

Vers le Remanufacturing 5.0: une approche méthodologique
pour la mise en œuvre de systèmes de refabrication intelligents
et durables

par

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Vers le Remanufacturing 5.0: une approche méthodologique pour la mise en œuvre de systèmes de refabrication intelligents et durables

Camilo MEJIA-MONCAYO

RÉSUMÉ

Cette thèse aborde la mise en œuvre des principes de l'Industrie 5.0 dans les systèmes de refabrication (en anglais « remanufacturing ») afin de surmonter leurs principaux défis. La refabrication est une stratégie d'économie circulaire qui, par le biais de processus industriels, redonne aux produits en fin de vie un état similaire, voire supérieur, à celui des produits neufs. Cela permet de réduire la consommation d'énergie et de matières premières par rapport à la fabrication de nouveaux produits. Cependant, sa mise en œuvre est complexe car elle implique de relever d'importants défis intrinsèques, tels que l'incertitude quant à la quantité, l'état et les taux de retour des produits usagés, la complexité des processus et des produits, et la méfiance des consommateurs, entre autres. De plus, des préoccupations persistent quant à sa durabilité, car sa mise en œuvre privilégie les critères économiques au détriment des critères environnementaux et sociaux, négligeant ainsi les besoins de toutes les parties prenantes. Dans ce contexte, l'implémentation des principes de l'Industrie 5.0 en la refabrication, qui incluent la durabilité, l'approche centrée sur l'humain et la résilience des systèmes, représentent la meilleure alternative pour surmonter ces défis.

La thèse commence par identifier les liens entre la durabilité, les parties prenantes et le système de refabrication. Ceci est réalisé en identifiant et en analysant ses principaux indicateurs clés de performance. À partir de ces éléments, une définition de la refabrication durable est formulée, ainsi qu'un cadre méthodologique permettant d'évaluer le démontage, le recyclage et la refabrication durables des produits.

Une architecture intelligente, constituant le cœur du système, est présentée. Cette architecture intègre les principes de l'Industrie 5.0 et relie le modèle d'affaires, les parties prenantes et les opérations du système tout au long de la chaîne d'approvisionnement grâce à des systèmes intelligents. Sa pertinence et son applicabilité sont illustrées par une étude de cas portant sur la refabrication de moteurs électriques.

Une architecture de refabrication cellulaire reconfigurable est introduite en tant qu'architecture productive. Celle-ci est intégrée à une stratégie d'entreprise afin de gérer l'incertitude quant à la quantité et à l'état des produits usagés. Un modèle d'optimisation multi-objectif est proposé pour configurer l'architecture. Les résultats montrent que les configurations proposées gèrent efficacement l'incertitude.

Le Remanufacturing 5.0 est introduit à travers une étude de cas basée sur la revalorisation des batteries lithium-ion de véhicules électriques au Québec, au Canada. Cette étude comprend une simulation du cycle de vie des batteries, une prédiction de leur durée de vie et un modèle d'optimisation multi-objectif qui synthétise les principes de l'Industrie 5.0. La démarche

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entreprise permet de comprendre le fonctionnement du système et fournit des informations sur son adoption et sa mise en œuvre.

Cette thèse contribue à la compréhension de l'intégration des principes de l'Industrie 5.0 dans la refabrication, d'un point de vue méthodologique. À cette fin, elle établit comment ces principes interagissent avec le système de refabrication ; puis les intègre à la structure du système ; et enfin, simule le fonctionnement du système de Remanufacturing 5.0 afin d'illustrer ses différentes dimensions et ses avantages.

Mots-clés: Industrie 5.0, Refabrication, Développement durable, Chaîne d'approvisionnement en boucle fermée, Optimisation multi-objectifs, Apprentissage automatique , NSGA2.

Towards Remanufacturing 5.0 : A Methodological Approach for Implementing Smart Sustainable Remanufacturing Systems

Camilo MEJIA-MONCAYO

ABSTRACT

This thesis addresses the implementation of Industry 5.0 principles in remanufacturing systems to overcome their main challenges. Remanufacturing is a circular economy strategy that, through industrial processes, restores end-of-life products to a condition similar to or better than new. This reduces energy and material consumption compared to manufacturing new products. However, its implementation is challenging because it involves addressing significant intrinsic challenges, such as uncertainty about the quantity, condition, and return rates of used products, the complexity of its processes and products, and consumer distrust, among others. Furthermore, concerns about its sustainability persist, as its implementations prioritize economic criteria over environmental and social ones, neglecting the needs of all stakeholders. In this context, the implementation of Industry 5.0 principles in remanufacturing, which include sustainability, a human-centered approach and system resilience, represents the best alternative to overcome these challenges.

It begins by identifying the links between sustainability, stakeholders, and the remanufacturing system. This is achieved by identifying and analyzing its main key performance indicators. From these, a definition of sustainable remanufacturing is formulated, along with a methodological framework that evaluates the disassembly, recycling, and remanufacturing of products sustainably.

An smart architecture representing the core of the system is presented. This architecture integrates Industry 5.0 principles and links the business model, stakeholders, and system operations throughout the supply chain using smart systems. Its relevance and applicability are illustrated through a case study on the remanufacturing of electric motors.

A reconfigurable cellular remanufacturing architecture is introduced as a productive architecture. This is integrated into a business strategy to address uncertainty in the quantity and condition of used products. A multi-objective optimization model is offered to configure the architecture. The results show that the proposed configurations efficiently manage uncertainty.

Remanufacturing 5.0 is introduced through a case study based on the revalorization of lithium-ion batteries from electric vehicles in Quebec, Canada. This includes battery life cycle simulation, lifespan prediction, and a multi-objective optimization model that synthesizes Industry 5.0 principles. The process undertaken helps to understand the system's operation and provides information on its adoption and implementation.

This thesis contributes to the understanding of the integration of Industry 5.0 principles into remanufacturing from a methodological perspective. To this end, it establishes how these principles interact with the remanufacturing system; then integrates them into the system's

structure; and finally, simulates the operation of the Remanufacturing 5.0 system to illustrate its different dimensions and advantages.

Keywords: Industry 5.0, Remanufacturing, Sustainability, Closed-loop supply chain, Multi-Objective Optimization, Machine learning, NSGA2.

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LISTE DES ABRÉVIATIONS, SIGLES ET ACRONYMES

AM	Additive Manufacturing
AHP	Analytic hierarchy process
AI	Artificial intelligence
AR	Augmented Reality
BDA	Big data analytics
BCT	Blockchain
BM	Business model
CF	Cell formation
CMS	Cellular manufacturing systems
CE	Circular economy
CM	Circular manufacturing
CLSC	Closed-loop supply chains
CRM	Customer Relationship Management
CPS	Cyber-physical systems
DMS	Dedicated manufacturing systems
DT	Digital Twins
EV	Electric vehicle
EVs	Electric vehicles
EoL	End-of-life
EoU	End-of-Use
ERP	Enterprise Resources Planning
EMS	Environmental Management System
FTA	Fault tree analysis
FMS	Flexible manufacturing systems
GAMS	General algebraic modeling system

GA	Genetic algorithms
GHG	Greenhouse gas
HCN	Hazard control number
HMRMA	Hazard Modes & Risk Mitigation Analysis
HRN	Hazard risk number
HRC	Human-Robot Collaboration
CPLEX	IBM ILOG CPLEX Optimization Studio
I4.0	Industry 4.0
I5.0	Industry 5.0
ISO	International Organization for Standardization
IoT	Internet of Things
KPI	Key performance indicator
LCA	Life cycle assessment
LE	Linear economy
LIB	Lithium-ion battery
ML	Machine learning
MILP	Mixed integer linear programming
NSGA2	Non-dominated sorting genetic algorithm II
OEM	Original Equipment Manufacturer
PLCI	Product life cycle information
PLM	Product Lifecycle Management
PSS	Product Service Systems
QMS	Quality Management System
RFID	Radio Frequency Identification
RCRA	Reconfigurable cellular remanufacturing architecture
RMS	Reconfigurable Manufacturing System
R5.0	Remanufacturing 5.0

RQ	Research question
RL	Reverse logistics
Sim	Simulation
SME	Small and medium-sized enterprises
SA	Smart architecture
SM	Smart Manufacturing
SR	Sustainable remanufacturing
SLR	Systematic literature review
TS	Tabu search
3PRLP	Third-party reverse logistics provider
TBL	Triple bottom line
VR	Virtual Reality

INTRODUCTION

La refabrication est une stratégie clé dans l'économie circulaire, car elle permet de récupérer la valeur des produits en fin de vie, contribuant ainsi à la durabilité et à la lutte contre les changements climatiques. Cependant, son adoption comporte des défis importants liés aux produits, aux procédés et à la chaîne d'approvisionnement, et en considérant les trois piliers de la durabilité : économique, environnemental et social, l'économie est priorisée par rapport aux autres. Cela conduit à un déséquilibre entre ces éléments et montre que les besoins des parties prenantes ne sont pas suffisamment satisfaits.

Les systèmes intelligents de l'Industrie 4.0 offrent des solutions aux principaux problèmes de la refabrication, principalement l'incertitude liée au manque de connaissance de l'état, de la quantité et du temps de retour des produits usagés ainsi que de leurs effets sur l'exploitation. Les solutions proposées reposent sur la collecte, le traitement et l'analyse des informations sur le cycle de vie des produits, afin d'améliorer les processus, de soutenir la prise de décision, d'assurer la traçabilité des produits, de faciliter la durabilité, entre autres. Dans ce contexte de numérisation, l'Industrie 5.0 émerge, qui exploite la technologie pour un nouveau paradigme de production intégrant durabilité, approche centrée sur l'humain et résilience des systèmes.

Cette thèse explore la mise en œuvre de l'Industrie 5.0 dans la refabrication, afin de surmonter ses obstacles de façon durable, en tenant compte d'une approche centrée sur l'humain et des exigences des parties prenantes. Le processus mis en œuvre comprend la définition de la refabrication durable, les indicateurs de performance les plus fréquents dans la littérature, une architecture intelligente et une architecture productive sont formulées en intégrant les principes de l'Industrie 5.0, ainsi qu'une perspective méthodologique pour la mise en œuvre de la Refabrication 5.0.

Différentes approches méthodologiques sont mises en œuvre, incluant la revue systématique de la littérature, la simulation, l'optimisation et l'apprentissage automatique. Cette thèse est structurée

en sept chapitres. Le chapitre 1 présente une revue de la littérature sur la refabrication, ses défis, la durabilité dans la refabrication, le rôle de l'industrie 4.0 et la transition vers l'industrie 5.0. Le chapitre 2 détaille les objectifs de recherche et la méthodologie adoptée. Le chapitre 3 aborde la refabrication durable, ses indicateurs de performance les plus fréquents, et formule une définition de la refabrication durable. Le chapitre 4 présente une architecture intelligente pour des systèmes de refabrication durables. Le chapitre 5 présente une architecture productive cellulaire et reconfigurable pour une refabrication durable avec une approche de conception basée sur l'optimisation multi-objectifs. Le chapitre 6 simule un système basé sur l'Industrie 5.0 pour la réévaluation des batteries lithium-ion en fin de vie au Québec, ce qui sert à introduire le Remanufacturing 5.0. Enfin, une discussion générale de la thèse est menée. La thèse se conclut par une conclusion qui synthétise les résultats obtenus et propose des recommandations pour de futures recherches.

CHAPITRE 1

REVUE DE LITTÉRATURE

Cette revue de la littérature Introduit les concepts et études clés sur la refabrication durable et intelligente. Elle débute par une présentation des différentes dimensions de la refabrication en section 1.1, aborde ensuite les défis de la refabrication en section 1.2, la durabilité dans la refabrication en section 1.3, et le rôle de l'I4.0 en section 1.4, puis analyse la transition vers l'industrie 5.0 en section 1.5. Tout au long de ce parcours, les défis actuels sont illustrés et des opportunités de recherche pour de futurs travaux sont proposées. Les chapitres 3, 4, 5 et 6 comportent leurs propres revues de littérature, qui développent les thèmes présentés ici et abordent d'autres sujets spécifiques à chaque chapitre.

1.1 Refabrication

L'économie moderne fonctionne principalement selon un modèle linéaire, où les matériaux sont extraits, transformés en produits, utilisés jusqu'à la fin de leur vie utile, puis jetés. Ce processus entraîne la perte de valeur (fonctionnalité, esthétique, matériaux, énergie et savoir). La culture de consommation accélère ce cycle, provoquant l'épuisement des ressources naturelles, une augmentation de la consommation énergétique, la pollution des écosystèmes, le réchauffement climatique et des impacts sur les communautés (Gusmerotti, Testa, Corsini, Pretner & Iraldo, 2019).

L'économie circulaire vise à relever ces défis en fermant le cycle ouvert, en s'inspirant des cycles naturels où il n'y a pas de déchets (Ellen-MacArthur-Foundation, 2013). Elle applique des stratégies pour prolonger la durée de vie des produits ou valoriser les matériaux et l'énergie des produits usagés, telles que refuser les matériaux inutiles, réduire la consommation, réutiliser, réparer, reconditionner, refabrication, recycler et récupérer l'énergie (van Buren, Demmers, van der Heijden & Witlox, 2016), comme illustré dans la figure 1.1.

La refabrication se distingue parmi les stratégies de l'économie circulaire comme un processus fondamental pour la transition vers une fabrication durable (Paul & Reinhart, 2024; Sundin,

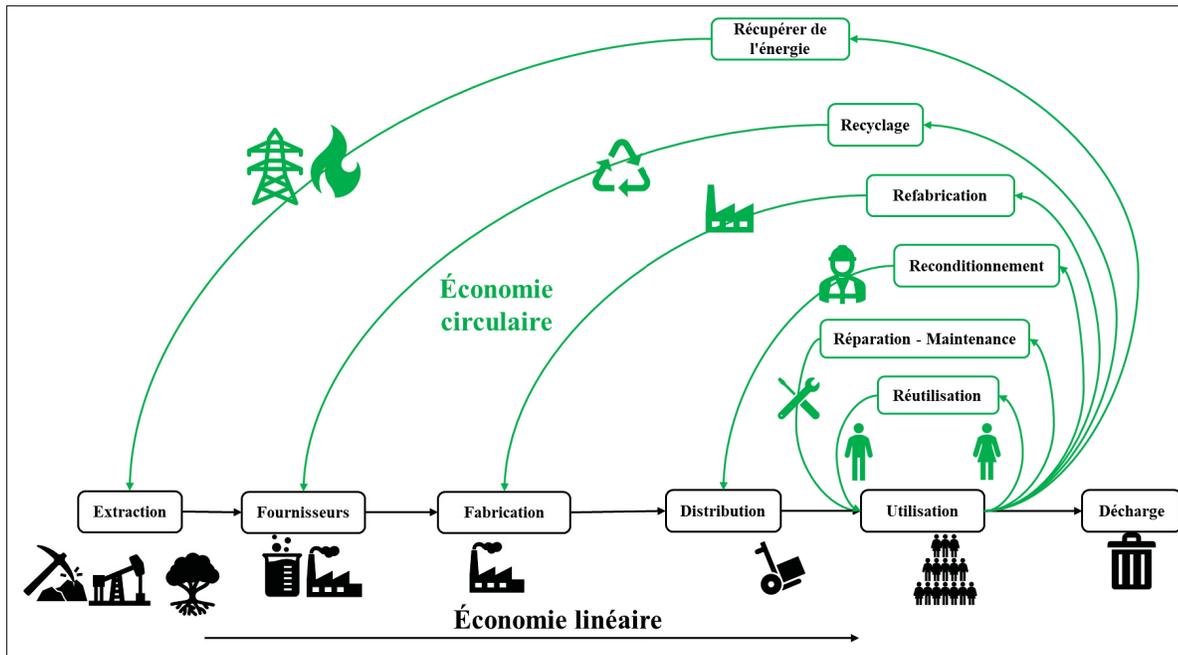


Figure 1.1 Schéma d'économie circulaire

2019). Elle consiste à restaurer des produits en fin de vie par des procédés industriels, leur redonnant une condition proche du neuf (Amaitik *et al.*, 2023; Liu, Yang & Liu, 2024; Vimal, Kandasamy & Gokhale, 2024). Cette capacité de restauration réduit la nécessité de ressources et d'énergie par rapport à la fabrication de nouveaux produits (Sundin, 2019). Contrairement à la réparation ou au recyclage, elle vise à récupérer la valeur ajoutée du produit original, pas seulement les matériaux (Russell & Nasr, 2023; Vimal *et al.*, 2024).

Il est crucial de distinguer la refabrication des autres procédés de récupération du valeur, comme illustré à la figure 1.2. Contrairement à la réparation, qui se limite à la correction de défauts spécifiques pour prolonger la durée de vie d'un produit de sa fin d'utilisation (FdU) à sa fin de vie prévue (FdV), ou au reconditionnement (en anglais « refurbishment »), qui consiste en des améliorations esthétiques ou fonctionnelles pour prolonger sa FdV prévue, ou encore à la réutilisation directe du produit, qui le transfère à un autre utilisateur jusqu'à sa FdV. La refabrication garantit des performances et une qualité comparables à celles d'un produit neuf (Stucki, Meierhofer, Gal, Gallina & Eisl, 2024). Le manque de compréhension du public quant à

cette distinction fondamentale – la refabrication impliquant une garantie de qualité équivalente à celle d’un produit neuf – est précisément à l’origine du frein à la perception des consommateurs, ce qui conduit souvent à confondre les produits refabriqués avec des produits d’occasion et nuit à leur acceptation sur le marché (Ngu, Lee & Osman, 2020).

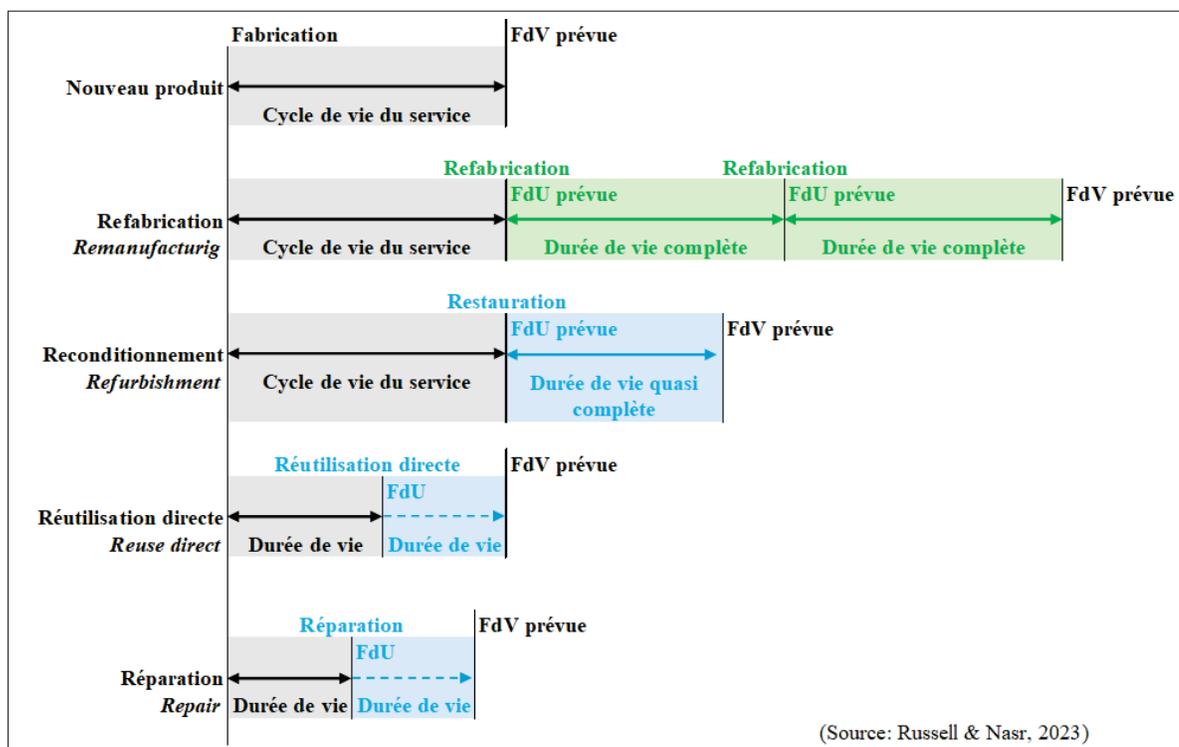


Figure 1.2 Comparaison des cycles de service, de la fin de vie et de la fin d'utilisation, entre la refabrication, le refabrication, la réutilisation directe et la réparation.

Des exemples de produits refabriqués incluent des pièces automobiles, des photocopieurs, des équipements médicaux, des chaudières (Yeo, Pepin & Yang, 2017) et des ordinateurs à composants interchangeables (Miyajima, Yamada, Yamada & Inoue, 2019; Inoue *et al.*, 2020). La refabrication est viable lorsque la valeur et la durabilité des produits sont élevées, le cycle technologique plus long que le cycle de vie utile, et que des technologies efficaces de restauration existent (Yeo *et al.*, 2017).

La refabrication est plus complexe que la réparation ou le refabrication. Elle implique la restauration systématique des composants pour répondre aux normes de qualité et de performance originales. Le processus comprend la collecte du produit usagé via la logistique inverse, l'inspection, le démontage, le nettoyage, le refabrication, la réparation, le assemblage et les tests pour garantir la conformité aux spécifications originales (Karvonen, Jansson, Behm, Vatanen & Parker, 2017; Parkinson & Thompson, 2003), comme illustré dans la figure 1.3.

La refabrication englobe toutes les étapes, de la collecte du produit usagé, appelé « noyau », à sa remise sur le marché en tant que produit de qualité garantie. Les principales étapes sont décrites ci-dessous :

1. Collecte et logistique inverse : La première phase consiste à récupérer les produits en fin de vie grâce aux systèmes de logistique inverse (Han, Wang, Xu & Park, 2025). Cette étape est fondamentale et présente des défis spécifiques liés à la planification et à la gestion d'une chaîne d'approvisionnement fonctionnant à l'inverse de la chaîne traditionnelle (Hajipour, Kaveh, Yiğit & Gharaei, 2025).
2. Inspection et tri : Une fois collectés, les noyaux font l'objet d'une inspection rigoureuse afin d'évaluer leur état, d'identifier les défauts et de déterminer leur potentiel de refabrication. À cette étape, il est décidé quels produits peuvent être traités et lesquels doivent être éliminés de manière appropriée (Caterino *et al.*, 2025).
3. Démontage : Le démontage consiste à séparer le produit en ses composants individuels. Il s'agit d'une opération essentielle du refabrication, qui peut parfois s'avérer complexe en raison de sa complexité ou des risques encourus (Reula, Parreño-Torres & Ramírez, 2025).
4. Nettoyage : Les composants démontés sont soumis à un nettoyage approfondi. Dans certains cas, cette opération est effectuée avant l'inspection afin de mieux évaluer l'état du produit ou du composant (Karvonen *et al.*, 2017).
5. Réparation et reconditionnement : Les pièces usées ou défectueuses sont ensuite réparées, reconditionnées ou remplacées afin de garantir leur conformité aux spécifications techniques requises (Stucki *et al.*, 2024).

6. Assemblage : Lors de la phase finale, les composants récupérés et les nouveaux composants sont assemblés pour reconstituer le produit (Parkinson & Thompson, 2003).
7. Contrôle qualité : Le produit assemblé est soumis à des tests rigoureux de qualité et de performance afin de garantir qu'il respecte, voire dépasse, les spécifications du produit d'origine (Stucki *et al.*, 2024).

Bien que ces étapes suivent une logique linéaire, leur mise en œuvre concrète est semée d'embûches et de complexités inhérentes qui représentent d'importants défis stratégiques.

