-34. https://doi.org/10.1287/msom.1100.0298

Zhou, S. X., & Yu, Y. (2011). Optimal product acquisition, pricing, and inventory management for systems with remanufacturing. *Operations Research*, *59*(2), 514-521.

Zouadi, T., Yalaoui, A., & Reghioui, M. (2018). Hybrid manufacturing/remanufacturing lot-sizing and supplier selection with returns, under carbon emission constraint. *International Journal of Production Research*, *56*(3), 1233-1248.