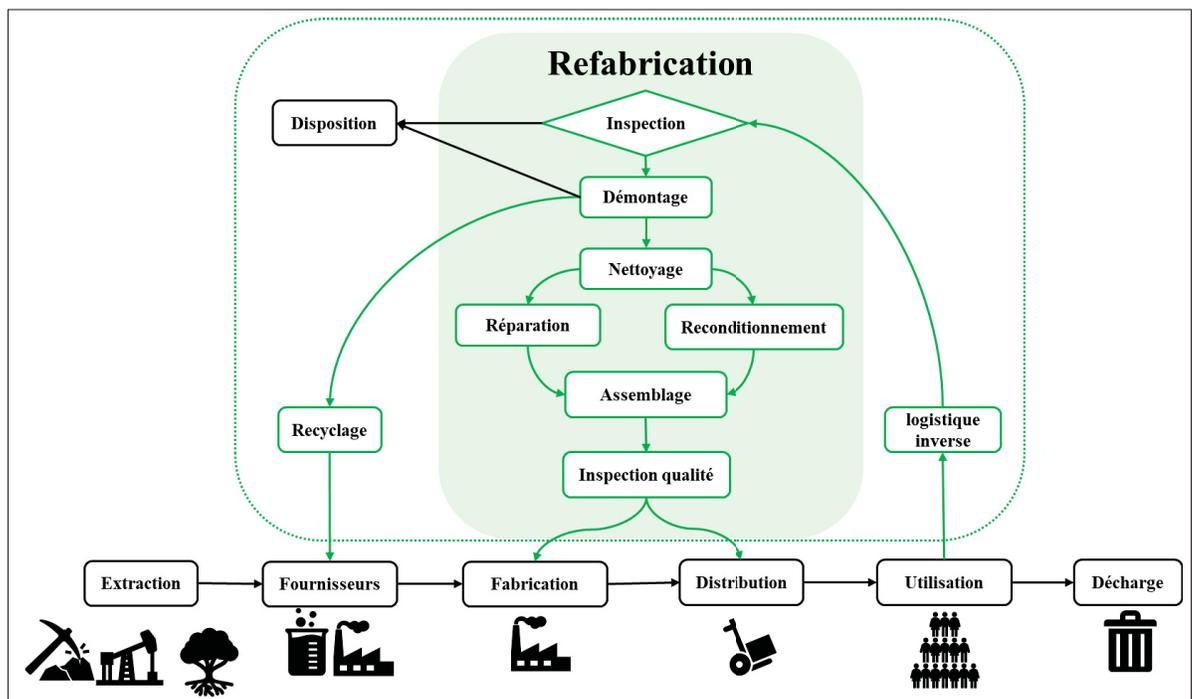


Figure 1.3 Schéma du processus de refabrication

Parmi les avantages économiques, la refabrication permet de réduire les coûts en réutilisant des composants et en diminuant la dépendance aux matériaux vierges (Haque, Pervin & Mondal, 2024). Elle offre des économies allant jusqu'à 60 % en énergie, 70 % en matériaux et plus de 50 % en coûts par rapport à la production de nouveaux produits (Wang, Wang, Yang, Zhu & Liu, 2020). Cette réduction des coûts se traduit par des prix souvent jusqu'à 50 % inférieurs à ceux d'un nouveau produit. Cette stratégie permet non seulement de surmonter les réticences initiales

des consommateurs, mais aussi d'ouvrir la voie à de nouveaux segments de marché, renforçant ainsi la compétitivité de l'entreprise (Spadafora & Rapaccini, 2025).

Sur le plan environnemental, l'extension de la durée de vie des produits réduit la nécessité de nouveaux processus de fabrication, ce qui diminue l'empreinte carbone, conserve les ressources, minimise les déchets et économise l'énergie (Zhao *et al.*, 2019; Sharma *et al.*, 2023). Cette économie de ressources a un impact direct sur l'atténuation du réchauffement climatique, car elle réduit considérablement les émissions de carbone liées aux procédés d'extraction et de fabrication (Tabassum, Brabanter & Kremer, 2024). De plus, en évitant la mise en décharge des produits en fin de vie, elle joue un rôle crucial dans la réduction des déchets solides (Karkasinas, Rentizelas & Corney, 2025).

Au-delà de la rentabilité directe, la refabrication génère des bénéfices socio-économiques par la création d'emplois et le développement de compétences spécialisées (Liu *et al.*, 2024). Les opérations de démontage, diagnostic, réparation et remontage requièrent une main-d'œuvre qualifiée, ce qui nécessite des investissements en formation (Qin *et al.*, 2024; Khan, Piprani & Yu, 2022). De plus, en rendant les produits de haute qualité plus abordables, la refabrication améliore l'accessibilité pour un plus grand nombre de consommateurs, démocratisant ainsi l'accès à des biens durables et performants (Spadafora & Rapaccini, 2025).

1.2 Défis de la refabrication

Malgré ses avantages, la refabrication fait face à des défis majeurs. Les difficultés liées à la refabrication proviennent essentiellement de ses matières premières. Contrairement à la production conventionnelle, qui repose sur des composants neufs et standardisés, la refabrication dépend d'un flux d'approvisionnement par nature imprévisible.

Le principal défi pour toute opération de refabrication réside dans la variabilité de la qualité et de la quantité des produits usagés collectés, également appelés « noyaux » (terme utilisé dans l'industrie pour désigner les produits usagés servant de matières premières ou en anglais « cores »). Les principales sources d'incertitude sont les suivantes :

- Retour des produits usagés : Le calendrier, la quantité et la qualité des produits usagés retournés au fabricant présentent une variabilité importante. Cette imprévisibilité rend la planification de la production extrêmement difficile (Kim *et al.*, 2024; Haque *et al.*, 2024; Paul & Reinhart, 2024). Alors que la production traditionnelle est optimisée pour l'efficacité grâce à la répétabilité, la refabrication doit être optimisée pour la flexibilité et l'adaptabilité face à une variabilité constante (Reula *et al.*, 2025).
- Disponibilité des matériaux : L'état des noyaux retournés est incertain, ce qui complique la prévision des composants réutilisables et de ceux qui devront être remplacés ou recyclés. Cela influe directement sur les coûts et l'efficacité du processus (Liu *et al.*, 2024).
- Demande du marché : La demande de produits refabriqués est difficile à prévoir, car elle est sensible à la perception du consommateur, à l'écart de prix avec les produits neufs et à la confiance dans la qualité du produit refabriqués (Caterino *et al.*, 2025).

Le retour des produits en fin de vie à l'usine représente un défi pour la logistique inverse. Cela pose des problèmes spécifiques en matière de collecte, de transport et de stockage de produits non standardisés. Le processus s'en trouve complexifié et coûteux à gérer (Kurilova-Palisaitiene, Golinska-Dawson, Gorroño-Albizu & Duberg, 2025). De plus, la plupart des chaînes d'approvisionnement actuelles sont conçues pour une économie linéaire (extraire-produire-jeter), ce qui constitue un obstacle systémique à la circularité nécessaire au remanufacturing (Urbinati, Franzò & Chiaroni, 2021).

D'un point de vue technique, les produits actuels ne sont pas conçus pour un second cycle de vie. Des opérations telles que le démontage et l'inspection sont laborieuses et requièrent des connaissances spécialisées (Paul & Reinhart, 2024; Yuan *et al.*, 2025), ce qui rend la standardisation et l'automatisation difficiles. Le démontage est la première étape cruciale du processus, mais c'est souvent l'une des opérations les plus difficiles, coûteuses et chronophages, notamment pour les produits complexes comportant des assemblages permanents (Reula *et al.*, 2025).

L'absence de conception pour la refabrication fait que la structure du produit peut être un obstacle ou un facilitateur de la refabrication. La grande majorité des produits sont conçus pour un seul cycle de vie, privilégiant l'assemblage au démontage. Ce manque de prévoyance lors de la conception initiale entrave, voire empêche, une réparation et la refabrication (Verkuilen, Zijderveld, de Buck & Coenen, 2025; Hickcox & Smith, 2022).

Par ailleurs, des tensions peuvent surgir entre les différents acteurs de la chaîne d'approvisionnement (fabricants, fournisseurs, clients), qui se perçoivent parfois comme des concurrents. Ce manque de collaboration entrave l'échange d'informations et de matériaux nécessaires à un système de refabrication efficace (Kurilova-Palisaitiene *et al.*, 2025). Le manque d'information sur le cycle de vie du produit aussi, c'est critique pour les refabricateurs, habituellement tiers sans lien direct avec les fabricants originaux. Cela complique l'accès à des données essentielles comme les listes de matériaux ou le design (Hu *et al.*, 2023).

Des barrières à l'entrée existent sur le marché. Les consommateurs sont souvent enclins à acheter les derniers modèles, ce qui réduit la demande pour les produits refabriqués. Certains consommateurs peuvent hésiter à acheter un produit refabriqué par crainte d'une mauvaise performance (Govindan, 2024; Yi, He, Li & Li, 2024). De nombreux consommateurs perçoivent encore, à tort, un produit refabriqué comme un simple produit d'occasion, sans comprendre qu'il a été restauré selon des normes de qualité équivalentes à celles d'un produit neuf (Ngu *et al.*, 2020). Aussi, le coût représente l'un des principaux obstacles à la refabrication. Dans certains cas, le processus peut s'avérer plus onéreux que la fabrication d'un produit entièrement neuf (Alfnes, Gosling, Naim, Dreyer & Høgseth, 2025). Fixer un prix à la fois compétitif sur le marché et suffisamment raisonnable pour couvrir les coûts variables de la refabrication constitue un défi majeur susceptible de nuire à la rentabilité des entreprises (Kurilova-Palisaitiene *et al.*, 2025).

Ces défis affectent l'efficacité du système, la chaîne d'approvisionnement, la commercialisation et la volonté d'adopter la refabrication. Les approches pour les surmonter doivent donc considérer tous les acteurs de la chaîne d'approvisionnement en cycle fermé.

1.3 Durabilité dans la refabrication

En 1987, la Commission Brundtland des Nations Unies a défini le développement durable comme « la capacité des générations futures à répondre aux besoins du présent sans compromettre leur capacité à répondre aux leurs » (UN, 1987). Elkington (1998) a concrétisé ce concept à travers le modèle du triple bilan (ou triple performance), également connu sous le nom de « personnes, planète et prospérité ». Ce modèle introduit les trois dimensions ou piliers de la durabilité ou développement durable : les personnes (aspect social), la planète (aspect environnemental) et la prospérité (aspect économique) (Contini & Peruzzini, 2022). Cette approche a permis d'établir des indicateurs quantitatifs de performance et d'impact des activités humaines sur la durabilité (Elkington, 1998).

La durabilité dans le secteur manufacturier est liée à la performance des procédés et des produits développés. Ainsi, pour qu'une entreprise soit considérée comme durable, elle doit garantir l'efficacité de ses opérations et réduire l'impact environnemental de ses produits (Kusiak, 2018). C'est pourquoi l'industrie s'est concentrée sur la création de matériaux, de procédés et de produits toujours plus performants et respectueux de l'environnement (de Souza Junior, Dantas, Zanghelini, Cherubini & Soares, 2020). Parmi les actions les plus pertinentes figurent la réduction de la consommation d'énergie et de matières premières, le recours aux énergies renouvelables et la mise en œuvre d'initiatives visant à minimiser les impacts environnementaux négatifs (Liu, Trevisan, Yang & Mascarenhas, 2022; Zhang, Ao, Cai, Jiang & Zhang, 2019; Esmailian, Behdad & Wang, 2016). Par ailleurs, les stratégies d'économie circulaire, telles que la refabrication, ont pris une importance considérable, car elles permettent de valoriser les produits usagés, tout en consommant moins d'énergie et de matières premières que la fabrication de nouveaux produits (Asif *et al.*, 2018).

Diverses études abordent la durabilité dans la refabrication sous différents angles : produits refabriqués (Fatimah, Biswas, Mazhar & Islam, 2013; Yadav, Luthra, Jakhar, Mangla & Rai, 2020), durabilité des entreprises (Fatimah & Aman, 2018; Golinska, Kosacka, Mierzwiak & Werner-Lewandowska, 2015), impacts économiques et environnementaux (Russell & Nasr, 2023),

conception de produits (Zwolinski, Lopez-Ontiveros & Brissaud, 2006; Inoue *et al.*, 2020) et chaîne d'approvisionnement (Ansari, Kant & Shankar, 2022). Le rôle de la logistique inverse est mis en avant (Das, 2020; Mota, Gomes, Carvalho & Barbosa-Povoa, 2018), notamment en ce qui concerne le coût du transport (Chirumalla, Kulkov, Vu & Rahic, 2023) et les émissions de gaz à effet de serre (Alkhayyal, 2018). Malgré la diversité des approches, il n'existe pas de consensus sur la définition de la refabrication durable.

1.3.1 Dimension économique

La viabilité économique demeure le facteur déterminant pour les entreprises qui adoptent des pratiques durables. Pour que des initiatives comme la refabrication dépassent le simple cadre de la conformité réglementaire et deviennent un véritable avantage concurrentiel, il est essentiel de maximiser les profits, d'optimiser les coûts et de concevoir des modèles économiques rentables. Toutefois, si la rentabilité est essentielle, elle ne doit pas être analysée isolément ; les dimensions environnementales et sociales doivent également être prises en compte pour parvenir à une performance véritablement durable.

Dans ce contexte, plusieurs indicateurs clés permettent d'évaluer la performance économique du développement durable et de la refabrication. Ces indicateurs englobent les coûts et les avantages, l'efficacité opérationnelle, la qualité et la fiabilité. Les coûts et les avantages comprennent des indicateurs financiers traditionnels, mais adaptés à l'ensemble du cycle de vie du produit, tels que le coût total de possession, la valeur actuelle nette, les profits et les investissements (Wlazlak & Johansen, 2024). Parmi ceux-ci, plusieurs catégories importantes se distinguent : les coûts de production et de refabrication comprennent à la fois les dépenses liées à la fabrication de nouveaux produits et le coût généralement inférieur de la refabrication de produits usagés récupérés (Alkhayyal, 2019; Dai, Shu, Chen, Wang & Lai, 2020). Les coûts de récupération et de logistique inverse comprennent les dépenses liées à la collecte, au contrôle, au tri et au transport des produits en fin de vie, du consommateur aux installations de traitement (Dai *et al.*, 2020; Agrawal, Singh & Murtaza, 2016). Enfin, les coûts sociaux des pénalités carbone et des émissions englobent les taxes carbone et autres sanctions gouvernementales appliquées aux

émissions de gaz à effet de serre, intégrant ainsi les externalités environnementales dans le calcul des coûts (Alkhayyal, 2019; Shu, Liu, Chen, Wang & Lai, 2018).

L'efficacité opérationnelle se concentre sur l'optimisation des processus, en tenant compte de la productivité du travail, du temps de cycle et de la flexibilité nécessaire pour s'adapter à la variabilité inhérente des produits retournés (Wlazlak & Johansen, 2024; Fatimah & Aman, 2018). De même, la qualité et la fiabilité sont essentielles pour évaluer la performance des produits refabriqués, en considérant la fiabilité du produit et les taux de réutilisation des composants (Wlazlak & Johansen, 2024).

Le niveau de durabilité d'un système dépend directement du modèle économique adopté, car celui-ci définit les directives de fonctionnement du système de refabrication et spécifie le processus de valorisation des produits usagés (Moro, Cauchick-Miguel & de Sousa Mendes, 2022). Le modèle économique est un élément stratégique qui influence considérablement les opérations (Garcia-Muiña, González-Sánchez, Ferrari & Settembre-Blundo, 2018), l'innovation (Blomsma *et al.*, 2019), la compétitivité (Kravchenko, Pigosso & McAloone, 2019), le soutien structurel à la circularité du système (Ünal & Shao, 2019) et les interactions avec les parties prenantes (Kim, Kuah & Thirumaran, 2022) d'une entreprise.

De plus, cela implique de prendre en compte les préoccupations des parties prenantes (Moro *et al.*, 2022), élément fondamental pour une démarche durable, notamment une communication transparente (Garcia-Muiña *et al.*, 2019) et la prise en compte des intérêts spécifiques de chaque partie prenante (Dwivedi, Agrawal, Jha & Mathiyazhagan, 2023). Afin d'harmoniser les intérêts de toutes les parties prenantes et d'éviter les conflits susceptibles d'affecter la performance globale, la mise en œuvre de mécanismes contractuels avancés établissant des règles claires est recommandée. Par conséquent, les initiatives d'économie circulaire devraient adopter des modèles économiques intégrant, mesurant et contrôlant toutes les dimensions du développement durable.

1.3.2 Dimension environnementale

La dimension environnementale est essentielle à la transition d'une économie linéaire traditionnelle vers un modèle circulaire. L'objectif fondamental de cette transition est de minimiser l'empreinte écologique générée par les activités humaines, ce qui implique une réduction drastique des déchets, la préservation des ressources naturelles et la lutte contre la pollution. Pour atteindre ces objectifs, il est essentiel de mettre en œuvre des stratégies permettant de boucler les cycles de la matière et de l'énergie, c'est-à-dire de garantir la réutilisation et le maintien des ressources le plus longtemps possible (Russell & Nasr, 2023).

La littérature spécialisée recense diverses stratégies pratiques adoptées par les organisations pour réduire leur impact environnemental. Parmi les plus pertinentes figure la reconception pour la durabilité (Zwolinski *et al.*, 2006; Inoue *et al.*, 2020), connue sous le nom d'approche des 6R : réduire, réutiliser, recycler, repenser, récupérer et refabriquer. Ce cadre guide l'innovation dans le développement des produits et des procédés (Vimal, Kandasamy & Duque, 2021). L'efficacité énergétique est un autre pilier fondamental de la transition vers une économie circulaire. L'adoption de pratiques circulaires a un impact direct et mesurable sur la consommation d'énergie (Subramaniam, Elangovan & Venkatakrishnan, 2025). La réduction des émissions est tout aussi essentielle. La refabrication, en tant que stratégie de réduction des émissions, offre des avantages environnementaux directs et quantifiables (Alkhayyal, 2019). Ce processus consomme nettement moins d'énergie et de matières premières que la fabrication de produits neufs (Russell & Nasr, 2023).

Pour quantifier l'impact environnemental des produits et des procédés, on utilise l'analyse du cycle de vie, une méthodologie qui permet d'analyser des indicateurs tels que les émissions de CO_2 ou l'acidification de l'air. Cet outil fournit une base scientifique à la prise de décision et à l'amélioration continue, garantissant ainsi que les actions mises en œuvre contribuent réellement au développement durable (Vogiantzi & Tserpes, 2023; Vimal *et al.*, 2021). Dans ce contexte, l'économie circulaire, et la refabrication en particulier, en bouclant les cycles des matériaux, apparaît comme une réponse stratégique aux défis environnementaux mondiaux, tels

que l'épuisement des ressources naturelles et l'augmentation des gaz à effet de serre (Alkhayyal, 2019).

La gestion des émissions de carbone a été intégrée aux modèles de prise de décision des organisations, principalement sous l'impulsion des réglementations gouvernementales. Des mécanismes tels que les taxes carbone et les systèmes de récompenses et de sanctions incitent les entreprises à réduire leurs émissions totales (Shu *et al.*, 2018; Alkhayyal, 2019).

1.3.3 Dimension sociale

La dimension sociale de la durabilité, pourtant essentielle à un développement authentique et équitable, est souvent l'aspect le moins développé tant dans la théorie que dans la pratique de l'économie circulaire (Erro, Odriozola & de Durana, 2023). Les études privilégient souvent l'aspect économique (Taddei, Sassanelli, Rosa & Terzi, 2022; Haque *et al.*, 2024), tandis que les préoccupations sociales sont peu intégrées ou abordées de façon partielle (Kaya, Ayçin & Pamucar, 2023; Tsalis, Stefanakis & Nikolaou, 2022) et stratégique (Henaou, Sarache & Gomez, 2021). Dans la plupart des cas, les critères économiques tendent à primer sur les critères environnementaux et sociaux (Lieder, Asif, Rashid, Mihelič & Kotnik, 2017; Alonso-Muñoz, González-Sánchez, Siligardi & García-Muiña, 2021). De nombreuses entreprises ont tendance à privilégier les pratiques environnementales uniquement lorsqu'elles génèrent des avantages économiques directs (Gusmerotti *et al.*, 2019).

De plus, les mises en œuvre de l'économie circulaire négligent souvent les impacts sociaux et privilégient les critères environnementaux et économiques (Tsalis *et al.*, 2022). Cette situation est principalement due au manque d'approches détaillées et métriques liés aux variables du processus ou de l'opération, permettant une mesure quantitative de la durabilité sociale (Kazakova & Lee, 2022). Une durabilité véritable doit impérativement prendre en compte l'équité, le bien-être humain et la justice sociale. Négliger ce pilier risque de créer des systèmes qui, bien que circulaires, perpétuent, voire aggravent, les inégalités existantes (Erro *et al.*, 2023). Bien que la durabilité comporte trois dimensions, un déséquilibre subsiste.

La littérature spécialisée a commencé à identifier des indicateurs et des aspects clés pour évaluer la performance sociale dans les contextes de la refabrication et de l'économie circulaire. Parmi ceux-ci, le bien-être des travailleurs se distingue, englobant la santé et la sécurité ergonomiques, les conditions de travail sûres et le taux d'accidents du travail (Kazancoglu & Ozkan-Ozen, 2020; Wlazlak & Johansen, 2024). Le développement et l'équité comprennent le renforcement des compétences, la formation continue, la promotion de l'égalité des genres au travail et la mesure de la satisfaction des employés comme indicateur de bien-être général (Wlazlak & Johansen, 2024; Fatimah & Aman, 2018). De plus, l'impact sur la communauté et les consommateurs est fondamental, car la durabilité sociale s'étend au-delà de l'entreprise pour inclure la satisfaction des consommateurs vis-à-vis des produits refabriqués, la gestion des réclamations des communautés et l'acceptation publique des pratiques circulaires – autant d'aspects essentiels à la réussite à long terme (Wlazlak & Johansen, 2024; Fatimah & Aman, 2018).

1.3.4 Les parties prenantes

L'équilibre réussi entre les dimensions économiques, environnementales et sociales n'est pas la responsabilité d'un seul acteur, mais le fruit d'actions coordonnées menées par un écosystème de parties prenantes. Chaque groupe de parties prenantes joue un rôle unique et exerce une influence distincte sur la chaîne de valeur, des fabricants et détaillants aux fournisseurs, opérateurs externes, consommateurs et gouvernements (Dai *et al.*, 2020; Shu *et al.*, 2018). La pression des parties prenantes est un moteur essentiel de l'adoption de l'économie circulaire et des pratiques de responsabilité sociale, notamment au sein des petites et moyennes entreprises (PME). Lorsque les clients, la communauté ou les organismes de réglementation exigent de meilleures performances sociales et environnementales, les PME sont incitées à innover et à collaborer pour mettre en œuvre des pratiques circulaires, ce qui renforce leur participation aux initiatives de responsabilité sociale des entreprises (Baah, Agyabeng-Mensah, Afum & Kumi, 2023).

Les pouvoirs publics et le secteur public agissent comme catalyseurs du changement grâce à des cadres juridiques, des politiques et des incitations, établissant ainsi les règles susceptibles d'accélérer ou de freiner la transition (Czerwionka *et al.*, 2025). Le secteur privé, et notamment

les entreprises, est le principal moteur et acteur de l'économie circulaire, bien que son pouvoir soit limité par l'aversion au risque et sa dépendance à des cadres réglementaires stables (Loviscek, 2025). Les organisations non gouvernementales et le monde universitaire jouent un rôle de conseil, de soutien et de structuration des connaissances, en plaidant pour des politiques plus strictes et en comblant les lacunes en matière de connaissances (Vogiantzi & Tserpes, 2023; Loviscek, 2025). Les consommateurs et la société civile constituent une force motrice essentielle par leurs décisions d'achat et la pression sociale qu'ils exercent, même si leur pouvoir dépend de leur niveau de sensibilisation, d'éducation et d'accès à des alternatives durables (Erro *et al.*, 2023).

Malgré le potentiel de collaboration, d'importants obstacles, tels que les lacunes en matière d'information et de connaissances, entravent la coordination et les progrès vers une durabilité globale et la satisfaction de toutes les parties prenantes (Loviscek, 2025). L'analyse de ces acteurs et de leurs interactions est fondamentale pour comprendre la dynamique du changement et concevoir des interventions efficaces qui mènent à une transition circulaire et durable réussie.

1.4 Refabrication intelligente – Industrie 4.0

La quatrième révolution industrielle (Industrie 4.0 ou I4.0) est caractérisée par la numérisation et l'Internet des objets (IoT), qui connectent les processus commerciaux et d'ingénierie pour une fabrication décentralisée, efficace et durable (Rosa, Sassanelli, Urbinati, Chiaroni & Terzi, 2020; Bag, Gupta & Kumar, 2021). La refabrication intelligente se définit comme l'application des technologies de l'Industrie 4.0 au produit, à l'équipement, à la chaîne d'approvisionnement et aux systèmes de gestion (Kerin & Pham, 2020; Kim *et al.*, 2024). Elle permet de récupérer, traiter et analyser les données du cycle de vie du produit, réduisant l'incertitude et améliorant la planification et l'exécution des processus (Hu *et al.*, 2023; Kim *et al.*, 2024; Yu & Sun, 2024).

Les technologies de l'I4.0 incluent l'IoT, les systèmes cyberphysiques (CPS), l'analyse de données massives (BDA), l'intelligence artificielle (IA), l'apprentissage automatique (ML), la fabrication additive (AM), la blockchain (Afari, Gosavi, Hu & Marley, 2025; Kim *et al.*, 2024;

Pietrangeli, Mazzuto, Ciarapica & Bevilacqua, 2023), et la robotique (Daneshmand, Noroozi, Corneanu, Mafakheri & Fiorini, 2023).

L'IoT et les capteurs constituent un réseau d'objets physiques, tels que des machines et des produits, équipés de capteurs et de logiciels leur permettant de se connecter et d'échanger des données via Internet. Cette connectivité permet le suivi en temps réel des produits et des composants, par exemple grâce à des étiquettes Identification par Radiofréquence, et la surveillance de leur état et de leur condition tout au long de leur cycle de vie (Delpla, Kenné & Hof, 2021).

Les CPS intègrent la computation, la communication et le contrôle avec des éléments physiques, permettant une interaction en temps réel (Chen & Huang, 2021; Xu, de Vrieze, Lu & Wang, 2022). Un CPS surveille et contrôle un processus physique, en créant une copie numérique avec laquelle il peut interagir. Grâce à cette technologie, il est possible de contrôler et optimiser des processus de refabrication complexes (Yang, R., Kaminski & Pepin, 2018b).

L'analyse de données massives permettent d'examiner des ensembles de données volumineux et variés afin de révéler des tendances cachées et d'obtenir des informations utiles à la prise de décision. Dans le contexte de la refabrication, ces outils sont utilisés pour analyser les données du cycle de vie des produits et déterminer la meilleure option de fin de vie, telle que la réutilisation, le recyclage ou la refabrication, ainsi que pour prévoir la demande de produits (Chau *et al.*, 2021), cartographier les marchés de la refabrication et à comprendre leur dynamique (Ren *et al.*, 2019; Chau *et al.*, 2021).

L'IA permet d'imiter les fonctions cognitives humaines, telles que l'apprentissage et la résolution de problèmes, afin d'effectuer des tâches intelligemment. Dans le domaine de la refabrication, l'IA est utilisée pour optimiser la planification de la production en temps réel, prédire les défaillances des composants grâce à la maintenance prédictive et automatiser l'identification des défauts (Valamede & Akkari, 2020). L'IA et le ML améliorent la qualité et l'efficacité de la refabrication, notamment dans la gestion de la garantie et la fiabilité des composants en fin de vie (Shafiq, Ayub, kumar Muthevi & Prabhu, 2024; Govindan, 2024).

La fabrication additive (impression 3D) consiste à créer des objets tridimensionnels couche par couche à partir d'un modèle numérique, en ajoutant de la matière au lieu d'en enlever. Cette technologie permet la production de pièces de rechange à la demande, notamment pour les produits anciens ou personnalisés, facilitant les réparations et prolongeant la durée de vie des produits (Su *et al.*, 2024).

La blockchain est une base de données distribuée et immuable qui enregistre les transactions de manière sécurisée et transparente, créant ainsi une chaîne de blocs d'informations. Dans le domaine de la refabrication, la blockchain garantit la traçabilité et la transparence de la chaîne d'approvisionnement inverse, en vérifiant l'origine et l'historique des produits et composants récupérés, facilitant la gestion responsable du cycle de vie (Govindan, 2022; Psarommatis & May, 2024; Wickremasinghe, Frost, Rafferty & Sharma, 2025).

La robotique et l'automatisation consistent à utiliser des robots pour effectuer des tâches répétitives, dangereuses ou de haute précision, souvent en collaboration avec des humains. Ces technologies permettent l'automatisation des processus d'assemblage et de démontage, améliorant ainsi l'efficacité et la sécurité, notamment pour les tâches complexes ou très incertaines (Daneshmand *et al.*, 2023).

Les architectures intelligentes décrivent la structure et les fonctionnalités des systèmes intelligents conçus pour atteindre les objectifs du système. Elles structurent l'intégration des technologies de l'I4.0 pour soutenir la refabrication et la durabilité (Mejía-Moncayo, Kenné & Hof, 2023b). Parmi les fonctionnalités courantes figurent la capture, le stockage, le traitement et l'analyse des données afin de faciliter les opérations et la prise de décision. Les technologies de l'I4.0 jouent un rôle similaire dans ces approches, en mettant l'accent sur la communication et le traitement de l'information entre les parties prenantes, malgré les préoccupations liées à la cybersécurité et aux risques d'utilisation abusive des données (Kerin & Pham, 2020).

Les architectures intelligentes répondent à des défis tels que l'incertitude sur la condition (Yang *et al.*, 2018b), la qualité, la quantité et le moment de retour des produits usagés (Soldatos *et al.*, 2020), l'automatisation et l'optimisation des processus, soutenir la durabilité (Kerin & Pham,

2020), la traçabilité des composants et l'intégration des systèmes numériques dans la chaîne d'approvisionnement (Panza, Bruno & Lombardi, 2022), notamment la logistique inverse (Bensassi, Rezzai, Wafaa & Medromi, 2022).

1.5 Industrie 5.0 dans la refabrication

L'Industrie 5.0 représente un tournant stratégique dans l'évolution industrielle, marquant la transition de l'Industrie 4.0, axée sur l'automatisation et la numérisation, vers un modèle privilégiant l'équilibre entre progrès technologique et impératifs sociaux et environnementaux. Ce nouveau paradigme ne vise pas à remplacer l'Industrie 4.0, mais à l'affiner en intégrant les valeurs humaines et environnementales au cœur même de la production.

Contrairement à son prédécesseur, l'Industrie 5.0 repose sur trois piliers : l'humain au centre, la durabilité et la résilience. Cette évolution implique que la technologie doit être au service des personnes et de la planète, en favorisant une collaboration avancée entre humains et machines, notamment grâce aux robots collaboratifs ou « cobots » (Ivanov, 2023; Skèrè, Bastida-Molina, Skèrys & Molina-Palomares, 2025). Ces systèmes ne sont pas destinés à remplacer les travailleurs, mais plutôt à renforcer leurs compétences, à améliorer la qualité des opérations et à garantir leur bien-être et leur sécurité (Simone, Pasquale, Farina & Iannone, 2025). L'approche centrée sur l'humain se traduit par des environnements de travail où la créativité, la prise de décision et l'esprit critique des opérateurs sont renforcés par la précision et la puissance des machines. Parmi les exemples de cette collaboration, citons l'utilisation de cobots pour améliorer l'ergonomie et la sécurité (Bongomin *et al.*, 2025), ainsi que l'intégration de jumeaux numériques humains pour une analyse ergonomique personnalisée (He, Li, Wu & Izui, 2024).

Parallèlement, le développement durable devient un objectif stratégique incontournable. L'Industrie 5.0 promeut les modèles d'économie circulaire, la réduction des déchets et l'optimisation énergétique, en s'attaquant à l'impact écologique de la production (Oyekan, Turner, Bax & Graf, 2025; Furbino, Olmo, Revilla & Graeve, 2025). Ces pratiques contribuent directement à des

objectifs mondiaux tels que l'Objectif de développement durable n° 12 des Nations Unies - La consommation et la production durables (Ashkbous, Ghorbani & Keivanpour, 2026).

Le troisième pilier, la résilience, désigne la capacité des systèmes industriels à s'adapter et à réagir aux perturbations et aux changements imprévus, en développant des chaînes de valeur flexibles et agiles (Skèrè *et al.*, 2025; Ivanov, 2023). Dans le domaine de la refabrication, ce pilier est particulièrement pertinent, car ces processus sont très variables et dépendent fortement du savoir-faire humain.

La refabrication est présentée comme le domaine idéal pour l'application des principes de l'Industrie 5.0. Ses pratiques, telles que la réparation et la réutilisation des composants, prolongent le cycle de vie des matériaux et réduisent la consommation de ressources vierges, en accord avec les objectifs de développement durable (Furbino *et al.*, 2025). De plus, la collaboration homme-robot dans des tâches complexes et non standardisées, comme le démontage, illustre comment la technologie peut s'adapter aux besoins et aux conditions des opérateurs, améliorant ainsi la productivité et la sécurité (Yuan *et al.*, 2025).

L'application de technologies avancées, telles que l'intelligence artificielle et les modèles de langage complexes, renforce la résilience en permettant une plus grande adaptabilité dans des environnements de production incertains. Par exemple, les modèles de langage peuvent générer des instructions personnalisées pour l'assemblage de produits à partir de composants récupérés, facilitant ainsi une production flexible et efficace (Anandhabalaji, 2025; Oyekan *et al.*, 2025).

Toutefois, l'intégration de l'Industrie 5.0 dans la refabrication se heurte à des défis importants. Parmi ceux-ci figurent la gestion des facteurs humains, le manque de standardisation technologique et les risques de cybersécurité. La variabilité de l'efficacité collaborative entre les opérateurs et les robots, la difficulté à modéliser le comportement humain et l'absence de protocoles de qualité unifiés pour des technologies telles que la fabrication additive métallique constituent des obstacles à surmonter pour une mise en œuvre efficace (Yuan *et al.*, 2025; Furbino *et al.*, 2025).

De plus, l'interconnexion croissante des systèmes et le recours à l'intelligence artificielle accroissent les vulnérabilités en matière de cybersécurité, exigeant des protocoles robustes pour protéger les actifs et les données (Hassan, Zardari, Farooq, Alansari & Nagro, 2024). L'automatisation collaborative pose également des défis en matière de formation et d'adhésion des employés, qui doivent être formés à collaborer efficacement avec les systèmes avancés et comprendre que leur rôle est d'améliorer la technologie, et non d'être remplacés par elle.

1.6 Conclusions

La refabrication est une stratégie clé de l'économie circulaire, ce qui la distingue. Il consiste à remettre en état des produits en fin de vie grâce à des procédés industriels garantissant une qualité équivalente à celle d'un produit neuf. Cette approche réduit la consommation de ressources et d'énergie, diminue les coûts et facilite l'accès aux biens durables pour un plus grand nombre de consommateurs. Elle se différencie ainsi d'autres procédés tels que la réparation et le reconditionnement. De plus, elle génère des avantages environnementaux en prolongeant la durée de vie des produits et en minimisant la production de déchets, ainsi que des avantages socio-économiques en créant des emplois et en favorisant le développement de compétences spécialisées.

Cependant, la refabrication est confrontée à des défis importants qui affectent l'efficacité et la performance de ses procédés et de sa chaîne d'approvisionnement. Par ailleurs, malgré les efforts et les différentes approches mises en œuvre pour y remédier, ces défis demeurent à la fois une contrainte et une opportunité de recherche. Parmi ces défis figurent la variabilité et l'incertitude quant à la qualité et à la quantité des produits usagés utilisés comme matières premières, la planification et la gestion efficaces de la production, la logistique inverse, le démantèlement, la traçabilité des produits tout au long de leur cycle de vie, la collaboration entre les différents acteurs de la chaîne d'approvisionnement, la perception des consommateurs, et les autres défis intrinsèques à ce processus sont autant d'éléments importants.

Du point de vue de la durabilité, bien que les dimensions économiques, environnementales et sociales soient reconnues, leur intégration reste inégale. L'approche sociale est souvent moins développée et priorisée que les approches économique et environnementale, et les entreprises ont tendance à adopter des pratiques environnementales uniquement lorsqu'elles génèrent des avantages économiques directs. De plus, les indicateurs et les modèles reliant les variables de processus à la durabilité sociale au niveau opérationnel font défaut, il n'existe pas de consensus sur la définition de la refabrication durable, et une approche multidimensionnelle est nécessaire pour équilibrer les trois dimensions du développement durable et satisfaire toutes les parties prenantes.

La transition technologique vers l'Industrie 4.0 et 5.0 ouvre de nouvelles perspectives et soulève de nouveaux défis. L'application de technologies avancées améliore l'efficacité, la traçabilité et la planification de la refabrication. Cependant, elle pose des problèmes en matière de cybersécurité, d'interopérabilité et de normalisation technologique. L'Industrie 5.0, quant à elle, favorise une collaboration avancée entre humains et machines, plaçant le bien-être humain et la durabilité au cœur de ses préoccupations. Cependant, sa mise en œuvre nécessite de surmonter les obstacles liés à la formation, à la gestion des facteurs humains et à la variabilité de l'efficacité collaborative.

La littérature montre que l'Industrie 5.0 offre une perspective centrée sur l'humain, axée sur la durabilité et la résilience, et s'appuyant sur des systèmes intelligents pour améliorer le bien-être et la satisfaction des parties prenantes. Ceci représente une opportunité majeure pour relever les défis évoqués précédemment en appliquant les principes de l'industrie 5.0 à la refabrication.

En résumé, la refabrication durable et intelligente apparaît comme une solution stratégique. Toutefois, sa mise en œuvre efficace requiert la conception de la structure, de la configuration et des fonctions du système afin de surmonter les défis mentionnés précédemment tout en intégrant les principes de l'Industrie 5.0.

CHAPITRE 2

PROBLÈME ET MÉTHODOLOGIE

2.1 Introduction

La revue de littérature a présenté les divers défis auxquels la refabrication fait face dans ses processus, sa chaîne d'approvisionnement et sa durabilité. L'industrie 5.0 apparaît comme une alternative viable pour surmonter ces défis. Ce travail de recherche développe cette idée en appliquant systématiquement les principes de l'industrie 5.0 à la refabrication.

2.2 Problématique

Divers gouvernements, institutions à travers le monde et auteurs consultés dans la revue de littérature s'accordent sur les avantages de la refabrication comme stratégie de rétention de valeur, essentielle dans la lutte contre le changement climatique et l'épuisement des ressources naturelles. Ils reconnaissent également les défis que la refabrication aborde et le potentiel des systèmes intelligents pour les surmonter. La durabilité est une préoccupation dans différents contextes, principalement en évaluant la performance économique et environnementale. Toutefois, il n'existe pas de consensus sur la définition de la refabrication durable. De plus, il y a un manque de prise en compte des préoccupations sociales ou d'une approche centrée sur l'humain dans la prise de décision opérationnelle, et les exigences des différentes parties prenantes sont considérées partiellement. Dans ce contexte, l'industrie 5.0 se présente comme une alternative prometteuse pour répondre à ces préoccupations.

La mise en œuvre des principes de l'industrie 5.0 dans la refabrication soulève la question de recherche (**QR**) suivante :

QR : Comment intégrer les principes de l'industrie 5.0 dans les systèmes de refabrication ?

Cette question est au cœur de la recherche, et le processus méthodologique proposé vise à y répondre. Cependant, le problème est complexe et vaste, ce qui conduit à formuler les questions de recherche suivantes :

QR1 : Comment la durabilité, les parties prenantes et le système de refabrication sont liés ?

QR2 : Comment structurer un système de refabrication intelligent et durable ?

QR3 : Comment aborder méthodologiquement les principes de l'industrie 5.0 dans les systèmes de refabrication ?

La première question nécessite d'identifier les liaisons entre la refabrication, la durabilité et ses parties prenantes. La refabrication est un concept complexe aux multiples perspectives qu'il convient d'appréhender simultanément pour parvenir à une vision durable. Ce processus doit traiter conjointement la refabrication et le développement durable, en tenant compte des dimensions économiques, environnementales et sociales. Il est également indispensable d'identifier les principales parties prenantes, leurs interactions avec le système et de mettre en place des mécanismes permettant d'intégrer leurs exigences.

La deuxième question souligne la nécessité de définir la structure du système, ou ses architectures, intelligente et productive. Celle-ci doit intégrer les principes de l'industrie 5.0 pour surmonter les défis de la refabrication et répondre aux exigences des parties prenantes, atteindre les objectifs, faciliter le modèle d'affaires et soutenir les opérations, leur gestion et leur contrôle. La structure du système doit permettre l'opération selon les principes de l'industrie 5.0, tant au niveau opérationnel qu'en gestion et contrôle. Les systèmes intelligents doivent soutenir les processus de production, la chaîne d'approvisionnement et la prise de décision à différents niveaux hiérarchiques.

La troisième question intègre les deux précédentes et apporte une perspective méthodologique au processus. Elle aborde les étapes nécessaires pour intégrer les principes de l'industrie 5.0 dans la refabrication. En répondant à cette question, une perspective pratique est offerte pour faciliter l'adoption de ces principes.

Ce travail vise à répondre aux questions de recherche tout en comblant les lacunes identifiées dans la littérature, avec une approche méthodologique orientée vers une adoption possible. Trois objectifs ont été définis.

2.3 Objectifs de la recherche

L'objectif principal de ce travail est d'implanter les principes de l'industrie 5.0 dans les systèmes de refabrication, afin de relever simultanément les défis intrinsèques de la refabrication, la durabilité du système en équilibrant ses trois dimensions, les exigences des parties prenantes et la résilience du système. Cet objectif est atteint en répondant aux questions de recherche précédemment posées, qui se déclinent en sous-objectifs :

Sous-objectif 1 : Identifier les liens entre la durabilité, les parties prenantes et le système de refabrication.

Sous-objectif 2 : Proposer la structure d'un système de refabrication intelligent et durable, en formulant des architectures productives et intelligentes compatibles avec les principes de l'industrie 5.0.

Sous-objectif 3 : Proposer une approche méthodologique pour implanter les principes de l'industrie 5.0 dans les systèmes de refabrication.

2.4 Méthodologie

Pour atteindre les objectifs mentionnés, la recherche est divisée en trois étapes :

1. Refabrication durable.
2. Structure du système de refabrication.
3. Remanufacturing 5.0.

Pour chaque point, différentes représentations sont attendues, principalement des articles scientifiques.

2.4.1 Refabrication durable

Identifier les liens entre la durabilité, les parties prenantes et le système de refabrication. Le processus a été réalisé par une revue systématique de la littérature sur les indicateurs de performance de la refabrication durable. Il comprend :

- Recherche de documents dans la base de données Scopus
- Acceptation ou rejet des documents selon leur pertinence
- Analyse des documents pour identifier les indicateurs proposés ou utilisés dans chaque étude
- Désambiguïsation linguistique pour établir les indicateurs les plus fréquents dans la littérature
- Synthèse de la revue permettant de formuler une définition de la refabrication durable et un cadre méthodologique pour aborder le démontage et la refabricabilité de façon durable.

Ce travail contribue à l'atteinte du premier et du troisième sous-objectif, et son développement est présenté dans le chapitre 3. Ce chapitre est l'article publié « Key performance indicators for sustainable remanufacturing : A literature review and methodological framework » publié dans « Cleaner Logistics and Supply Chain ».

2.4.2 Structure du système de refabrication

La deuxième étape principale de la méthodologie vise à établir la structure du système de refabrication pour atteindre le premier, le deuxième et le troisième sous-objectif. Elle consiste à définir l'architecture intelligente du système et son architecture productive ou couche opérationnelle. L'architecture intelligente est définie à partir d'une revue systématique de la littérature qui permet d'aborder la production circulaire, les défis et barrières de la refabrication, ainsi que les principales technologies intelligentes et leur rôle dans la refabrication. Une architecture intelligente conceptuelle pour un système de refabrication durable basé sur l'industrie 5.0 est proposée. Cette architecture harmonise les dimensions de la durabilité, intègre les exigences des parties prenantes, aborde les défis et barrières de la refabrication, tout en soutenant le modèle d'affaires, la prise de décision et l'opération du système. Ce processus est présenté dans le chapitre 4. Ce chapitre est l'article publié « On the development of a

smart architecture for a sustainable manufacturing-remanufacturing system : A literature review approach » publié dans « Computers & Industrial Engineering ».

L'architecture productive est abordée par une approche d'optimisation multi-objectifs pour formuler une architecture cellulaire et reconfigurable pour la refabrication. La méthodologie commence par traiter l'incertitude liée à la condition, la quantité et le moment du retour dans la refabrication, la fabrication cellulaire et la fabrication reconfigurable. Les caractéristiques de l'architecture sont ensuite établies et leur configuration est modélisée mathématiquement par un modèle d'optimisation multi-objectifs. Une évaluation numérique du modèle est réalisée en utilisant trois méthodes de résolution et une analyse de sensibilité. La sélection de la meilleure solution est abordée par deux méthodes et des perspectives de gestion sont proposées pour enrichir l'approche méthodologique. Ce processus est présenté dans le chapitre 5. Ce chapitre est l'article publié « A Reconfigurable Cellular Remanufacturing Architecture : a multi-objective design approach » publié dans « Journal of Remanufacturing ».

2.4.3 Remanufacturing 5.0

La troisième étape de la méthodologie introduit la remanufacturing 5.0 à travers une étude de cas sur la revalorisation des batteries lithium-ion en fin de vie provenant de véhicules électriques au Québec, Canada. Cette étape synthétise les étapes précédentes en simulant un système de refabrication basé sur l'industrie 5.0. Le processus inclut :

- Définition des composantes du système, incluant le réseau de logistique inverse et l'architecture intelligente.
- Simulation et optimisation du système, incluant la formulation d'un modèle d'optimisation multi-objectifs, la simulation du cycle de vie du produit et la prédiction de la durée de vie.
- Évaluation numérique du système et analyse de sensibilité.

Ce travail offre une vision détaillée des étapes réalisées, décrit les composantes et leur fonctionnement, tout en établissant les liens entre les composantes du système, l'information

sur le cycle de vie du produit, l'opération du système et le rôle des systèmes intelligents pour atteindre la durabilité, l'approche centrée sur les parties prenantes et la résilience du système. Ce travail contribue au troisième sous-objectif et son développement est présenté dans le chapitre 6, ce chapitre est l'article « Towards Remanufacturing 5.0 : A Smart Sustainable Approach for End-of-Life Electric Vehicle Lithium-ion Battery Revalorization » soumis pour publication dans « Resources, Conservation and Recycling ».

2.5 Conclusion

Les différentes sources consultées ont permis d'identifier les défis et les lacunes des systèmes de refabrication, pour lesquels l'industrie 5.0 émerge comme une alternative prometteuse pour les aborder de façon simultanée. Cela conduit à la question de recherche qui guide ce projet : Comment intégrer les principes de l'industrie 5.0 dans les systèmes de refabrication ?

Trois sous-questions de recherche sont formulées, avec leurs sous-objectifs respectifs, qui ensemble permettent d'implanter les principes de l'industrie 5.0 dans la refabrication. Différentes approches méthodologiques contribuent à établir les liens entre la durabilité, les parties prenantes et le système de refabrication, à proposer des architectures intelligentes et productives qui rendent possible la refabrication 5.0, tout en mettant en œuvre une approche méthodologique illustrant les étapes et points importants à considérer. Ce travail ouvre la voie à de futures recherches sur les stratégies de récupération de valeur de manière durable, intelligente et centrée sur l'humain.

La figure 2.1 présente la relation entre les questions de recherche, les sous-objectifs et les articles scientifiques qui constituent les chapitres de cette thèse.

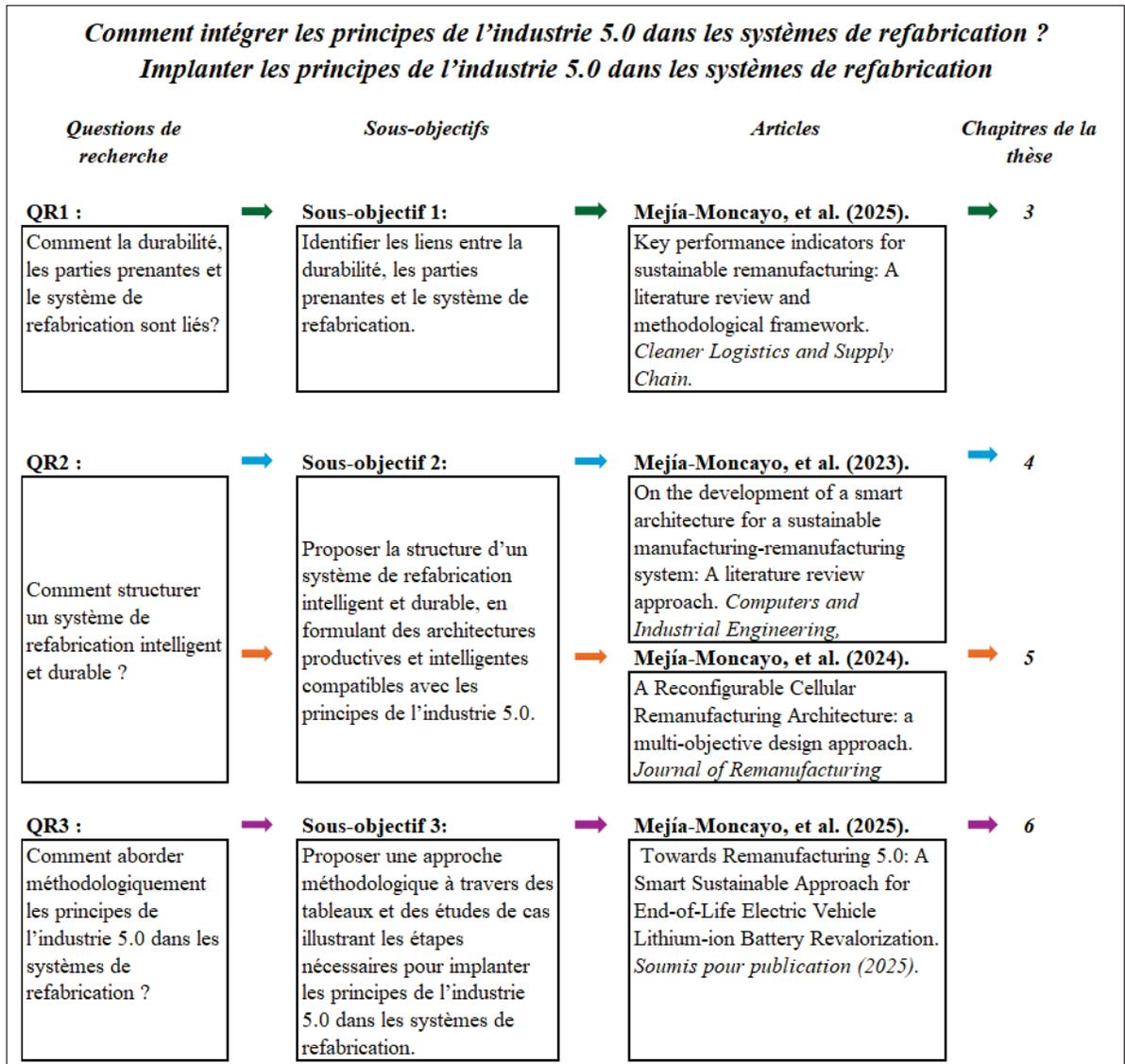


Figure 2.1 Relation entre les questions de recherche, les sous-objectifs et les articles scientifiques qui constituent les chapitres de cette thèse

CHAPITRE 3

KEY PERFORMANCE INDICATORS FOR SUSTAINABLE REMANUFACTURING : A LITERATURE REVIEW AND METHODOLOGICAL FRAMEWORK

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Abstract

Remanufacturing is a strategy within the circular economy (CE) that has gained significance in the industrial sector due to its potential to contribute to sustainability efforts and combat climate change. Its adoption is a challenging process that requires analyzing several factors about products, processes, and the supply chain. Even more, when considering the three pillars of sustainability - economic, environmental, and social - for integration of remanufacturing practices, the difficulty grows significantly for decision-makers. Hence, practitioners and academics have put much effort into creating different key performance indicators (KPIs) to assess remanufacturing, circular economy strategies, or sustainability. However, a concurrently focus on sustainable remanufacturing is still lacking. This study sheds light on this issue through a systematic literature review (SLR), which aims to provide insights on the definition of sustainable remanufacturing, its main performance indicators and fields of application, and providing practical guidance about its use. The developed SLR, based on 106 Scopus documents, identified a total of 1021 KPIs related to sustainable remanufacturing, of which 32 economic, 16 environmental and 3 social indicators were identified as the KPIs most frequently referenced in the literature. The SLR also identified six frequent fields of use or application for the KPIs. This study also presents a methodological framework focused on assessing product from disassembly, recycling,

and remanufacturing sustainably ; to guide decision-makers in using KPIs in the transition to sustainable remanufacturing.

Keywords : Remanufacturing, Sustainability, Key performance indicators, Closed-loop supply chains, Circularity, Remanufacturability, Disassembly, Product design.

3.1 Introduction

Remanufacturing stands out among circular economy (CE) strategies for combating material depletion and global warming by reducing material and energy consumption (Russell & Nasr, 2019). Indeed, through remanufacturing, the expected end-of-life (EoL) of a used item can be prolonged, thereby initiating a new full-service cycle (Ingarao, 2017; Mejía-Moncayo *et al.*, 2023b). Through remanufacturing operations, the product's functionalities are restored to their original, as-new levels. This process enables the extension of the product's lifespan beyond its EoL. As a result, it offers a new full-service cycle and reduces materials and energy consumption compared to manufacturing new products (Russell & Nasr, 2023).

Despite its advantages, the adoption of remanufacturing is a challenging process, and there is currently a growing demand to address CE strategies sustainably (Fatimah & Aman, 2018). Companies face significant challenges in balancing environmental and economic goals, often prioritizing environmentally friendly practices only when they offer economic advantages (Gusmerotti *et al.*, 2019; Lieder *et al.*, 2017). Additionally, CE implementations often overlook social impacts, prioritizing only environmental and economic criteria (Kaya *et al.*, 2023; Tsalis *et al.*, 2022). This raises concerns about its impacts, as it should be rational for CE implementations to be conducted in a sustainable manner.

Key performance indicators (KPIs) are essential tools for guiding decisions and measuring business performance. In the process of transitioning to sustainable remanufacturing (SR), KPIs are crucial at various stages (Mejía-Moncayo, Chaabane, Kenne & Hof, 2025b). Different literature reviews present a considerable number of KPIs to assess sustainability and CE strategies. Some of them are described in the following paragraph. Mengistu & Panizzolo (2023)

identified 1041 KPIs (290 economic, 410 environmental, and 341 social) to measure industrial sustainability. These KPIs can evaluate the sustainable performance of products, processes, raw materials, suppliers, or companies. Contini & Peruzzini (2022) presented 117 KPIs for the same purpose. Joung, Carrell, Sarkar & Feng (2013) categorized the quantifiable indicators related to sustainable manufacturing, while Henao *et al.* (2021) focused their study on social performance indicators for sustainable manufacturing.

Tableau 3.1 Focus of current literature reviews on remanufacturing or sustainability KPIs

Authors	Economic Sustainability	Environmental Sustainability	Social Sustainability	Circularity	Remanufacturability	Disassembly	Product Design	Closed-loop supply chains
Ansari <i>et al.</i> (2022)						✓	✓	✓
Contini & Peruzzini (2022)	✓	✓	✓					
Halter, Wietschel, Thorenz & Tuma (2025)	✓	✓	✓	✓				
Henao <i>et al.</i> (2021)			✓					
Hernandez-Marquina, Dain, Zwolinski & Joly (2022)	✓	✓	✓	✓				✓
Joung <i>et al.</i> (2013)	✓	✓	✓					
Kristensen & Mosgaard (2020)	✓	✓	✓	✓	✓	✓		
Kurt, Cortes-Cornax, Cung, Front & Mangione (2021)		✓		✓				✓
Mesa, Sierra-Fontalvo, Ortegón & Gonzalez-Quiroga (2024)	✓	✓		✓				
Matos, Martins, Simões & Simoes (2023a)	✓	✓	✓	✓	✓	✓		
Mengistu & Panizzolo (2023)	✓	✓	✓					
Priyono, Ijomah & Bititci (2016)	✓	✓				✓	✓	
Saidani, Yannou, Leroy, Cluzel & Kendall (2019)				✓	✓	✓	✓	
This study	✓	✓	✓	✓	✓	✓	✓	✓

Similar studies were conducted on the CE ; Saidani *et al.* (2019) synthesized and classified 55 KPIs to assess circularity at various levels and for different CE strategies. Halter *et al.* (2025) provided a comprehensive techno-sustainable analysis of 67 CE KPIs at the micro (company)

and nano (product) levels. Kristensen & Mosgaard (2020) and Matos *et al.* (2023a) focused their studies on micro-level indicators for the CE. Kurt *et al.* (2021) introduced a classification tool for circular supply chain indicators. Mesa *et al.* (2024) performed a critical review and assessment of indicators for circular bioeconomy. Priyono *et al.* (2016) addressed disassembly for remanufacturing from a strategic perspective. Hernandez-Marquina *et al.* (2022) analyzed the sustainable performance of circular supply chains, while Ansari *et al.* (2022), identified and evaluated KPIs for the remanufacturing supply chain.

Table 3.1 summarizes the focus addressed by the literature review studies mentioned above. These studies encompass KPIs, metrics, or indices related to economic, environmental, and social sustainability, as well as circularity, remanufacturability, disassembly, product design, and closed-loop supply chains (CLSC). The broad range of KPIs demonstrates the interest and engagement of both academia and industry in assessing sustainability and CE strategies in the industrial sector. However, the extensive range of KPIs makes it challenging to identify the most appropriate ones to use in a specific case or situation. Table 3.1 also shows that sustainability and CE indicators are frequently studied as separate or partially interrelated entities. This study conducts a systematic literature review (SLR) to address the distinct categories described in table 3.1. The aim is to provide a holistic overview of KPIs in SR, along with their fields of application and methodological implementation. Indeed, this SLR seeks to answer the following research questions (RQ) :

RQ1 : What are the main KPIs reported in the literature related to sustainable remanufacturing ?

RQ2 : What are the main fields of application of the KPIs identified in RQ1 ?

RQ3 : How to define sustainable remanufacturing ?

RQ4 : How to guide decision-makers in using the KPIs identified in the previous research questions ?

The first question refers to identifying the main KPIs across the three dimensions of sustainability in remanufacturing. The second question enables the determination of the fields of application of KPIs in SR. The third question builds upon the previous ones and aims to deepen the

understanding of SR. The fourth question addresses the practical implementation of the identified KPIs to support decision-makers in the transition to SR. The developed SLR also aims to contribute to the academic discussion by identifying research gaps and opportunities in sustainable remanufacturing.

The presented study is organized as follows : Section 3.2 describes the research methodology. Section 3.3 presents the main KPIs for sustainable remanufacturing . Section 3.4 addresses, through a literature review, the principal fields of application of the KPIs, and their links with smart sustainable remanufacturing. Section 3.5 presents the analysis and discussion of the literature review. Section 3.6 introduces a proposed methodological framework. Finally, section 3.7 presents the conclusions.

3.2 Research methodology

In this study, a SLR was conducted to determine the main KPIs in SR. Following the methodology outlined by Tranfield, Denyer & Smart (2003), this process was formulated to answer four research questions (RQ1 - RQ4, introduced in section 3.1). A detailed overview of the methodology used in this study is provided in figure 3.1 This figure outlines the methodological steps involved, including the document search process, criteria for acceptance or rejection of documents, document analysis, and synthesis of the literature review.

The methodology starts by conducting a document search process, which is performed using the Scopus database as a primary source of information. The search process encompasses journal articles, conference papers, and book chapters to cover a broad range of relevant documents that address the research questions. The documents included in this study must be written in English and span the period from 2000 to 2025, including all areas treated by Scopus. The search process used a combination of keywords that integrates remanufacturing and various synonyms of sustainability ("sustainab*", "triple bottom line" or "TBL") and KPIs ("metric*", "key performance indicator", "indicator", "criteria", or "kpi"), figure 3.1 describes the search string used in Scopus.

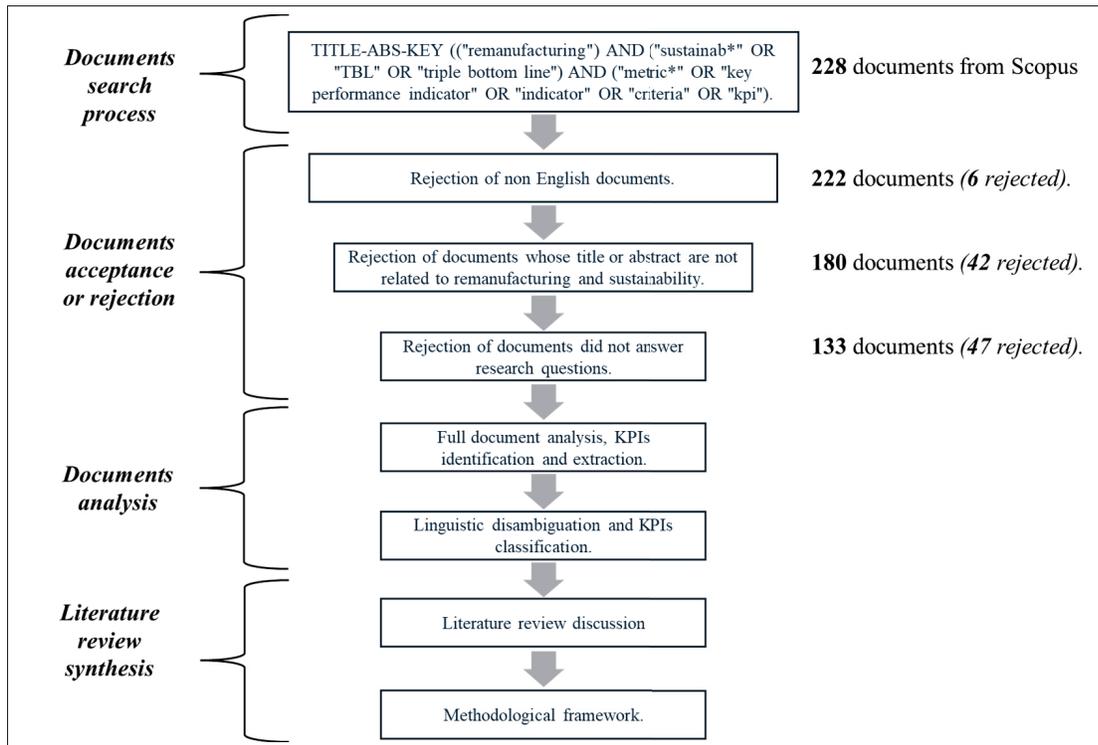


Figure 3.1 Systematic Literature Review (SLR) methodology steps implemented in this study

Once the document search process was finished, the acceptance or rejection of documents was conducted in a second step, as described in figure 3.1. A total of 228 documents were obtained through the search process. The documents' acceptance or rejection was based on considerations of language and relevance to SR and the research questions. During the initial classification phase, 6 documents non-written in English were rejected based on language : 3 in Chinese, 2 in German, and 1 in Portuguese. Based on the examination of the title and abstract of the documents, 47 documents were rejected. Indeed, these documents were not directly related to remanufacturing and sustainability. After reading and analyzing the documents, 42 of them were rejected because they did not contribute to answering the research questions. As a result of these steps, a final set of 133 documents was compiled, which were then used for the analysis performed in this study. The distribution of documents at the acceptance and rejection stages is depicted in figure 3.1.

A comprehensive assessment of each document entails a complete analysis of the document, including KPI identification and extraction, as well as the linguistic disambiguation of the identified KPIs. The complete document analysis revealed six primary fields of application for the KPIs in the analyzed literature. These include : 1) the sustainability assessment of remanufacturing products, processes, or companies, 2) the design of products for remanufacturing, 3) product disassembly assessment, 4) product remanufacturability assessment, 5) remanufacturing circularity assessment, and 6) design, planning, or optimization of closed-loop supply chains for remanufacturing. These categories were also used to group the documents during the analysis and presentation of the results.

The KPIs identified in the documents were extracted and consolidated into a Microsoft Excel database, allowing for easy access and analysis. The database contains various metadata, including the authors, title, source or journal name, publication year, and country of origin of the document. It also includes the KPIs, its classification as economic, environmental, or social indicators, its primary use/application field, and the document's main theme.

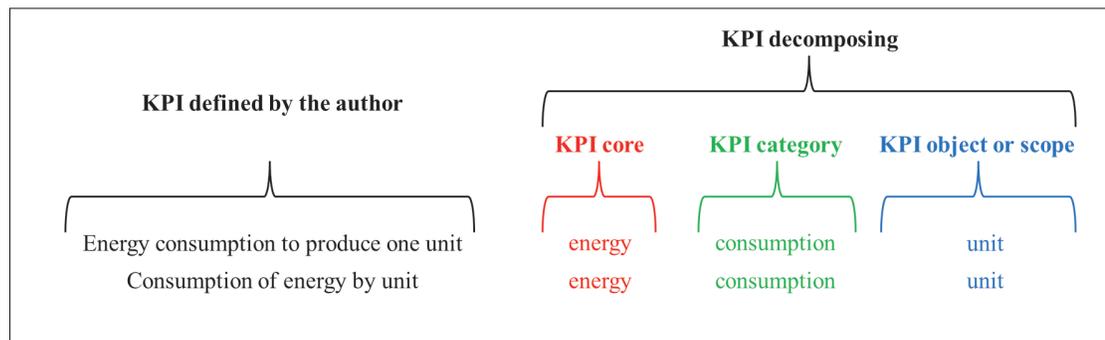


Figure 3.2 Example of a key performance indicator decomposing for the disambiguation process

Once the database compilation was completed, a linguistic disambiguation process was implemented to account for the diverse ways in which authors may mention the same indicator. The process involved decomposing each KPI into its core, category, and the object or scope of its application field. An example of this process is illustrated in figure 3.2, where two authors wrote the same KPI differently. They share the same KPI core (energy), KPI category (consumption),

and KPI object or scope (unit). KPI decomposition allows for grouping, classification, and establishing the frequency of use of the KPI, along with the literature analyzed.

After completing this process, a literature review synthesis was conducted to classify and analyze the KPIs, summarize the contributions of each document, and propose a methodological framework based on the findings of the systematic literature review (SLR) process. The following sections will present the main KPIs related to sustainability performance in remanufacturing.

3.3 Key performance indicators for sustainable remanufacturing

The SLR conducted in this study resulted in the identification of 1021 KPIs in SR, extracted from 1616 records obtained from the analysis of 106 documents. The KPIs are distributed across three sustainable dimensions, comprising 643 economic indicators, 273 environmental indicators, and 105 social indicators. Tables 3.2, 3.3, and 3.4 summarize the most frequently referenced KPIs in the literature : 32 economic, 16 environmental, and 3 social indicators. These tables also include the document counts and the distribution of KPIs along with their fields of use or application (as detailed in sections 3.4.1 to 3.4.6 of the literature review), These applications encompass areas such as sustainability assessment, product design, disassembly, remanufacturability, remanufacturing circularity, and closed-loop supply chains.

The different KPIs in tables 3.2 to 3.4 present a multidimensional approach to SR that extends beyond the sustainable manufacturing KPIs described by Mengistu & Panizzolo (2023). SR also requires considering technical and CE KPIs related to disassembly, remanufacturability, circularity, CLSC, and even product design. This provides decision-makers with a comprehensive understanding of which KPIs to consider when evaluating the adoption, transition, or operation of SR systems or their CLSC. Regarding the distribution of the KPIs in Tables 3.2 to 3.4, the greater number of economic KPIs reveals its prominent position as a driver of SR, outshining the environmental and social dimensions. Economic KPIs provide an exhaustive overview of the main concerns regarding remanufacturing and CLSC operations.

Tableau 3.2 Economic key performance indicators identified in the SLR in four or more documents

Performance indicator	Documents	SA	RCLSCs	RCir	Rem	Dis	PDRem	References
Transport cost	15		✓	✓	✓		✓	Ali, Paksoy, Torğul & Kaur (2020); Alkhayyal (2018); Chirumalla <i>et al.</i> (2023); Das (2020); Das & Mehta (2015); Das & Posinasetti (2015); Erdmann, Koller, Brimaire & Döpfer (2023); Inoue <i>et al.</i> (2020); Miyajima <i>et al.</i> (2019); Noor <i>et al.</i> (2018); Schau, Traverso & Finkbeiner (2012); Taleizadeh, Haghghi & Niaki (2019); Yu & Solvang (2017); Zorbakhshnia, Soleimani & Ghaderi (2018)
Remanufacturing cost	13	✓	✓	✓	✓	✓	✓	Abdullah (2024); Ali <i>et al.</i> (2020); Aydin, Brown, Ali & Badurdeen (2014); Chirumalla <i>et al.</i> (2023); Choudhary, Qaiser, Choudhary & Fernandes (2022); Noor <i>et al.</i> (2018); Priyono <i>et al.</i> (2016); Taleizadeh <i>et al.</i> (2019); Tian <i>et al.</i> (2017); Wang & Tseng (2010); Zhang, Tang, Zhang, Jiang & Cai (2021a); Zhao & Zhou (2023)
Disassembly Time	13	✓		✓	✓	✓	✓	Ali, Enyoghasi & Badurdeen (2021); Ansari <i>et al.</i> (2022); Aydin <i>et al.</i> (2014); Das, Yedlarajiah & Narendra (2000); Favi, Marconi, Rossi & Cappelletti (2021); Kazancoglu & Ozkan-Ozen (2020); Mandolini, Favi, Germani & Marconi (2018); Marconi, Germani, Mandolini & Favi (2019); Mishra, Verma & Tiwari (2022); Ren <i>et al.</i> (2021); Shrivastava, Zhang, Li & Whitely (2005); Vanegas <i>et al.</i> (2018); Zhang <i>et al.</i> (2022a)
Disassembly cost	11	✓	✓	✓	✓	✓	✓	Ali <i>et al.</i> (2020); Amaitik <i>et al.</i> (2023); Ansari <i>et al.</i> (2022); Favi <i>et al.</i> (2021); Jeng & Lin (2017); Ren <i>et al.</i> (2021); Shrivastava <i>et al.</i> (2005); Tchertchian, Millet & Pialot (2013); van Loon & Wassenhove (2018); Wang & Tseng (2010); Zhang <i>et al.</i> (2022b)

Tableau 3.2 Economic key performance indicators identified in the SLR in four or more documents (Continuation).

Performance indicator	Documents	SA	RCLSCs	RCir	Rem	Dis	PDRem	References
Labour cost	8		✓	✓	✓	✓		Ali <i>et al.</i> (2021); Alkhayyal (2018); Inoue <i>et al.</i> (2020); Miyajima <i>et al.</i> (2019); Noor <i>et al.</i> (2018); Mota <i>et al.</i> (2018); Ren <i>et al.</i> (2021); Schau <i>et al.</i> (2012)
Disposal cost	8		✓	✓	✓			Ali <i>et al.</i> (2020); Ansari <i>et al.</i> (2022); Choudhary <i>et al.</i> (2022); Kazancoglu & Ozkan-Ozen (2020); Li, Ying, Chin, Yang & Xu (2018); Noor <i>et al.</i> (2018); Taleizadeh <i>et al.</i> (2019); Yu & Solvang (2017)
Fixed cost	7		✓					Ali <i>et al.</i> (2020); Das (2020); Das & Mehta (2015); Li <i>et al.</i> (2018); Mota <i>et al.</i> (2018); Taleizadeh <i>et al.</i> (2019); Yu & Solvang (2017)
Recycling cost	7	✓	✓			✓	✓	Ali <i>et al.</i> (2020); Aydin <i>et al.</i> (2014); Choudhary <i>et al.</i> (2022); Jeng & Lin (2017); Li <i>et al.</i> (2018); van Loon & Wassenhove (2018); Taleizadeh <i>et al.</i> (2019)
Total cost	7	✓	✓		✓			Arredondo-Soto, Sanchez-Leal, Reyes-Martinez, Salazar-Ruiz & Maldonado-Macias (2018); Boyer <i>et al.</i> (2021); Inoue <i>et al.</i> (2020); Jeng & Lin (2017); Mishra, Rani, Saha, Pamucar & Hezam (2023); Zorbakhshnia <i>et al.</i> (2018); Zhang, Xu, Zhang, Jiang & Wang (2021b)
Recovery cost	6		✓		✓	✓		Aydin <i>et al.</i> (2014); Das (2020); Das & Mehta (2015); Das & Posinasetti (2015); Ren <i>et al.</i> (2021); Taleizadeh <i>et al.</i> (2019)
Products price	6	✓	✓		✓			Das (2020); Das & Mehta (2015); Goepf, Zwolinski & Caillaud (2014); Taleizadeh <i>et al.</i> (2019); Yang <i>et al.</i> (2018a); Zhao & Zhou (2023)
Production cost	6	✓	✓				✓	Das (2020); Das & Mehta (2015); Das & Posinasetti (2015); Fatimah & Aman (2018); Abellan-Nebot, Jasiulewicz-Kaczmarek, Centoamore & Pinto (2024); Zhao & Zhou (2023)

Tableau 3.2 Economic key performance indicators identified in the SLR in four or more documents (Continuation).

Performance indicator	Documents	SA	RCLSCs	RCir	Rem	Dis	PDRem	References
Materials cost	6	✓	✓	✓	✓		✓	Chirumalla <i>et al.</i> (2023); Das & Mehta (2015); Fatimah & Aman (2018); Inoue <i>et al.</i> (2020); Sarwar, Zafar, Hamza & Qadir (2021); Shrivastava <i>et al.</i> (2005) Ansari <i>et al.</i> (2022); Chirumalla <i>et al.</i> (2023); Govindan, Kadziński, Ehling & Miebs (2019); Li <i>et al.</i> (2018); Prajapati, Kant & Shankar (2021); Sethanan, Pitakaso, Kosacka-Olejnik, Werner-Lewandowska & Wasyniak (2019)
Market Share	6	✓	✓	✓				Ali <i>et al.</i> (2021); Aydin <i>et al.</i> (2014); Kazancoglu & Ozkan-Ozen (2020); Mishra <i>et al.</i> (2022); Taleizadeh <i>et al.</i> (2019) Alkhayyal (2018); Das (2020); Das & Mehta (2015); Li <i>et al.</i> (2018); Prajapati <i>et al.</i> (2021)
Core quality condition	5		✓		✓	✓	✓	Alkhayyal (2018); Fatimah & Aman (2018); Sarwar <i>et al.</i> (2021); Schau <i>et al.</i> (2012); Yu & Solvang (2017)
Warehouse Capacity	5		✓					Das (2020); Das & Mehta (2015); Li <i>et al.</i> (2018); van Loon & Wassenhove (2018); Yang <i>et al.</i> (2018a)
Energy cost	5	✓	✓	✓	✓		✓	Ali <i>et al.</i> (2021); Amaitik <i>et al.</i> (2023); Ansari <i>et al.</i> (2022); Jeng & Lin (2017); Noor <i>et al.</i> (2018)
Distribution cost	5		✓		✓			Deveci, Simic & Torkayesh (2021); Jindal & Sangwan (2016); Mota <i>et al.</i> (2018); Tian <i>et al.</i> (2017); Zhang, Li, Wang & Yan (2021c)
Cleaning cost	5		✓		✓			Abdullah (2024); Aziz, Wahab & Ramli (2017); Fatimah <i>et al.</i> (2013); Tchertchian <i>et al.</i> (2013); Vimal <i>et al.</i> (2021)
Operational cost	5		✓		✓		✓	Aydin <i>et al.</i> (2014); Goepf <i>et al.</i> (2014); Jeng & Lin (2017); Li <i>et al.</i> (2018); Zwolinski <i>et al.</i> (2006)
Reliability	5	✓					✓	Deveci <i>et al.</i> (2021); Mejía-Moncayo, Kenné & Hof (2024); Mota <i>et al.</i> (2018); Peng <i>et al.</i> (2019)
Revenue of Recycled	5	✓	✓	✓	✓		✓	Choudhary <i>et al.</i> (2022); Goepf <i>et al.</i> (2014); van Loon & Wassenhove (2018); Zwolinski <i>et al.</i> (2006)
Investment cost	4	✓	✓	✓				
Refurbishment cost	4		✓					

Tableau 3.2 Economic key performance indicators identified in the SLR in four or more documents (Continuation).

Performance indicator	Documents	SA	RCLSCs	RCir	Rem	Dis	PDRem	References
Waste cost	4		✓		✓		✓	Fatimah & Aman (2018); Jeng & Lin (2017); Prajapati <i>et al.</i> (2021); Sarwar <i>et al.</i> (2021)
Quality	4			✓	✓		✓	Inoue <i>et al.</i> (2020); Justham, Rosamond, Goodall, Conway & West (2013); Mishra <i>et al.</i> (2023); ZARBakhshnia <i>et al.</i> (2018)
Distance to collection centre	4		✓		✓			Ali <i>et al.</i> (2020); Chakraborty, Mondal & Mukherjee (2017); Mandolini <i>et al.</i> (2018); Wang & Tseng (2010)
Total number of Components	4		✓		✓		✓	Ali <i>et al.</i> (2021); Chakraborty <i>et al.</i> (2017); Mandolini <i>et al.</i> (2018); Wang & Tseng (2010)
Remanufactured product price	4		✓		✓	✓	✓	Ali <i>et al.</i> (2020); Aydin <i>et al.</i> (2014); Priyono <i>et al.</i> (2016); Zwolinski <i>et al.</i> (2006)
Inspection cost	4		✓					Ali <i>et al.</i> (2020); Amaitik <i>et al.</i> (2023); Jeng & Lin (2017); Mishra <i>et al.</i> (2022)
Production capacity	4		✓	✓				Das (2020); Das & Mehta (2015); Mota <i>et al.</i> (2018); Taleizadeh <i>et al.</i> (2019)
Products Weight	4		✓			✓		Alkhayyal (2018); Mandolini <i>et al.</i> (2018); Mota <i>et al.</i> (2018); Ren <i>et al.</i> (2021)
Table criteria : SA - Sustainability assessment, RCLSCs - Remanufacturing CLSCs, RCir - Remanufacturing circularity assessment, Rem - Remanufacturability, Dis - Product disassembly assessment for remanufacturing, PDRem - Product design for remanufacturing.								

Transport cost emerges as the most frequent KPI, followed by remanufacturing cost, disassembly time, disassembly cost, and labor cost. Disassembly is a technical enabler of remanufacturing, as it is commonly used to evaluate a product's complexity and remanufacturability. CE strategies, such as recycling, reuse, and refurbishing, represent other cost categories. Most of the KPIs described are related to CLSC. This shows the main role of remanufacturing in the CLSC.

Tableau 3.3 Environmental key performance indicators identified in the SLR in four or more documents

Performance indicator	Documents	SA	RCLSCs	RCir	Rem	Dis	PDRem	References
GHG emissions	23	✓	✓	✓			✓	Alamerew, Kambanou, Sakao & Brissaud (2020); Ali <i>et al.</i> (2020); Alkhayyal (2018); Das (2020); Das & Mehta (2015); Das & Posinasetti (2015); Fatimah <i>et al.</i> (2013); Golinska <i>et al.</i> (2015); Golinska & Kuebler (2014); Golinska-Dawson & Pawlewski (2015); Govindan <i>et al.</i> (2019); Erdmann <i>et al.</i> (2023); Inoue <i>et al.</i> (2020); Jayakrishna & Vinodh (2017); Jensen, Prendeville, Bocken & Peck (2019); Miyajima <i>et al.</i> (2019); Prajapati <i>et al.</i> (2021); Russell & Nasr (2023); Shakourloo (2017); Taleizadeh <i>et al.</i> (2019); Vimal <i>et al.</i> (2021); Yadav <i>et al.</i> (2020); Yanikara, Kuhl & Thorn (2014)
Energy Consumption	20	✓	✓	✓	✓	✓	✓	Chen <i>et al.</i> (2023); Das (2020); Das & Mehta (2015); Das & Posinasetti (2015); Favi <i>et al.</i> (2021); Golinska <i>et al.</i> (2015); Golinska-Dawson & Pawlewski (2015); Govindan <i>et al.</i> (2019); Jayakrishna & Vinodh (2017); Kazancoglu & Ozkan-Ozen (2020); Kurt <i>et al.</i> (2021); Lu <i>et al.</i> (2020); Prajapati <i>et al.</i> (2021); Ren <i>et al.</i> (2021); Russell & Nasr (2023); Sarwar <i>et al.</i> (2021); Shakourloo (2017); Taleizadeh <i>et al.</i> (2019); Vimal <i>et al.</i> (2021); Yu & Solvang (2017)
Environmental Impact	13	✓	✓	✓	✓		✓	Abdullah (2024); Aydin <i>et al.</i> (2014); Bhatia, Dora & Jakhar (2019); Goodall, Rosamond & Harding (2014); Hummen & Wege (2021); Jensen <i>et al.</i> (2019); Jindal & Sangwan (2016); Lampón (2023); van Loon & Wassenhove (2018); Mota <i>et al.</i> (2018); Shrivastava <i>et al.</i> (2005); Tchertchian <i>et al.</i> (2013); Yang <i>et al.</i> (2018a)

Tableau 3.3 Environmental key performance indicators identified in the SLR in four or more documents (Continuation).

Performance indicator	Documents	SA	RCLSCs	RCir	Rem	Dis	PDRem	References
Recycling	6	✓	✓				✓	Boorsma, Polat, Bakker, Peck & Balkenende (2022); Golinska & Kuebler (2014); Govindan <i>et al.</i> (2019); Sarwar <i>et al.</i> (2021); Yu & Solvang (2017); Zarbakhshnia <i>et al.</i> (2018)
Remanufactured Parts	5		✓		✓		✓	Ali <i>et al.</i> (2020); Aydin <i>et al.</i> (2014); Goepp <i>et al.</i> (2014); Justham <i>et al.</i> (2013); Zwolinski <i>et al.</i> (2006)
Disposal	5	✓	✓		✓			Aydin <i>et al.</i> (2014); Golinska & Kuebler (2014); Govindan <i>et al.</i> (2019); Justham <i>et al.</i> (2013); Zarbakhshnia <i>et al.</i> (2018)
Acidification potential	5			✓	✓		✓	Alamerew <i>et al.</i> (2020); da Silva <i>et al.</i> (2012); Schau <i>et al.</i> (2012); Spreafico (2022); Vogtlander, Scheepens, Bocken & Peck (2017)
Global Warming Potential	5				✓		✓	De Barba, de Oliveira Gomes, Salis & Bork (2013); Favi <i>et al.</i> (2021); da Silva <i>et al.</i> (2012); Schau <i>et al.</i> (2012); Spreafico (2022)
Solid Waste	4	✓			✓	✓		Jiang, Zhang & Sutherland (2011); Kazancoglu & Ozkan-Ozen (2020); Pan & Liu (2009); Zhang <i>et al.</i> (2021b)
Remanufacturing	4		✓		✓		✓	Boorsma <i>et al.</i> (2022); Govindan <i>et al.</i> (2019); Zarbakhshnia <i>et al.</i> (2018); Zhang, Matsubae & Nakajima (2021d)
Remanufactured Products	4	✓	✓				✓	Ansari <i>et al.</i> (2022); Goepp <i>et al.</i> (2014); Yu & Solvang (2017); Zwolinski <i>et al.</i> (2006)
Eutrophication potential	4			✓	✓		✓	Alamerew <i>et al.</i> (2020); Goepp <i>et al.</i> (2014); Yu & Solvang (2017); Zwolinski <i>et al.</i> (2006)
Number of parts	4		✓		✓		✓	Ali <i>et al.</i> (2020); Aydin <i>et al.</i> (2014); Goepp <i>et al.</i> (2014); Zwolinski <i>et al.</i> (2006)
Reused Parts	3		✓				✓	Ali <i>et al.</i> (2020); Goepp <i>et al.</i> (2014); Zwolinski <i>et al.</i> (2006)

Tableau 3.3 Environmental key performance indicators identified in the SLR in four or more documents (Continuation).

Performance indicator	Documents	SA	RCLSCs	RCir	Rem	Dis	PDRem	References
Energy Saved	3					✓	✓	Goepp <i>et al.</i> (2014); Ren <i>et al.</i> (2021); Zwolinski <i>et al.</i> (2006)
Energy Embodied	3	✓			✓	✓		Justham <i>et al.</i> (2013); Ren <i>et al.</i> (2021); Russell & Nasr (2023)
Table criteria : SA - Sustainability assessment, RCLSCs - Remanufacturing CLSCs, RCir - Remanufacturing circularity assessment, Rem - Remanufacturability, Dis - Product disassembly assessment for remanufacturing, PDRem - Product design for remanufacturing.								

Greenhouse gas (GHG) emissions, energy consumption, and environmental impact are the driving factors behind the environmental KPIs, followed by CE practices as recycling materials, remanufactured and reused parts. The literature identifies several commonly used KPIs in life cycle assessment (LCA). These include acidification potential, disposal of materials, global warming potential, solid waste, and eutrophication potential within the environmental category.

The social dimension places significant emphasis on strategic KPIs, including but not limited to health and safety measures for both employees and users. The actors involved in the CLSC also consider factors like job creation and employment stability. Unfortunately, social KPIs are less considered in comparison with the other dimensions.

Tableau 3.4 Social key performance indicators identified in the SLR in three or more documents

Performance indicator	Documents	SA	RCLSCs	RCir	Rem	Dis	PDRem	References
Health and safety	17	✓	✓	✓	✓	✓	✓	Alkouh, Keddar & Alatefi (2023); Aziz <i>et al.</i> (2017); Deveci <i>et al.</i> (2021); Golinska <i>et al.</i> (2015); Govindan <i>et al.</i> (2019); Kazancoglu & Ozkan-Ozen (2020); Mishra <i>et al.</i> (2022, 2023); Mouflih, Gaha, Bosch & Durupt (2023); Sarwar <i>et al.</i> (2021); Sethanan <i>et al.</i> (2019); Taleizadeh <i>et al.</i> (2019); Ullah, Muhammad & Ko (2016); Vimal <i>et al.</i> (2021); Vogtlander <i>et al.</i> (2017); ZARBAKHSHNIA <i>et al.</i> (2018); Zhang <i>et al.</i> (2021b)
Job Creation	3	✓	✓	✓				Alamerew <i>et al.</i> (2020); Fatimah & Aman (2018); Taleizadeh <i>et al.</i> (2019)
Employment Stability	3		✓					Li <i>et al.</i> (2018); Prajapati <i>et al.</i> (2021); ZARBAKHSHNIA <i>et al.</i> (2018)
Table criteria : SA - Sustainability assessment, RCLSCs - Remanufacturing CLSCs, RCir - Remanufacturing circularity assessment, Rem - Remanufacturability, Dis - Product disassembly assessment for remanufacturing, PDRem - Product design for remanufacturing.								

Some KPIs, such as transportation costs, transportation distance, fixed costs, and investment costs among others, play a crucial role in CLSC network design. This is because the proximity to customers and suppliers reduces energy consumption, operational costs, and environmental impacts. This also emphasizes the importance of supporting local or regional supply chains, which helps minimize the environmental effects of long-distance transportation.

The price of new products is used as a reference for remanufactured products. Reverse logistics demands consideration of collection costs, distance to the collection centre, storage capacity, and employment stability. The inspection operation assesses the quality conditions of the core or used product.

Quality conditions can be assessed by evaluating various factors, including product deterioration, technical standards, regulatory requirements, maintenance data, as well as an organization's experience and expertise. Depending on the types of materials and their conditions, the disposal process and its cost are established.

The disassembly time is directly proportional to the complexity of the operation, thereby impacting its cost. When assessing remanufacturing operations, it is important to consider various KPIs, including remanufacturing costs, cleaning costs, the price of remanufactured products, and production capacity. The energy saved and embodied in the product plays a crucial role in determining the overall energy savings achieved through remanufacturing. The assessment also examines the quantity of reused and remanufactured parts and their effects on acidification, eutrophication, and global warming.

Each of these indicators plays a role in assessing the feasibility of remanufacturing. The costs and revenue in the recycling operation are strongly influenced by the recycled materials and the energy they contain. When evaluating energy savings for subsequent transformation processes, it is essential to consider this energy as a determining factor. In the following sections, a descriptive analysis of each field of application will be exposed. The different approaches identified in the literature are described and analyzed in the next section.

3.4 Literature review

The following sections will provide an in-depth analysis of the six different application fields of use for the KPIs and their relationship with smart technologies identified through the SLR. This will be accompanied by a thorough examination of the scope of the reviewed literature.

3.4.1 Sustainability assessment in remanufacturing

The three dimensions of sustainability (economic, environmental, and social) are part of the concerns of remanufacturing companies. The development of indicators to assess environmental performance is a concern in various studies, including those by Pan & Liu (2009), Tsiliyannis

(2014), and Haupt & Hellweg (2019), 2019). Pan & Liu (2009), developed a system of environmental indicators for the automotive remanufacturing industry in China. This system encompasses aspects such as durability, environmental policies, green technology, environmental development, utilization, standard authentication systems, and noise ranking, among others. Tsiliyannis (2014), presented the cycle rate as a method for achieving environmental improvement. This method is based on three main criteria : reducing final waste, minimizing the extraction of virgin raw materials, and lowering manufacturing impacts. Haupt & Hellweg (2019), proposed the concept of Retained Environmental Value in response to the fact that mass-based indicators, such as recycling rates, cannot fully capture the environmental perspective. This indicator measures the proportion of environmental impact that is retained in products and materials through reuse, remanufacturing, repair, or recycling.

Yadav *et al.* (2020), identify and analyze several indicators that influence the adoption of the CE. They include strategic, management, informational, technological, supply chain, and organizational indicators. Its results show that strategic and management indicators have the most significant influence on the development of other indicators. Ansari *et al.* (2022) assessed the KPIs of the remanufacturing supply chain using the Supply Chain Operations Reference Model.

The sustainability of remanufactured products in Indonesian small and medium-sized enterprises (SMEs) was analyzed by Fatimah *et al.* (2013). Its proposal introduces a framework that considers life cycle cost, reliability, warranty, sales, GHG emissions, solid waste, and employment opportunities. Similarly, Fatimah & Aman (2018), introduce remanufacturing sustainability indicators, a guide for measuring the sustainability of SMEs in Indonesia. It aims to help SMEs understand and evaluate their economic, social and environmental performance. Sethanan *et al.* (2019), developed a set of sustainability indicators for remanufacturing in small and medium-sized enterprises (SMEs). These indicators serve as guidelines for creating a sustainable measurement system that is adaptable to different company sizes and types of products.

Golinska & Kuebler (2014), presented a method for assessing the sustainability maturity of remanufacturing companies and identifying areas that require improvement. Golinska *et al.* (2015) introduced a set of indicators to classify the level of sustainability of remanufacturing companies. While Golinska-Dawson & Pawlewski (2015) assessed environmental issues in remanufacturing supply chains using simulation.

Arredondo-Soto *et al.* (2018) analyzed the current state of remanufacturing in Mexico. The study identifies the elements of the productive systems of companies and compares them to identify similarities, differences, advantages, and disadvantages. Russell & Nasr (2023) proposed a methodology for assessing the environmental and economic impacts of value-retention processes, including reuse, repair, refurbishment, and remanufacturing. This study demonstrates that these processes have different forms of value and varying degrees of environmental and economic impact.

Jensen *et al.* (2019) examined remanufacturing as a strategy for circular business models, emphasizing its value. They also highlighted the importance of considering social, environmental, and profitability perspectives while ensuring market protection.

Price and service competition in remanufacturing systems is addressed by Yang *et al.* (2018a). Their study examines various aspects, including demand uncertainty, recycling efforts, channel structure, sustainability analysis, pricing and marketing strategies, supplier relationships, emissions regulation, and more. Competitiveness and the interplay between greening and remanufacturing strategies in supply chains were examined by Zhao & Zhou (2023). Their study considers the uncertainty of performance and the behaviour of risk-averse manufacturers.

Over the past two decades, there has been a notable interest in quantifying the sustainable performance of remanufacturing, as evidenced by the approaches presented in this section. These studies have focused on providing insights from a sustainability standpoint regarding remanufacturing products, processes, companies, supply chains, and industries. They also emphasize the various interactions that remanufacturing entails within CLSCs. The subsequent section analyzes product design for remanufacturing.

3.4.2 Product design for remanufacturing

Product design plays a crucial role in remanufacturing, as its shape, dimensions, materials, joining processes, and other characteristics significantly determine the remanufacturability and sustainability of products. Therefore, it is essential to analyze the different approaches towards design in remanufacturing, as presented below.

Environmental impact assessment has become an essential criterion for evaluating design in remanufacturing, as demonstrated by approaches such as those of da Silva *et al.* (2012). Their study detailed a meticulous design of a grinding machine, including an environmental assessment and a discussion of product monitoring and maintenance. Spreafico (2022) analyzed design strategies for CE using LCA. This study examined the environmental impacts of design solutions that incorporate reuse, waste management, and remanufacturing compared to those that do not account for a CE strategy.

Tableau 3.5 Design frameworks focused on remanufacturing

Framework	Framework purpose
Remanufacturing Product Profiles (REPRO2) (Zwolinski <i>et al.</i> , 2006)	Support initial stages of design process by product profiles.
Design framework (Yang, Nasr, Ong & Nee, 2017)	Material selection for parts to be remanufactured
Remanufacturing quality function deployment (RQFD) (Vimal <i>et al.</i> , 2021)	RQFD integrates sustainability and remanufacturing strategies for product design considering the voice of customer.
Life Cycle Commonality Metrics (LCCM) (Wang & Tseng, 2010)	LCCM measure the product design's ability and convenience for implementing end-of-life strategies such as reuse, remanufacturing, and recycling.
Design framework based on eco-design (Favi <i>et al.</i> , 2021)	This framework guide companies in the use of eco-design methods and tools, towards eco-sustainability and CE.
Fuzzy Axiomatic Design (FAD) (Chakraborty <i>et al.</i> , 2017)	FAD helps to evaluate and rank product design alternatives for remanufacturing.

Tableau 3.5 Design frameworks focused on remanufacturing (Continuation).

Framework	Framework purpose
Circular Product Readiness (CPR) (Boorsma <i>et al.</i> , 2022)	CPR helps designers to monitor the implementation level when designing a circular product or service.
Modular design method. (Miyajima <i>et al.</i> , 2019)	This modular design method uses design structure matrix to generates modular architectures, that will be, and supply chain based on environmental load, cost, quality, and lead time.
Modular design strategy. (Inoue <i>et al.</i> , 2020)	This strategy helps to design and evaluate modular product architectures from the perspective of supply chain management, considering sustainability factors alongside traditional metrics.
The modular grouping explorer (MGE) tool (Tchertchian <i>et al.</i> , 2013)	MGE tool helps designers modify product architecture to optimize end-of-life strategies.
Joint Complexity Index (JCI) (Mesa, Illera, Esparragoza, Maury & Gómez, 2018)	JCI provides a holistic measurement of the complexity involved in the assembly and disassembly tasks of mechanical joints for open architecture products.
Design for Upgradability (DfU) (Aziz <i>et al.</i> , 2017)	DfU enhances the remanufacturing features of a product by incorporating upgrade strategies at the design stage.

Design frameworks for remanufacturing have been developed to support the design process ; some of them are listed in table 3.5 and explained as follows. Remanufacturing Product Profiles (REPRO2) (Zwolinski *et al.*, 2006), emerge as a tool to assist designers in the initial stages of the design process. This process involves analyzing the project context and identifying remanufacturable product profiles (RPPs) to help designers create products suited for remanufacturing. Goepf *et al.* (2014) adopted this strategy by integrating eco-design approaches based on product LCA.

Other frameworks address different remanufacturing edges, such as material selection (Yang *et al.*, 2017), product development regarding sustainability (Vimal *et al.*, 2021), or performing economic analysis into product design to achieve sustainability (Wang & Tseng, 2010). Also, Yang *et al.* (2017) addressed durability, cleanability, and restorability/upgradability. Here, durability

involves extending the service life and minimizing deterioration during usage. Cleanability pertains to the effortless elimination of impurities.

Restorability and upgradability refer to the ability to recover and enhance the properties or features of a part through various processes. Favi *et al.* (2021) presented a design-based eco-design framework for disassembly and modular components to facilitate remanufacturing and recycling. Chakraborty *et al.* (2017) analyzed the design characteristics of products for enhancing remanufacturability using a combination of axiomatic design and analytical hierarchy process (AHP). Boorsma *et al.* (2022), introduced the Circular Product Readiness (CPR) approach, a tool designed to evaluate the circularity of product designs.

Modular architectures integrate standardized, upgradable modules, which, thanks to effective supply chain management, enable products to be developed with interchangeable and upgradable components. Examples of such architectures in computer production are discussed in the work of Inoue *et al.* (2020) and Miyajima *et al.* (2019). Miyajima *et al.* (2019) presented a modular design and evaluation method for supply chain management. Inoue *et al.* (2020) propose a modular design strategy that considers sustainability and supplier selection in the initial design phase. The aim is to design products and their components with reuse, remanufacturing and future updating in mind.

Similarly, Tchertchian *et al.* (2013) analyzed the Modular Grouping Explorer (MGE) tool, which helps to identify and modify module limits in product design to increase remanufacturability and recyclability. Jayakrishna & Vinodh (2017) described the application of gray relational analysis for material selection and end-of-life (EoL) strategy selection in the automotive industry. Lampón (2023) examined the implementation of modular electric vehicle platforms in the automotive industry to achieve their sustainable development goals.

Aziz *et al.* (2017) introduce design for upgradability, considering KPIs, such as durability, ease of reprocessing, safety, interface between components, lifecycle similarities, useful lifetime, performance, reliability and technology cycles. Design for X enhances remanufacturing by improving service functionalities, circularity, and supporting design decisions and knowledge

management (Sassanelli, Urbinati, Rosa, Chiaroni & Terzi, 2020). Mesa *et al.* (2018) introduced the Joint Complexity Index (JCI) to assess the complexity of assembly and disassembly tasks in mechanical joints. This index evaluates various joining methods based on their functional characteristics and overall complexity. While Noor *et al.* (2018), addressed economic decision-making in the selection of the best alternative in design for remanufacturing.

The reviewed literature suggests that design for remanufacturing includes multiple dimensions. This necessitates a concurrent approach encompassing manufacturing, assembly, and disassembly to enhance performance, conserve materials, and reduce costs. Modular design emerges as an option that contributes to this purpose. Modularization refers to the process of breaking down products into their fundamental functions to create modules that are interchangeable and upgradable (Chavanel-Precloux, Maranzana & Hof, 2025). This approach facilitates subsequent remanufacturing and recycling, as seen in components for industries like automotive and computing. This requires the comprehensive development of standards that enable component interchangeability, quality control, and the integration of a comprehensive supply chain. Remanufacturing design requires a complete product lifecycle analysis, regardless of the chosen method (Shahhoseini, Heydari & Pedrammehr, 2023). This requires capturing, managing, and securing the traceability of product lifecycle information (Sassanelli *et al.*, 2020). This highlights the crucial role of technology in facilitating this task. Disassembly enables remanufacturability and represents a vital factor for product design for remanufacturing, as outlined in the next section.

3.4.3 Product disassembly assessment for remanufacturing

Disassembly is an essential step in remanufacturing, as the subsequent stages of the process - cleaning , repair, reconditioning, and assembly - depend on it. Thus, their assessment is crucial in determining the feasibility of remanufacturing or the level of remanufacturability. KPIs have been developed to evaluate the feasibility of disassembly through an analysis that considers operational time, disassembly sequence, and product complexity. Some of these KPIs are listed here : Ease of Disassembly Metric (eDiM) (Vanegas *et al.*, 2018), Effective Disassembly Time

(EDT) (Mandolini *et al.*, 2018; Marconi *et al.*, 2019), Disassembly Effort Index (DEI) (Das *et al.*, 2000), and Joint Complexity Index (JCI) (Mesa *et al.*, 2018).

The Ease of Disassembly Metric (eDiM) (Vanegas *et al.*, 2018) provides a systematic and quantitative approach to estimating disassembly time and assessing its ease. This process involves classifying tasks into six categories : tool change, identification, manipulation, positioning, disconnection, and removal. Erdmann *et al.* (2023), presented an adaptation of eDiM to evaluate the ease of disassembly of five e-bike motors. Effective Disassembly Time (EDT) (Mandolini *et al.*, 2018; Marconi *et al.*, 2019) helps determine the sequence and time of component disassembly in complex products. The Disassembly Effort Index (DEI) (Das *et al.*, 2000) calculates a score that considers factors such as fixation, access, instruction, hazard, and force requirements.

Sustainability has become a key focus in evaluating dismantling performance. Kazancoglu & Ozkan-Ozen (2020) analyzed the concept of sustainable balance of the disassembly line. Lu *et al.* (2020) examined energy efficiency in disassembly. Ren *et al.* (2021) concentrated on optimizing value recovery and energy conservation in the disassembly of electronic products.

Sustainability assessment involves additional challenges that smart technologies can help to solve. For instance, Xia, Gao, Li, Wang & Chao (2014) introduced a service-oriented framework of a cloud-based remanufacturing system (CBRS) for the sustainable management of waste electrical and electronic equipment (WEEE). Mouflih *et al.* (2023) identified the main Industry 4.0 technologies to improve sustainability in disassembly.

Operations research and Optimization-Based Approaches are commonly employed in disassembly. Lu *et al.* (2020) introduced a hybrid meta-heuristic algorithm to solve the problem of for-profit and energy-efficient disassembly sequencing. Ren *et al.* (2021) presented a multi-objective disassembly planning approach for end-of-life products to maximize value recovery and energy conservation. Zhang *et al.* (2022b) proposed a multi-objective optimization model for balancing bilateral disassembly lines in automotive engine remanufacturing. Zhang *et al.* (2022a) presented a selective parallel disassembly sequence planning methodology. Priyono *et al.* (2016) examined

the factors that affect the disassembly process, including organizational characteristics, process choices, and product attributes.

Disassembly time emerges as the primary metric for evaluating disassembly performance, as it provides a quantitative assessment of its complexity. However, to achieve a successful process, it is necessary to consider simultaneously both the disassembly sequence and the complexity of the product. Indeed, Industry 4.0 technologies can contribute to simplify dismantling operations and promoting the integration of sustainability criteria into processes. The following section 3.4.4 will examine the concept of remanufacturability.

3.4.4 Remanufacturability assessment

The remanufacturability of a product refers to the existence of conditions that allow for its remanufacture. This requires a multi-criteria focus analysis of the problem, which extends beyond the product's borders Tian *et al.* (2017). This concept requires the simultaneous harmonization of economic, environmental, social, and technical factors, as described by Zhang *et al.* (2021a). Their study also highlights the importance of assessing remanufacturing feasibility and the need to improve the required methods for deployment.

Shrivastava *et al.* (2005) proposed a decision support system that provides information on optimal disassembly methods, material composition, and environmental impact assessment of electronic products. This system enables the evaluation of various parameters, including dismantling analysis, product recycling, material evaluation, and environmental impact assessment. Jiang *et al.* (2011) presented a multi-criteria decision-making model for selecting remanufacturing technologies using the AHP.

The sustainability of remanufactured alternators, assessed using a life-cycle approach, was evaluated by Schau *et al.* (2012). According to their results, remanufacturing exhibits lower emissions and costs when compared to the production of new parts, and the conventional alternator design excels in all aspects. De Barba *et al.* (2013) suggested considering the voice of the customer in conjunction with technical, economic, and environmental assessments.

Goodall *et al.* (2014) examined the tools and techniques used to assess remanufacturability. They found that while decision factors are adequately covered, operational tools and consideration of uncertainty are often overlooked. This approach is also shared by Justham *et al.* (2013), who proposed a knowledge-based framework for assessing remanufacturability of products in a supply chain. Aydin *et al.* (2014) proposed a lifecycle-based methodology to determine the recoverability, reusability, remanufacturability, and recyclability of end-of-life products.

Ullah *et al.* (2016) aimed to find a standardized and efficient approach for decision-making in remanufacturing. This approach offers a systematic and effective method for determining the optimal strategy for remanufacturing machine tools. Jindal & Sangwan (2016), proposed a fuzzy framework for selecting the best recovery alternative among five recovery processes : repair, refurbishing, remanufacturing, cannibalizing, and recycling. Vogtlander *et al.* (2017) analyzed the costs, market value, and ecological costs of remanufactured products.

Peng *et al.* (2019), addressed the problem of selecting restoration technologies to recover the original dimensions of engine parts. Zhang *et al.* (2021d) investigated the impact of remanufacturing on reducing material losses in vehicle engines throughout their lifecycles. Zhang *et al.* (2021b), presented a model for assessing the sustainability of retired machinery. Hummen & Wege (2021) presented the Circular Economy Remanufacturing Indicator (CERI) to compare the environmental impacts and cost of new and remanufactured products.

Ali *et al.* (2021) analyzed the quantitative assessment of products to develop an EoL product remanufacturability index. Its methodology considers factors such as the complexity of the product design, the technological capability of the process, and the incoming quality, considering the remanufacturing time, and the score of the inspection tests. While Chen *et al.* (2023), evaluate the environmental impacts, recycling technologies, and sustainability of lithium-ion batteries (LIBs) used in electric vehicles (EVs). Chirumalla *et al.* (2023) analyzed the economic feasibility of remanufacturing, repurposing, and reusing Li-ion batteries for their second life in the heavy-duty vehicle industry.

In 2021, the French government (Écologie Logement, 2021) introduced the “reparability index” towards to promote CE and reduce waste in five product categories : smartphones, laptops, televisions, lawn mowers, and front-loading washing machines. The reparability index contributes to addressing planned obsolescence by raising consumer awareness to buy products that are more easily repaired. Canada is also exploring to implement a similar index based on the French experience (Équiterre, 2024). Alkough *et al.* (2023) presented the Repairability Index (IOR) as a mathematical score to assess the ease of repair of electronic equipment, considering the capacity of a part, component, core, or product to be repaired. Repairability refers to the feasibility of repairing a part, component, core, or product.

Different perspectives on the analysis of remanufacturability are presented in the aforementioned studies. In these approaches, economic and environmental criteria prevail, with a lesser presence of social ones. Both internal and external product factors are considered in these analyses. Internal factors are directly related to the product, its components, materials, geometry, deteriorating condition, and the processes necessary to their remanufacturing. Product’s reparability also emerges as an internal factor when pursuing remanufacturability. External factors analyze the remanufacturability of products within their specific context. This means conducting an economic, environmental, and social evaluation of the product. This is achieved by considering its impacts not only on remanufacturing, but also on the performance of the product in operation compared to new products. Section 3.4.5 examines circularity, with a particular focus on remanufacturing.

3.4.5 Remanufacturing circularity assessment

Assessing circularity in terms of sustainability requires KPIs that facilitate this task. Saidani *et al.* (2019) presented a comprehensive taxonomy of circularity indicators that considers implementation levels, types of CE strategies, performance, circularity perspective, and degree of transversality. Kristensen & Mosgaard (2020) and Matos *et al.* (2023a) explored and categorized circular economy micro-level indicators in the existing literature. Their findings show that indicators concentrate mainly on environmental and economic aspects while paying

less attention to the social dimension. In addition, their study provides practical guidelines for selecting and applying such KPIs.

The Product-Level Circularity Metric (PLCM), proposed (Linder, Sarasini & van Loon, 2017), is a metric that evaluates the ratio between recirculated economic value and the product's total value. The Decision Support Tool for Remanufacturing (DSTR) (van Loon & Wassenhove, 2018) evaluates the economic and environmental viability of remanufacturing in comparison to the production of new components. Current approaches present new indicators, such as those proposed by Bobba *et al.* (2023), who introduced the "Circular Input Rate" (CIR). This indicator is described as the relationship between material flows from reused, remanufactured, and recycled products or components and sector-specific demand for materials. Mishra *et al.* (2022) presented a quality indicator (QI) oriented to the circular economy for the evaluation and categorization of various basic types in recycling and remanufacturing procedures.

Other approaches, as proposed by Alamerew *et al.* (2020), include a multi-criteria assessment method to evaluate circularity strategies at the product level. Benini, Leroy, Tolio & Magnanini (2022) introduced a model to promote circular practices in the remanufacturing of EoL products and parts. Figge, Thorpe, Givry, Canning & Franklin-Johnson (2018) introduced measures for both resource circularity and resource longevity. Kurt *et al.* (2021) introduced a classification tool for circular supply chain indicators, aiming to evaluate the circularity of supply chains at a strategic level. Boyer *et al.* (2021) contributed to the understanding of circularity through a three-dimensional framework that considers material recirculation, utilization, and durability.

The different approaches to analyzing circularity depend strongly on the CE strategies under consideration. In the case of remanufacturing, it is necessary to consider simultaneously the three dimensions of circularity from a product-focused perspective. In practical terms, it is recommended to consider the KPIs previously described (PLCM, DSTR, CIR, or QI), which provide different perspectives on remanufacturing circularity. In the following section, the KPIs for closed-loop supply chains in remanufacturing will be analyzed.

3.4.6 Closed-loop supply chains KPIs for remanufacturing

The various approaches identified in the literature regarding the CLSC for remanufacturing are presented in this section. These include the design of reverse logistics (RL) networks, sustainable supply chain planning, remanufacturing planning, RL supplier selection, and logistics performance. Each of these aspects contributes to understanding the different approaches to consider throughout the CLSC of SR, including its main KPIs.

3.4.6.1 Design of reverse logistics networks

RL networks play a fundamental role in the collection of used products, connecting users and collection centers with facilities for disassembly, recycling, remanufacturing, and final disposal. The design of these networks presents challenges, such as uncertainty in product returns, as discussed by Yanikara *et al.* (2014). This study proposes a simulation-based methodology to evaluate different network configurations based on sustainability and productivity metrics. Performance metrics include total travel distance, GHG emissions, time in the system, and work in process. Yu & Solvang (2017) addressed the design of a RL network to capture the value of products at the end of their useful life. They proposed a stochastic, multi-product, multi-step optimization model that integrates carbon restriction for the design of a RL network.

Alkhayyal (2018) proposed a multi-criteria decision-making approach for designing a reverse supply chain in a carbon trading environment. This study optimizes part flow for remanufacturing, considering profit and GHG emissions. Ali *et al.* (2020) presented a model that evaluates four return strategies (reuse, remanufacturing, recycling and disposal), considering customer satisfaction, increasing market share, reducing costs and adding value to the logistics chain. Facility location is a sensitive decision for CLSC, addressed in various studies. Bhatia *et al.* (2019) proposed a framework for evaluating the ideal location of a remanufacturing plant. This approach considers initial investment, transportation costs, proximity to customers, availability of renewable energy, and availability of skilled labour.

Mota *et al.* (2018) optimize supply chain design using a multi-objective mixed-integer linear programming model that integrates facility location and capacity determination, supplier selection, and purchase levels definition, technology selection and allocation, transportation network definition (including both unimodal and intermodal options), supply planning, product recovery, and remanufacturing.

Deveci *et al.* (2021) proposed an integrated neutrosophic decision-making model to select the best location for an automotive lithium-ion battery remanufacturing facility. Grosse Erdmann, Koller, Amir, Mihelič & Döpfer (2023) proposed a multi-method simulation model for the design of product-service system (PSS) reverse supply chain networks. The model determines the optimal infrastructure and locations for storing, remanufacturing, and repairing used products in the reverse supply chain.

The design of remanufacturing facilities is also analyzed by Mejía-Moncayo, Kenné & Hof (2021). They introduced a hybrid manufacturing architecture that integrates cellular and reconfigurable manufacturing features. Mejía-Moncayo *et al.* (2024) presented a multi-objective approach to the design of a productive architecture for a smart sustainable remanufacturing system. The proposed architecture integrates reconfigurable features based on Industry 4.0 that mitigate the negative effects of uncertainty on the quality, quantity, and return time of used products. This study also highlighted the need to integrate productive architecture with smart architecture and a business model to achieve sustainable system performance.

3.4.6.2 Sustainable Supply Chain Planning

Environmental concerns in the design and planning of the CLSC are addressed by Das & Posinasetti (2015) to improve sustainability and business performance. Their proposal includes a system for collecting EoL products and managing customer returns, along with refurbishment, recovery, and repair operations, all of which are managed by service providers. They emphasized the importance of green modular design in product architecture as a facilitator of product recovery processes, environmental sustainability, and cost-effectiveness in CLSC operations.

Das & Mehta (2015) presented a model that integrates environmental and economic sustainability. Their model assesses the cost of the product, the cost of collecting returns, the cost of acquisition and recovery, the cost of transportation, distribution, and inventory, as well as the cost of energy and emissions penalties.

Taleizadeh *et al.* (2019) introduced a comprehensive model for planning a multi-period, multi-echelon sustainable CLSC that considers social and environmental impacts. This model also utilizes a quality-dependent discount offer to incentivize product returns and categorizes returned products by quality to inform recovery decisions. Das (2020) discussed practices and strategies to improve economic and environmental sustainability, including emissions trading schemes, sustainable transport and supplier management. Ansari, Kant & Shankar (2020) evaluated and classified solutions to mitigate risks in sustainable remanufacturing supply chains.

3.4.6.3 Remanufacturing Planning

Remanufacturing planning is a crucial factor in achieving reliable performance in an environment characterized by uncertainty in the conditions, quantity, and return time of used products. Jeng & Lin (2017), proposed a fuzzy cradle-to-cradle remanufacturing planning model for the recycled toner cartridge industry. Their model considers the entire product life cycle and uses fuzzy theory to define environmental laws and regulations, ecological reputation, and environmental performance indicators. Shakourloo (2017) developed a stochastic multi-objective goal programming model to optimize the sustainability and efficiency of the remanufacturing process, thereby increasing profit and reducing costs. Choudhary *et al.* (2022), introduce a comprehensive decision-making framework to select the optimal recovery strategy for electronics returns in India.

3.4.6.4 Selection of reverse logistics providers

The complexity of RL operations and the limited resources available to various companies make them prefer outsourcing their RL practices to a third-party reverse logistics provider (3PRLP)

as a strategic approach. One of the most essential and risky processes for outsourcing RL is selecting the optimal 3PRLP among the alternatives. Several studies have addressed this issue, including Li *et al.* (2018). Indeed, they deployed a case study of the computer manufacturing industry to illustrate their 3PRLP approach. Zarbakhshnia *et al.* (2018) analyzed the evaluation and selection of a sustainable 3PRLP using a multi-attribute decision-making model applied to a case study from the automotive industry.

Govindan *et al.* (2019) proposed a hybrid method for a case study in the Indian automobile remanufacturing industry. The study highlights the importance of incorporating sustainability criteria into supplier evaluation. Zhang *et al.* (2021c), implemented an approach that integrates multi-criteria decision-making and circularity to classify remanufacturing suppliers for medium-sized engines in China. While Mishra *et al.* (2023) proposed a framework to select a sustainable 3PRLP, considering the economic, environmental and social dimensions.

3.4.6.5 Logistics performance

Once the logistics network has been designed, it is necessary to measure its performance, as presented by Sagnak (2020). Their study proposes a framework for measuring logistics performance by focusing on sustainable procurement, sustainable distribution, and reverse logistics. Similarly, Prajapati *et al.* (2021) proposed a framework to identify and prioritize performance indicators for measuring the success of reverse logistics implementation. Environmental, industrial operations, customer, financial, and social indicators are considered. Sarwar *et al.* (2021), analyze the impact of green supply chain management practices on the economic, environmental, and social performance of Pakistani organizations.

3.4.6.6 KPIs distribution along with main concerns in remanufacturing's CLSC

This section addresses the distribution of sustainable KPIs along remanufacturing's CLSC concerns, which include the design of RL networks, sustainable supply chain planning,

remanufacturing planning, the selection of RL providers, and logistics performance. These concerns are outlined in table 3.6.

Table 3.6 summarizes the main sustainable KPIs in remanufacturing CLSCs, where the cost of transport is the most frequently adopted economic KPI. This table highlights its impact on remanufacturing and the main role of reverse logistics and distribution in SR. Similarly, fixed costs, warehouse capacity, production capacity, energy costs, investment costs, distribution costs, and operational costs. These highlight the need to consider the capacity and cost of the reverse logistics network, as different concerns share these key performance indicators (KPIs) in CLSC setting. The role of the government as an enabler of sustainable remanufacturing is evidenced by the KPI of government subsidies. The other economic KPIs in table 3.6 are mainly related to remanufacturing processes.

Environmental KPIs, as outlined in table 3.6, include GHG emissions, energy consumption, recycling, collection, and renewable energy. These KPIs once again reaffirm the crucial role of energy along transport and CLSC operations, as well as the need to decarbonize CLSCs. In conclusion, health and safety is the principal social KPIs for all CLSC concerns and stakeholders, while employment stability is critical for maintaining the quality of services provided by the CLSC and ensuring a good quality of life for its employees.

The KPIs listed in table 3.6 can be utilized by decision-makers at various stages of the CLSC network. Starting with the design of the RL network, the KPIs provide insights into the selection of criteria to consider in these projects. Then, plan the sustainable supply chain or remanufacturing systems, assess logistics performance, or even select an RL provider. This also highlights the need to address remanufacturing, considering its interactions with other CLSC actors.

Tableau 3.6 Distribution of Economic, environmental, and social key performance indicators identified in the literature in three or more documents, along with the main fields of application in remanufacturing closed-loop supply chains

Performance indicator	Documents	Main fields of application				References
		Design of reverse logistics networks	Sustainable Supply Chain Planning	Remanufacturing Planning	Selection of reverse logistics providers	
Economic						
Transport cost	10	✓	✓	✓		Ali <i>et al.</i> (2020); Alkhayyal (2018); Das (2020); Das & Mehta (2015); Das & Posinasetti (2015); Erdmann <i>et al.</i> (2023); Taleizadeh <i>et al.</i> (2019); Yu & Solvang (2017); Zarbakhshnia <i>et al.</i> (2018)
Fixed cost	7	✓	✓	✓		Ali <i>et al.</i> (2020); Das (2020); Das & Mehta (2015); Li <i>et al.</i> (2018); Mota <i>et al.</i> (2018); Taleizadeh <i>et al.</i> (2019); Yu & Solvang (2017)
Warehouse Capacity	5	✓	✓	✓	✓	Alkhayyal (2018); Das (2020); Das & Mehta (2015); Li <i>et al.</i> (2018); Prajapati <i>et al.</i> (2021)
Recycling cost	5	✓	✓	✓	✓	Ali <i>et al.</i> (2020); Aydin <i>et al.</i> (2014); Choudhary <i>et al.</i> (2022); Jeng & Lin (2017); Li <i>et al.</i> (2018); Taleizadeh <i>et al.</i> (2019)
Disposal cost	5	✓	✓	✓	✓	Ali <i>et al.</i> (2020); Ansari <i>et al.</i> (2022); Choudhary <i>et al.</i> (2022); Li <i>et al.</i> (2018); Taleizadeh <i>et al.</i> (2019); Yu & Solvang (2017)
Recovery cost	4		✓			Das (2020); Das & Mehta (2015); Das & Posinasetti (2015); Taleizadeh <i>et al.</i> (2019)
Distance to Collection centre	4	✓	✓			Ali <i>et al.</i> (2020); Chakraborty <i>et al.</i> (2017); Mandolini <i>et al.</i> (2018); Wang & Tseng (2010)
Production Capacity	4	✓	✓			Das (2020); Das & Mehta (2015); Mota <i>et al.</i> (2018); Taleizadeh <i>et al.</i> (2019)

Tableau 3.6 Distribution of Economic, environmental, and social key performance indicators identified in the literature in three or more documents, along with the main fields of application in remanufacturing closed-loop supply chains (Continuation).

Performance indicator	Documents	Fields of application			References
		Design of reverse logistics networks	Sustainable Supply Chain Planning	Remanufacturing Planning	
Energy cost	3	✓		✓	Alkhayyal (2018); Sarwar <i>et al.</i> (2021); Yu & Solvang (2017)
Investment cost	3	✓			Deveci <i>et al.</i> (2021); Mejía-Moncayo <i>et al.</i> (2024); Mota <i>et al.</i> (2018)
Transport Distance	3	✓	✓		Das (2020); Das & Mehta (2015); Yanikara <i>et al.</i> (2014)
Products Demand	3	✓	✓		Alkhayyal (2018); Das (2020); Das & Mehta (2015)
Waste Cost	3		✓	✓	Jeng & Lin (2017); Prajapati <i>et al.</i> (2021); Sarwar <i>et al.</i> (2021)
Distribution Cost	3		✓	✓	Das (2020); Das & Mehta (2015); Li <i>et al.</i> (2018)
Market Share	3			✓	Govindan <i>et al.</i> (2019); Li <i>et al.</i> (2018); Prajapati <i>et al.</i> (2021)
Operational Cost	3	✓		✓	Deveci <i>et al.</i> (2021); Mota <i>et al.</i> (2018); Zhang <i>et al.</i> (2021c)
Delivery	3			✓	Govindan <i>et al.</i> (2019); Li <i>et al.</i> (2018); Zarbakhshnia <i>et al.</i> (2018)
Government Subsidy	3	✓		✓	Bhatia <i>et al.</i> (2019); Sarwar <i>et al.</i> (2021); Yu & Solvang (2017)
Products Price	3		✓		Das (2020); Das & Mehta (2015); Taleizadeh <i>et al.</i> (2019)
Production Cost	3		✓		Das (2020); Das & Mehta (2015); Das & Posinasetti (2015)

Tableau 3.6 Distribution of Economic, environmental, and social key performance indicators identified in the literature in three or more documents, along with the main fields of application in remanufacturing closed-loop supply chains (Continuation).

Performance indicator	Documents	Main fields of application					References
		Design of reverse logistics networks	Sustainable Supply Chain Planning	Remanufacturing Planning	Selection of reverse logistics providers	Logistics performance	
Remanufacturing Cost	3	✓	✓	✓			Ali <i>et al.</i> (2020); Choudhary <i>et al.</i> (2022); Taleizadeh <i>et al.</i> (2019)
Total Cost	3			✓	✓		Jeng & Lin (2017); Mishra <i>et al.</i> (2023)
Environmental							
GHG emissions	11	✓	✓	✓	✓	✓	Ali <i>et al.</i> (2020); Alkhayyal (2018); Das (2020); Das & Mehta (2015); Das & Posinasetti (2015); Govindan <i>et al.</i> (2019); Erdmann <i>et al.</i> (2023); Prajapati <i>et al.</i> (2021); Shakourloo (2017); Taleizadeh <i>et al.</i> (2019); Yanikara <i>et al.</i> (2014)
Energy Consumption	9	✓	✓	✓	✓	✓	Das (2020); Das & Mehta (2015); Das & Posinasetti (2015); Govindan <i>et al.</i> (2019); Prajapati <i>et al.</i> (2021); Sarwar <i>et al.</i> (2021); Taleizadeh <i>et al.</i> (2019); Yu & Solvang (2017)
Recycling	4	✓			✓	✓	Govindan <i>et al.</i> (2019); Sarwar <i>et al.</i> (2021); Yu & Solvang (2017); Zarbakhshnia <i>et al.</i> (2018)
Collection	3		✓		✓		Das (2020); Govindan <i>et al.</i> (2019); Li <i>et al.</i> (2018)
Renewable Energy	3	✓		✓		✓	Bhatia <i>et al.</i> (2019); Prajapati <i>et al.</i> (2021); Shakourloo (2017)
Social							
Health and safety	6	✓	✓		✓	✓	Deveci <i>et al.</i> (2021); Govindan <i>et al.</i> (2019); Mishra <i>et al.</i> (2023); Sarwar <i>et al.</i> (2021); Taleizadeh <i>et al.</i> (2019); Zarbakhshnia <i>et al.</i> (2018)

Tableau 3.6 Distribution of Economic, environmental, and social key performance indicators identified in the literature in three or more documents, along with the main fields of application in remanufacturing closed-loop supply chains (Continuation).

Performance indicator	Documents	Design of reverse logistics networks Sustainable Supply Chain Planning Remanufacturing Planning Selection of reverse logistics providers Logistics performance	References
Employment Stability	3	✓ ✓	Li <i>et al.</i> (2018); Prajapati <i>et al.</i> (2021); Zarbakhshnia <i>et al.</i> (2018)

3.4.7 Smart sustainable remanufacturing

I4.0 technologies have been highlighted by various authors as enablers of sustainability and CE strategies, such as remanufacturing (Alshammari, Ani, Sarfraz, Okorie & Salonitis, 2025; Culot, Orzes, Sartor & Nassimbeni, 2020; Prajapati, Dable, Kant & Batra, 2025). I4.0 or smart technologies recover, process, and analyze product life cycle information (PLCI) along processes and CLSC (Taddei *et al.*, 2022), enabling the assessment or calculation of the KPIs in SR. Quality management systems, environmental management systems, and others utilize PLCI to quantify KPIs and support decision-making processes at various organizational levels (Mejía-Moncayo *et al.*, 2023b). Remanufacturing strategies have been incorporating various technologies to streamline their operations (Kerin & Pham, 2019; Tolio *et al.*, 2017), enhance CLSC operations ((Taddei *et al.*, 2022; Xin, Lang & Mishra, 2022), overcome their intrinsic barriers or challenges (Bressanelli, Adrodegari, Perona & Saccani, 2018), and to support sustainable decision-making processes (Kerin & Pham, 2020).

The Internet of Things (IoT) enables the recovery and tracking of PLCI along CLSCs to optimize resource usage (Delpla *et al.*, 2021), reconfigure supply chain processes, and provide data to support sustainable decision-making processes (Alam, Latif, Kokash & Ahsan, 2025). This is enabled through the digitization of collection, transportation, remanufacturing, recycling, and disposal (Sun, Yu & Solvang, 2023).

Cyber-physical systems (CPS) integrate sensors, actuators, and computer algorithms to achieve efficient, reliable, flexible, or reconfigurable processes (Alshammari *et al.*, 2025) or CLSC (Taddei *et al.*, 2022). Cloud manufacturing technologies enable online access to data and applications (Singh *et al.*, 2025). Big data analytics (BDA), artificial intelligence (AI), machine learning (ML), simulation, optimization, and other technologies or methodologies enable the processing and analysis of data to inform decision-making (Mejía-Moncayo *et al.*, 2023b).

Papacharalampopoulos, Toupalis, Lagios, Karagianni & Stavropoulos (2024) suggested that I4.0 facilitates the optimization of key performance indicators (KPIs) such as energy consumption, lead times, and material efficiency. Yannou, Bouillass, Saidani & Jankovic (2024) introduced the Circular Digital Cockpit, which uses IoT, simulation, and AI to monitor and optimize circularity. Prajapati *et al.* (2025) highlight the role of IoT, BDA, and cloud computing, in optimizing KPIs, such as resource efficiency and waste reduction. Oláh, Novotná, Sarihasan, Erdei & Popp (2022) affirmed the positive impact of robotics and BDA in operational efficiency. Mouflih *et al.* (2023) examined Virtual Reality (VR), Augmented Reality (AR), Human-Robot Collaboration (HRC), and Radio Frequency Identification (RFID) to optimize disassembly processes, addressing time efficiency, cost reduction, and operator safety. Noman, Akter, Pranto & Haque (2022) proposed a decision support system based on AI and ML to improve waste reduction and resource recovery. Xia *et al.* (2014) introduced a cloud-based remanufacturing system framework for the sustainable management of e-waste. Shahhoseini *et al.* (2023) emphasized the significance of PLCI in product design for remanufacturing.

Psarommatis, May & Azamfirei (2025) highlighted the contribution of IoT, AI, and blockchain (BCT) to enhanced traceability and predictive maintenance, impacting key performance indicators

(KPIs) such as resource efficiency and life cycle longevity. Neri *et al.* (2025) illustrated how Digital Product Passports (DPPs) enhance traceability and lifecycle management, Digital Twins (DTs) optimize disassembly and reassembly processes, and the Internet of Everything (IoE) facilitates real-time decision-making. Eldrandaly, Saber, Mohamed & Abdel-Basset (2022) proposed a hybrid multi-criteria decision-making framework for sustainable manufacturer selection based on BCT and BDA. (Govindan, 2022) emphasized the potential of BCT to increase customer trust in remanufactured products by enhancing traceability throughout the product lifecycle. (Bettín-Díaz, Mejía & Rojas, 2021) explored the integration of BCT to enhance quality management systems and build customers' confidence.

The transition from I4.0 to I5.0 is ongoing. In this new Industry 5.0 industrial paradigm, smart or Industry 4.0 technologies are integrated with a sustainable, human-centric approach (Castillo, Otero-Romero & Alvarez-Palau, 2025; Yannou *et al.*, 2024). In remanufacturing, human-robot collaborative disassembly plays a crucial role in this transition by integrating human agility with robotic capabilities (Lou, Zhang, Tan & Lv, 2024; Yuan *et al.*, 2025; Simone *et al.*, 2025). DTs are among the crucial technologies enabling I5.0 allowing to address uncertainty and improving sustainability in RL (Sun *et al.*, 2023; Guangju *et al.*, 2025). I5.0 also facilitates the linking of diverse analytical methods (optimization and simulation) in RL network planning for disruption mitigation (Yu & Sun, 2024).

Despite the advantages of I4.0 or I5.0 for remanufacturing, some challenges remain for their successful implementation. Papacharalampopoulos *et al.* (2024) revealed limitations in capturing specific I5.0 KPIs, such as human prosperity and resilience. Taddei *et al.* (2022) and Prajapati *et al.* (2025) highlighted unresolved challenges, including standardization, scalability, and social impact measurement. Oláh *et al.* (2022) and Psarommatis *et al.* (2025) identified I4.0 high costs and the shortage of skilled labour as major barriers to its implementation.

Yu & Sun (2024) suggested that, despite high initial technology investment, long-term cost and emission savings can be achieved. There are gaps in standardized sustainability metrics for disassembly (Mouflih *et al.*, 2023) and circularity in industrial systems (Noman *et al.*, 2022).

Additionally, concerns regarding data access and availability persist (Amaitik *et al.*, 2023), as well as issues related to data security and intellectual property (Neri *et al.*, 2025).

The consulted literature demonstrates how remanufacturing is adopting smart systems and sustainability to achieve smart sustainable remanufacturing. The following section synthesizes the main findings of the literature review that was performed.

3.5 Literature review analysis and discussion

The SLR conducted in this study presents a broad spectrum of KPIs in SR. Sections 3.3 and 3.4 focus on answering the first two research questions (RQ1 and RQ2) by presenting the KPIs that are most frequently referenced in the consulted documents. The identified KPIs offer a comprehensive view of sustainability in remanufacturing for decision-makers, encompassing the assessment of sustainability performance across remanufactured products, processes, companies, and CLSCs. These KPIs also highlight the multidimensional nature of SR along product dimensions (materials, parts, components, and cores), processes, CLSC, and stakeholders.

The KPIs presented in this study integrate CE and sustainable KPIs along with remanufacturing products, processes, and CLSC. This focus provides a holistic approach to understanding SR and shows the need to customize indicators directly related to the product, operation, process, company, or CLSC.

The assessment of remanufacturing sustainability relies on its precise definition within the context of the product, process, or organization that adopts or has already implemented remanufacturing. This approach is evident in the various studies that evaluate the sustainability of remanufacturing from different perspectives, as previously explained in section 3.4.1. However, this focus also creates a challenge when comparing the sustainability of remanufactured products or processes in different markets.

Product design for remanufacturing (section 3.4.2) integrates different focuses, as the topics previously considered for sustainability assessment, remanufacturability, circularity, and CLSC

concerns, along with section 3.4. Design frameworks for remanufacturing support this process from the early stages of new remanufacturable product design, as well as redesigning products to improve their remanufacturability or sustainability performance.

Among the deployed methods, design for X stands out, with a design approach towards modular architectures that contributes to product's remanufacturability. Repairability and upgradability emerge as key topics in product design, alongside remanufacturability and circularity. Indeed, longevity also plays an important role as an alternative to the design of non-remanufacturable products.

The focus of this study on CE includes assessing disassembly, remanufacturability, and circularity. This is crucial to achieving sustainable performance because these technical or CE KPIs contribute to measuring and improving the performance of products, processes, or operations. Disassembly and remanufacturability KPIs provide insights into the feasibility of recovering the value retained in materials, parts, components, and cores. These KPIs can be used in the early stages of remanufacturing adoption, product design, or process improvement.

This study presents a set of circularity KPIs focused on remanufacturing. These KPIs provide insight into the CE system and material loops involved in remanufacturing. Circularity is a concept that is evolving, and numerous approaches have been developed to address circularity in consideration of different CE strategies (Saidani *et al.*, 2019). Indeed, the large number of approaches makes it complicated to perform comparisons between circularity KPIs. It would be preferable to adopt a standardized method for evaluating the circularity of products.

The significant number of studies focusing on remanufacturing CLSCs emphasizes its importance in SR. These cover the design of RL networks, sustainable supply chain planning, selection of RL providers, remanufacturing planning, and logistics performance. CLSC actors must identify which KPIs apply specifically to a use case to assess its performance, taking into account the needs of their stakeholders.

The CLSC design, operation, and optimization are crucial perspectives to achieve SR. Various studies utilize optimization models based on the KPIs identified in this research to design or improve the performance of remanufacturing operations, systems, or CLSCs. These models employ a multi-criteria approach, comprehensively addressing sustainability dimensions.

I4.0 and I5.0 technologies enable the retrieval, processing, analysis, and utilization of PLCI for KPI-based decision-making in SR. I5.0 integrates smart systems with sustainability, which aligns with SR. The advantages of I4.0 and I5.0, as described in the reviewed literature, demonstrate the need to integrate technology into the implementation of KPIs in SR. These implementations must be integrated with organizations' management systems to fully leverage their potential. Traceability is highlighted as a crucial issue in remanufacturing, where IoT, AI, CPS, BDA, and BCT play a prominent role. Some authors also express concerns regarding social sustainability and the use, security, access, and management of data.

In summary, the conducted literature review has comprehensively discussed various KPIs and concepts that have been resulted in the formulation of the following definition of SR :

“Sustainable remanufacturing involves performing remanufacturing and CLSC processes or operations sustainably. This comprises ensuring concurrently the disassembly, remanufacturability and circularity of the product, its components, parts and materials, regarding economic, environmental, and social concerns of stakeholders through the product life cycle”.

A practical approach to supporting decision-makers will be introduced in section 3.6.

3.6 Methodological framework for decision makers

The scope of the KPIs identified in this study is broad. Therefore, decision-makers have concerns about their selection and use. Tables 3.2 to 3.4 present the distribution of the indicators among the main fields of application reported in the literature. These can be used as a reference to select the KPIs to be implemented. However, this study seeks to provide a closer approximation to

the user, enabling them to take advantage of the KPI's full potential through a methodological framework.

The proposed methodological framework jointly evaluates sustainability dimensions and the processes of product disassembly, recycling, and remanufacturing. A thorough analysis, shown in figure 3.3, is conducted across product layers (materials, parts, and components) and system layers (product, CLSC, and processes) to satisfy stakeholder requirements. This framework is applicable throughout the remanufacturing process, from initial adoption assessment to ongoing operational management and product design or redesign.

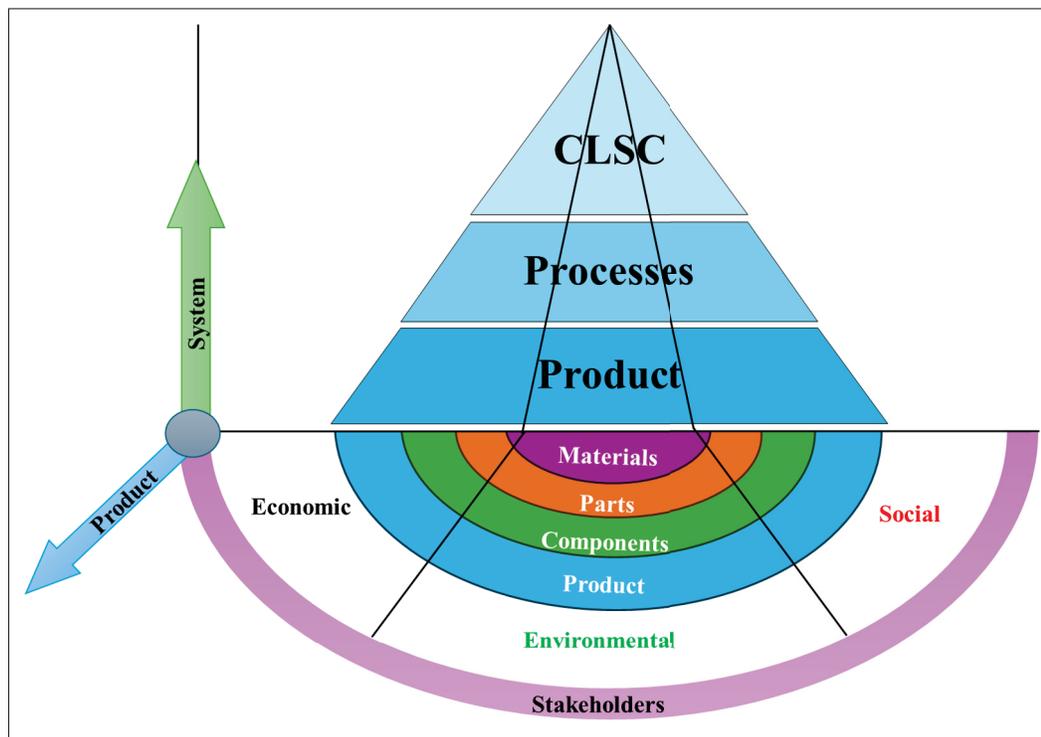


Figure 3.3 Product and system layers through sustainability dimensions and stakeholders' requirements in the proposed methodological framework

This methodological framework begins by recovering information on the product, the manufacturing processes involved, and its CLSC. Subsequently, a KPI assessment is undertaken to develop the decision-making criteria, which are then used to guide the final decision, a process illustrated in figure 3.4.

The first step of the framework recovers the information that feeds the KPIs and contributes to establish the stakeholders' requirements or objectives for each KPI. The required information could include the product's bill of materials, drawings or datasheets, material composition, CLSC information, process route, life cycle information, maintenance reports, quality reports, and stakeholders' requirements, such as governmental policies, technical standards, investors' objectives, employees and community requirements, or other relevant information sources. The recovery, process, and analysis of this information must be supported by I4.0 and I5.0 technologies, as suggested in section 4.7. The implementation of this methodological framework can be enhanced by a smart architecture that integrates technology, management systems, stakeholders and operations (Mejía-Moncayo et al., 2023).

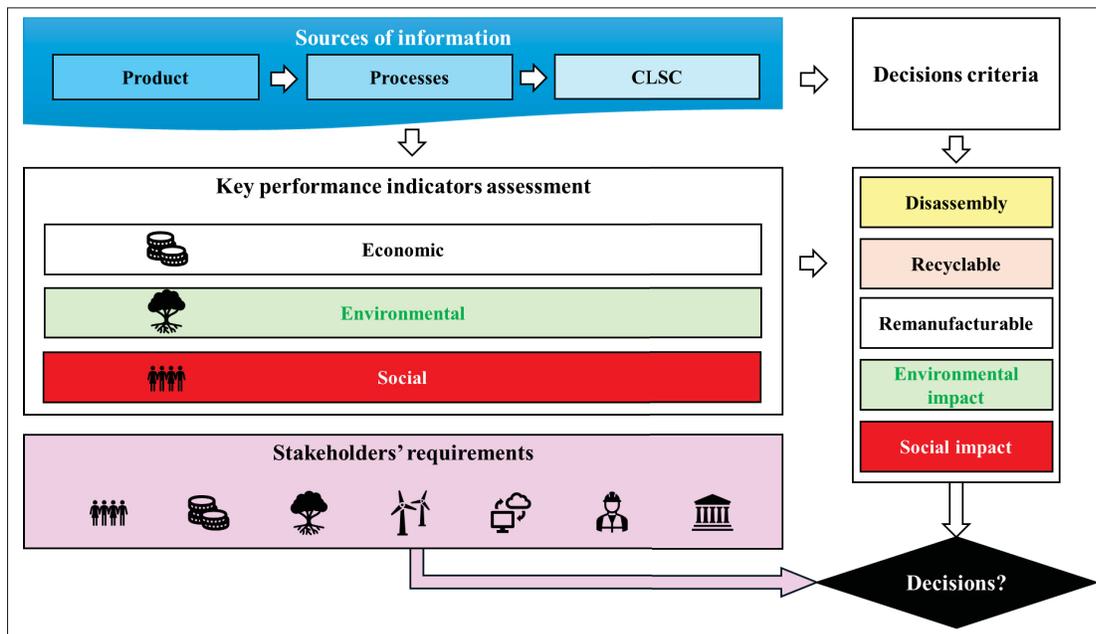


Figure 3.4 Three phases proposed methodology suggested for implementing the KPIs of tables 3.2 to 3.4

Once the information is recovered, the KPI assessment is performed by implementing the KPIs described in tables 3.2 to 3.4. This includes the analysis of materials, parts, components, processes, and CLSCs from product recovery to disassembly, recycling, and remanufacturing. A top-to-bottom, left-to-right KPI assessment sequence is recommended to determine decision criteria, as illustrated in figures 3.5 to 3.7.

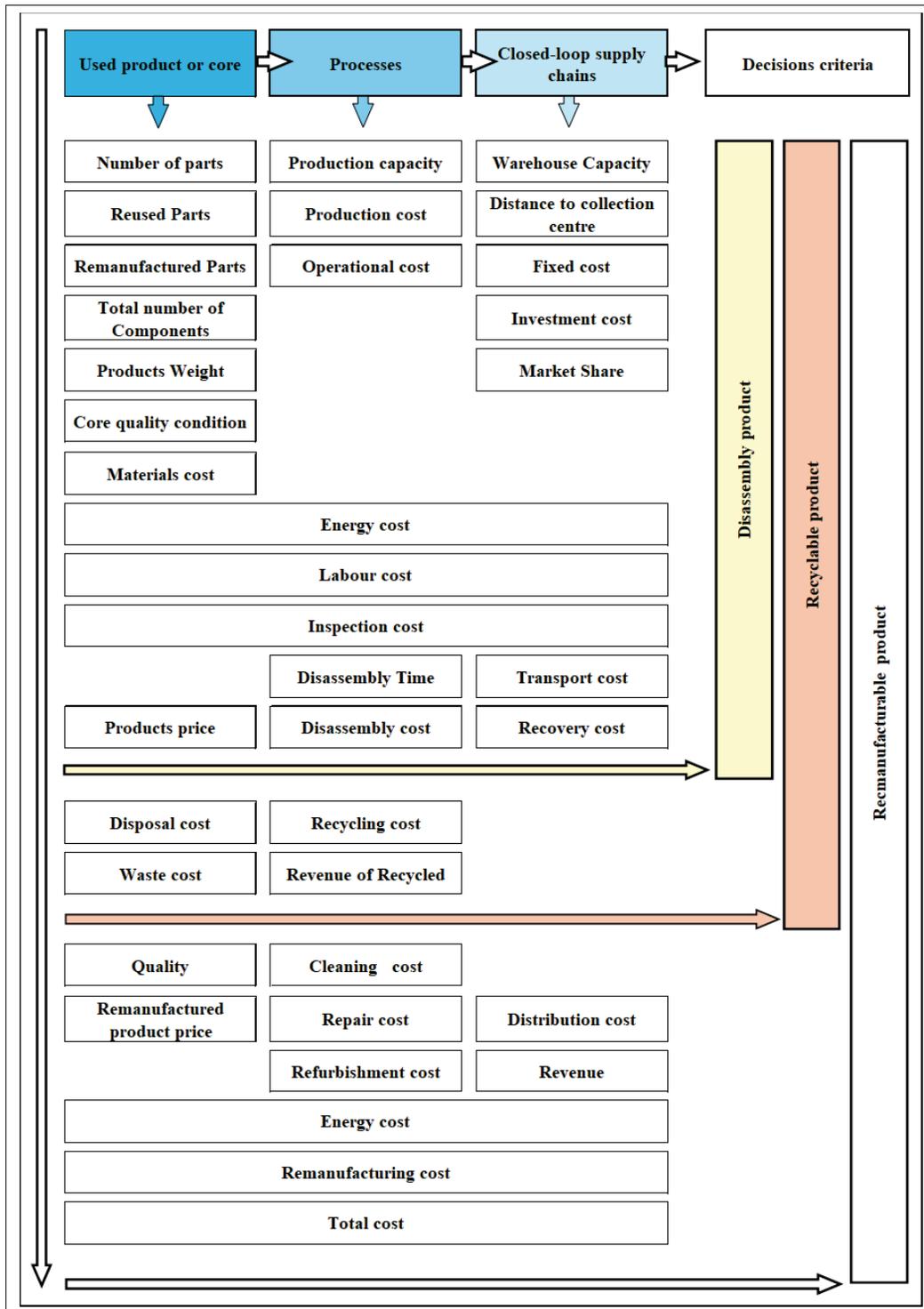


Figure 3.5 Proposed methodological framework assessment sequence of economic key performance indicators to determine if the product is disassembly, recyclable, or remanufacturable

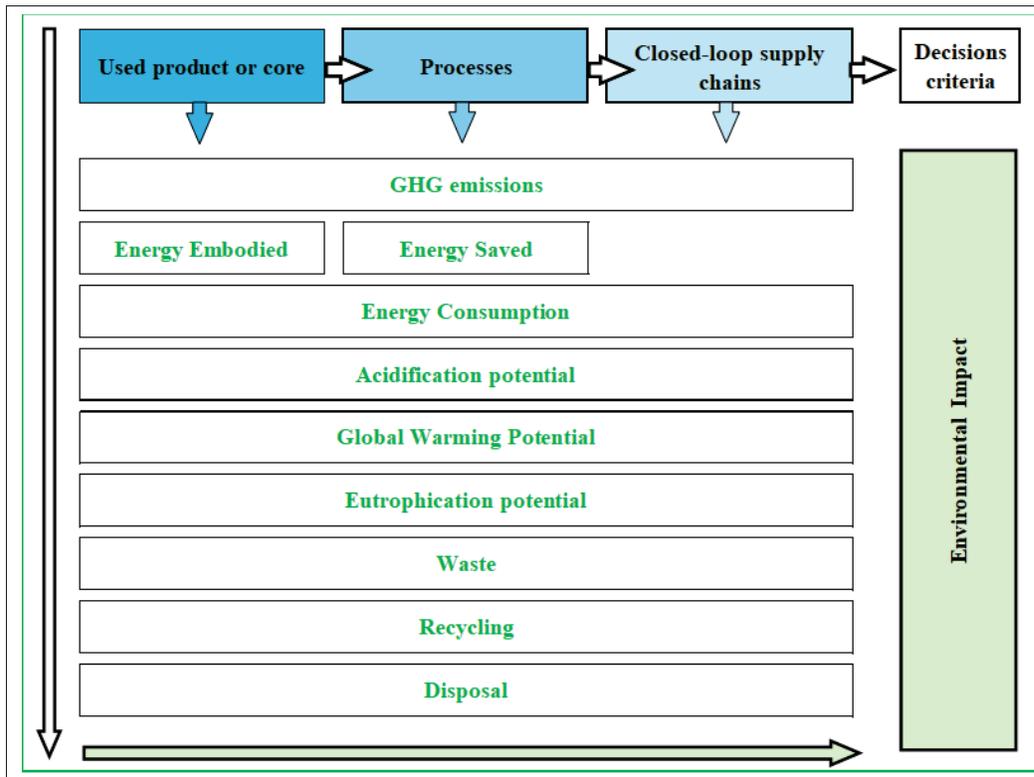


Figure 3.6 Proposed methodological framework assessment sequence of environmental key performance indicators to determine the environmental impact when evaluating if the product is disassembly, recyclable, or remanufacturable

Figure 3.5 presents the assessment of economic KPIs to evaluate disassembly, recycling and remanufacturing. Figure 3.6 focuses on environmental KPIs, and figure 3.7 on social KPIs, to determine the environmental and social impact of disassembly, recycling or remanufacturing.

This suggestion encompasses the three sustainability dimensions and focuses on KPIs related to disassembly, recycling, and remanufacturing, including disassembly cost, recycling cost, remanufacturing or total cost, environmental impact, and social impact, as illustrated in figures 3.5 to 3.7.

The final step of the framework is the decision-making process, which concurrently determines whether a product can be sustainably disassembled, recycled, or remanufactured. This step

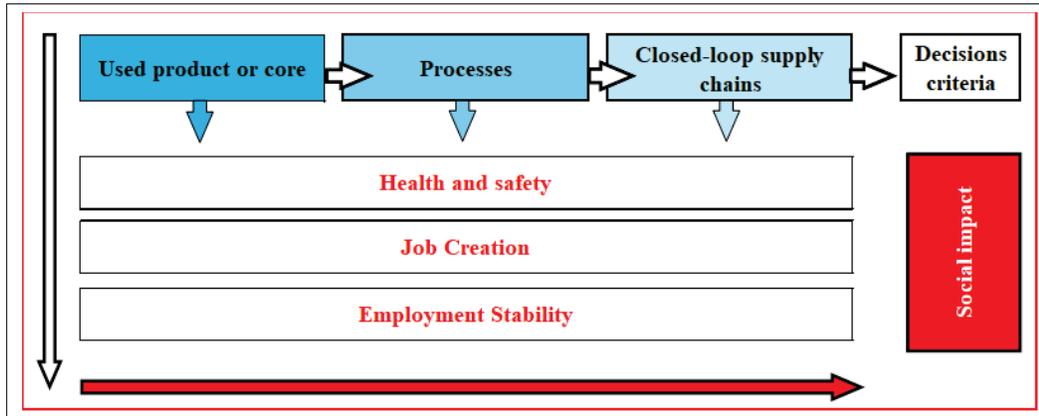


Figure 3.7 Proposed methodological framework assessment sequence of social key performance indicators to determine the social impact when evaluating if the product is disassembly, recyclable, or remanufacturable

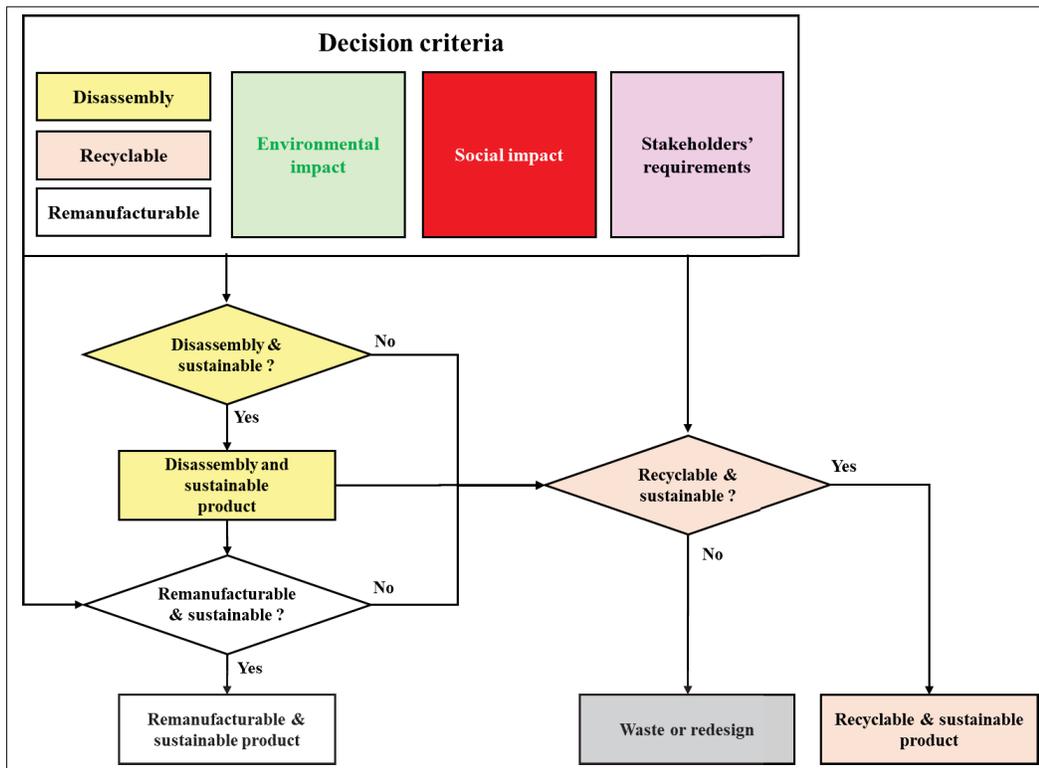


Figure 3.8 Decision-making process for the methodological framework

involves comparing decision criteria with stakeholder requirements, as illustrated in Figures 3.5 to 3.7, to inform decisions, as shown in Figure 3.8.

The process begins with evaluating the product's disassemblability and sustainability. If the product qualifies as disassembly- and sustainability-friendly, it is then assessed for its potential to be sustainably remanufactured. Suppose the product does not meet the criteria for sustainable disassembly or remanufacturing. In that case, the next step is to evaluate its recyclability in a sustainable manner to recover the value embedded in its materials. If sustainable recycling is also not feasible, redesign or responsible disposal should be considered.

In essence, the proposed methodology aims to support the evaluation of sustainable recovery options across products, processes, or CLSC by systematically aligning with stakeholder requirements from the initial adoption of SR strategies to the end-of-life management of remanufactured products.

3.7 Conclusions

This study conducts a systematic literature review to identify the primary key performance indicators in sustainable remanufacturing, determine their primary fields of application, define sustainable remanufacturing, and provide practical insights through a methodological framework. These objectives were appropriately achieved by answering the four research questions (RQ1-RQ4) introduced and discussed in sections 3.3 to 3.6.

The most referenced KPIs in SR (32 economic, 16 environmental, and 3 social) were identified by a comprehensive review process of 106 systematically selected published documents. In terms of frequency of use, the KPIs are distributed among economic, environmental, and social factors in descending order. The studies that were consulted have identified six fields of application, which include 1) the sustainability assessment, 2) product design for remanufacturing, 3) product disassembly assessment, 4) product remanufacturability assessment, 5) remanufacturing circularity assessment, and 6) closed-loop supply chains for remanufacturing, and its relationship with smart sustainable remanufacturing.

The conducted SLR presents the main KPIs in SR across the three sustainability dimensions. Economic KPIs are the costs of transport, remanufacturing, disassembly, labour, disposal, fixed and recycling, and disassembly time. Environmental KPIs include GHG emissions, energy consumption, environmental impact, recycling, remanufactured parts, materials disposal, and acidification potential. Social concerns are health and safety, job creation, and employment stability.

In summary, the KPIs included in this study enable a thorough evaluation of sustainability within remanufactured products, the processes involved in their remanufacture, the companies involved, and the closed-loop supply chain. This focus establishes a link between CE and sustainability KPIs, highlighting the multidimensional nature of SR along product dimensions (materials, parts, components, and cores), processes, CLSC, and stakeholders. This focus is developed in the proposed methodological framework, which allows a concurrent assessment of sustainable disassembly, recycling, and the remanufacturing of a generic product. The framework can also be customized by adding specific KPIs depending on the characteristics of the product, processes, or CLSC. The framework provides decision-makers with a broad and detailed perspective of SR. This enables them to consider the various challenges and opportunities associated with its adoption, implementation, and operation. The framework also suggests integrating a smart architecture to support its implementation.

Future research opportunities identified in this SLR include the identification of the obstacles hindering the integration of social considerations into SR assessments. The development of practical methodological tools to guide the implementation of KPIs in SR based on I5.0. Implementing the international standard ISO 59000 in SR, its integration into the company management system, the challenges it presents in an I5.0 context, and its integration with smart architectures. Planned obsolescence versus design for remanufacturing, considering repairability, upgradeability, and product lifespan, also must be addressed. Finally, there is a gap in the development of sustainable models for designing, planning, and controlling remanufacturing systems and their corresponding closed-loop supply chains.

This study has inherent limitations in terms of its scope, as it solely relies on documents sourced from the Scopus database and focused on SR. As a result, it may inadvertently exclude other valuable perspectives that could have contributed to a more comprehensive analysis. A lack of an empirical assessment of the methodological framework also represents a limitation of this study. It is also advisable to customize the framework according to the context of implementation and to validate the obtained results.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ProWritingAid and ChatGPT in order to improve document readability. After using these services, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

CRedit authorship contribution statement

Camilo Mejía-Moncayo : Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **Amin Chaabane** : Writing – review & editing, Validation. **Jean-Pierre Kenné** : Writing – review & editing, Validation, Supervision. **Lucas Hof** : Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CHAPITRE 4

ON THE DEVELOPMENT OF A SMART ARCHITECTURE FOR A SUSTAINABLE MANUFACTURING-REMANUFACTURING SYSTEM : A LITERATURE REVIEW APPROACH

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Abstract

Remanufacturing is a circular manufacturing (CM) strategy that emerges as a sustainable manufacturing approach to recover the value of end-of-life products. It is a challenging process that requires to overcome intrinsic remanufacturing barriers or challenges, while addressing sustainability concerns, and achieving business model (BM) objectives. The lack of product life cycle information (PLCI) is the main source of these issues, generating significant inefficiencies and negative impacts in CM operations. Smart and industry 4.0 (I4.0) technologies have the ability to recover, process, and analyze PLCI. In fact, research is ongoing and suggested approaches are focused on implementing CM strategies using I4.0 to address reverse logistic issues, and to develop new BMs for CM. However, questions remain about on how to structure and configure these technologies as a smart architecture (SA) that simultaneously addresses : 1) remanufacturing barriers and challenges ; 2) sustainability ; and 3) BMs in the context of CM. The present study addresses this question by conducting a systematic literature review (SLR) to discuss current approaches, identify challenges and opportunities, and to improve understanding of SAs for CM strategies. Based on these SLR findings, this study proposes a novel conceptual design of a SA for a sustainable manufacturing-remanufacturing system towards Industry 5.0. As well, the proposed SA covers novel elements, such as a sustainable stakeholders focus, a modular customizable structure integrated in BM, and a blockchain quality and remanufacturability certificate, that are typically omitted or only partially considered by other studies. Finally, a case

study based on an electric motor is used to illustrate the relevance, capabilities, and utilization of the proposed architecture.

Keywords : Smart architecture, Smart manufacturing, Industry 4.0, Industry 5.0, Remanufacturing, Circular economy, Sustainability.

4.1 Introduction

Remanufacturing is a prominent circular manufacturing (CM) strategy that restores, by industrial processes, end-of-life (EoL) products with similar or even improved features or characteristics as new products (Sundin, 2019). It has positive impacts, such as reduced consumption of natural resources (e.g. materials, energy and water) and lower manufacturing costs compared to newly manufactured products (Russell & Nasr, 2019). However, remanufacturing also presents intrinsic barriers and challenges that hinders its adoption process, such as uncertainty in the quantity, time, and condition of used products, and customer confidence (Kurilova-Palisaitiene, Sundin & Poksinska, 2018). Most of these limitations are related to the lack of product life cycle information (PLCI) along the circular supply chain (Taddei *et al.*, 2022). Typically, when products reach their End-of-Life (EoL) state, there is either no or only partial information available on their deterioration state, location, or quantity of used products (Xin *et al.*, 2022). This lack of information hinders the planning and control of the operations along the circular manufacturing system. Hence, it becomes essential to close the information loop (Ozkan-Ozen, Kazancoglu & Mangla, 2020). Industry 4.0 (I4.0) and smart manufacturing (SM) technologies have the potential to provide such EoL product information and can act as digital enablers and drivers for remanufacturing (Bressanelli *et al.*, 2018; Pedrazzoli *et al.*, 2022). I4.0 and SM can provide the tools to capture, process, and analyze PLCI (Liu *et al.*, 2022), and consequently contribute to reduce the uncertainty in time, quantity, and the condition of used products in a CM system, or support addressing other remanufacturing challenges (Kerin & Pham, 2019).

In addition, sustainability issues are solely partially addressed in existing circular economy (CE) implementations (Bressanelli, Saccani, Perona & Baccanelli, 2020). Economic focus keeps the

main attention of organizations followed by environmental criteria (Alonso-Muñoz *et al.*, 2021), which progressively gains more interest thanks to stricter governmental regulations. Meanwhile, social concerns are commonly omitted (Kaya *et al.*, 2023), generating incomplete sustainable CE implementations. Thus, future CE approaches must include social concerns towards a fair transition to CE model applications (Gyori, 2022), and to integrate sustainability in business models (BM) (Maffei, Grahn & Nuur, 2019). The transition from linear to circular manufacturing systems, such as including remanufacturing operations, is a challenging process that requires expanding the producer's responsibility (Turner, Okorie, Emmanouilidis & Oyekan, 2020), while simultaneously considering business perspectives, technological developments, policies, and sustainability (Lieder *et al.*, 2017; Shayganmehr, Kumar, Garza-Reyes & Moktadir, 2021). This effort requires a holistic and interdisciplinary approach for the development of sustainable CE implementations (Garcia-Muiña *et al.*, 2018). Therefore, there is a consensus on the positive relationship among I4.0, SM, and remanufacturing strategies (Agarwal, Tyagi & Garg, 2022; Nascimento *et al.*, 2019). In fact, these smart technologies have strong potential to contribute in addressing the remanufacturing barriers or challenges (Bressanelli *et al.*, 2018), and support sustainability (Khan *et al.*, 2022; Khan, Razzaq, Yu & Miller, 2021a).

However, it is still not well understood how to successfully structure and configure a smart architecture (SA) to address simultaneously : 1) remanufacturing barriers and challenges ; 2) sustainability, and 3) BMs in CM strategies. Therefore, this study performs a systematic literature review (SLR) to discuss current approaches, identify challenges and potential opportunities, and to improve understanding of SAs for CM strategies. Indeed, the present study evolves from the following main research question : How to address simultaneously remanufacturing barriers or challenges, sustainability, and business model by a smart architecture in the context of circular manufacturing? This research question was sub-divided in four specific research questions (RQ) :

RQ1 : How does circular manufacturing address sustainability and business models ?

RQ2 : What are the main remanufacturing barriers or challenges ?

RQ3 : How do smart or industry 4.0 technologies support circular economy strategies, remanufacturing, and sustainability ?

RQ4 : How to structure a smart architecture for a remanufacturing system ?

The SLR responds to each RQ, while identifying research gaps and opportunities in SAs for CM. Considering these findings, this study proposes a new conceptual SA for a sustainable manufacturing-remanufacturing system. The developed architecture enables to control, optimize, and execute remanufacturing and closed loop supply chain operations, to communicate between supply chain actors, and to support sustainable BMs. A SA for a remanufacturing system for electric motors is introduced as case study. It represents an effective example for potential remanufacturable products thanks to their widespread applications in home appliances, and in equipment for industrial, construction, mining, agriculture, or transport applications. The developed case study also contributes to understand the functionalities and characteristics of a SA, as well as revealing a new focus on the interactions between stakeholders and CM system components, while nourishing the academic discussion on I4.0 and CE integration.

The present study is organized as follows : Section 4.2 presents the deployed research methodology to achieve the study's objectives. Section 4.3 presents the literature review, which addresses and discusses emerging circular manufacturing, remanufacturing, smart manufacturing, and Industry 4.0 concepts. Section 4.4 introduces the proposed SA for a sustainable remanufacturing system, an illustrative case study considering an electric motor, and discusses the SA. Section 4.5 finalizes the study with the main conclusions and future research directions.

4.2 Research methodology

A systematic literature review (SLR) was conducted in this study to identify how to address remanufacturing barriers, challenges and sustainability by a SA based on industry 4.0 technologies. To achieve this objective, the SLR followed the methodology described by Tranfield *et al.* (2003). Seeking a wide spectrum of relevant high quality academic documents, the search process was performed in the Scopus database using the following keywords : TITLE-ABS-KEY (((

"smart" OR "digital" OR "ICT" OR "industry 4.0" OR "industry 5.0") AND ("architecture" OR "framework" OR "barriers" OR "challenges")) AND (("circular economy" OR "circular manufacturing") AND ("sustainable" OR "sustainability") AND ("manufacturing" OR "production" OR "remanufacturing"))) AND (LIMIT-TO (LANGUAGE , "English")) .

The keywords are consistent with the language used in the existing literature and selected to ensure that the results of the document search were close to this study's objectives. Results were limited to those written in English. In order to eliminate articles that were off-topic, a selection process was conducted, verifying their relevance or proximity to the research questions.

The search process generated 253 results, which were classified according to their relevance to the research questions RQ1-4. After a first classification process based on the results' titles, 60 documents were discarded. Following a second classification phase considering the results' abstracts the final number of documents was reduced to 125.

These selected articles were analyzed using “Taguette” software; an open-source tool for qualitative research (Rampin & Rampin, 2021). The main contribution of each selected document was identified and classified using 89 tags. Then, the results were organized and synthesized to identify the typical CM system components and their relationship with sustainability, remanufacturing barriers or challenges, SM or I4.0 technologies applications in CM, and current SAs and frameworks for CM strategies.

Once the interactions among CM components with sustainability and BM were established by the SLR, a novel SA including its main components and characteristics was defined along the full circular supply chain. This methodological process aims to address jointly sustainable requirements, barriers, and challenges associated with remanufacturing, BMs, and smart or I4.0 technologies. Finally, a case study illustrates the developed SA design key advantages.

4.3 Literature review

This section presents current research advancements in literature related to smart CM approaches and technologies. Section 4.3.1 introduces circular manufacturing concepts and identifies their main components and sustainable features. Section 4.3.2 presents remanufacturing, highlighting their main barriers and challenges. Section 4.3.3 discusses smart manufacturing and industry 4.0 technologies integrated in circular economy concepts. Section 4.3.4 presents current approaches to smart architectures and preliminary frameworks for circular manufacturing are reviewed. Finally, section 4.3.5 discusses the key literature review findings.

4.3.1 Circular Manufacturing

In the traditional linear economy (LE) model, materials are transformed into products that are consumed until they reach their EoL state, followed by their disposal as waste in a landfill. This implies that the resources, such as raw materials, energy, knowledge, and any value-added actions are wasted. On the other hand, the circular economy (CE) paradigm aims to address the negative impacts of a LE (Malek & Desai, 2020). CE principles are based on a circular system in which economic systems try to emulate natural cycles, closing the materials and energy flows, hence minimizing waste generation. The materials or parts that constitute a product must then be integrated in a CE strategy for reuse, redistribute, repair, refurbish, remanufacture, recycle, or ultimately recover its energy through incineration, depending on the EoL product's state upon return (van Buren *et al.*, 2016). CE strategies contribute to reducing negative impacts on the environment, e.g. by reducing anthropogenic greenhouse gas emissions (Turner *et al.*, 2020), increasing economic benefits (Gusmerotti *et al.*, 2019), and generating positive social impacts (Shankar, Kannan & Kumar, 2017).

Within this context arises circular manufacturing (CM), which Takata (2013) defines as a manufacturing system that considers the physical and functional state of products to satisfy users' requirements, based on the artifacts' diagnosis, restoration, upgrading, and delivery technologies through maintenance, reuse, and remanufacturing. Similarly, Acerbi & Taisch (2020) state

that CM is the concurrent implementation and adoption of CE strategies in manufacturing considering stakeholders' needs, while reducing resource consumption, extending product life cycles, and closing their material loops. Therefore, a CM system must incorporate a BM, a reverse logistic system, and a smart architecture into their system components, as illustrated in figure 4.1. These components in the overarching system need to work concurrently to achieve these CM objectives (Avila-Gutiérrez, Martín-Gómez, Aguayo-González & Lama-Ruiz, 2020; Kristoffersen, Blomsma, Mikalef & Li, 2020).

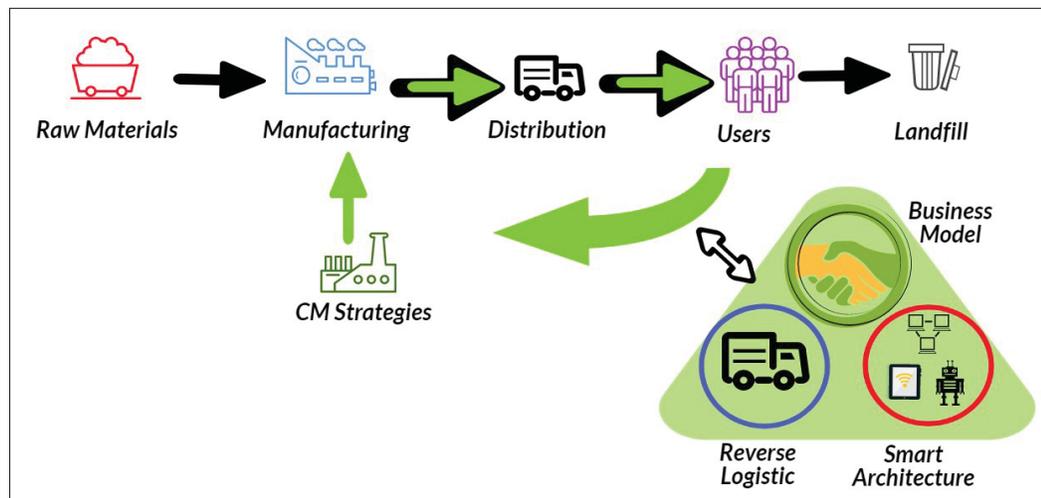


Figure 4.1 Schema of a circular manufacturing system illustrating the BM, RL, and SA as enablers of the materials and information streams along circular supply chain actors

Reverse Logistics (RL) close material loops by recovering used products (van Buren *et al.*, 2016) and SAs close information loops of recovered PLCI, which is captured and analyzed to identify and manage the value-added of used products to support the BM (Asif *et al.*, 2018). Finally, a BM integrates CE strategies into a company's business strategy in a synergetic way to achieve an effective, sustainable business model for value-added recovery of the used EoL products (Gusmerotti *et al.*, 2019).

Sustainability in manufacturing is becoming increasingly popular in society due to pressure from buyers and the global market (Moktadir, Rahman, Rahman, Ali & Paul, 2018). It can be defined as the capacity of continue over a long time period, i.e. it aims for humans to safely co-exist

with nature on earth for long time (United-Nations, 1987). Also, sustainable systems require a profound understanding of their environment, considering their different impacts, for taking informed decisions that allow implementing ethically fair actions (Shayganmehr *et al.*, 2021). It spans both the social, economic, and environmental domains, as was introduced in triple bottom line (TBL) (Elkington, 1998), often referred to as the three “P’s”; “people”, “planet” and “prosperity”, and widely accepted as synonym for sustainability (Contini & Peruzzini, 2022).

In manufacturing, sustainability has a strong relationship with the performance of a process or product (Kusiak, 2018). Hence, manufacturing industry has focused their efforts on developing more efficient and environmentally friendly materials, processes, and products (de Souza Junior *et al.*, 2020), reducing energy and material consumption (Liu *et al.*, 2022), using renewable energy sources (Zhang *et al.*, 2019), and other initiatives to minimize its negative environmental impacts (Esmailian *et al.*, 2016). CM strategies contribute to this goal by recovering the value-added in used products, which requires less energy and material consumption (Asif *et al.*, 2018). For example, it was demonstrated that a remanufactured cylinder head uses up to 99% less material than a new one and the remanufacturing process emits 61% less greenhouse gas, uses 93% less water and 86% less energy, and takes up to 99% less area in a landfill compared to conventional manufacturing processes (Russell & Nasr, 2019). As well, automated processes based on I4.0 technology contribute to improve energy efficiency and material consumption in numerous industries (Ma *et al.*, 2020; Nascimento *et al.*, 2019).

Although there is a clear interest on sustainability concerns, in practice its implementation is complex and the influence of economic criteria prevails over environmental and social interests (Alonso-Muñoz *et al.*, 2021; Lieder *et al.*, 2017). In fact, numerous companies seem to avoid recognizing and managing the tensions between environmental and economic objectives, and they tend to select environmental practices only when they generate economic benefits (Gusmerotti *et al.*, 2019). Typically, CE implementations omit the consideration of social impacts and prioritize environmental and economic criteria (Tsalis *et al.*, 2022). This is mainly due to the lack of crucial detailed and metrics-driven approaches in the manufacturing sector in order to quantitatively address social sustainability (Kazakova & Lee, 2022). Indeed, a system’s

sustainability level depends directly on the deployed BM, as this defines the guidelines for a (re)manufacturing system's operation and it specifies the process to recover the value added in used products (Moro *et al.*, 2022). Consequently, future CE implementations should adopt BMs that integrate, measure, and control all sustainability dimensions.

Indeed, a BM is a strategic element that has a significant influence on company operations (Garcia-Muiña *et al.*, 2018), innovation (Blomsma *et al.*, 2019), business competitiveness (Kravchenko *et al.*, 2019), structural support for system circularity (Ünal & Shao, 2019), and company's stakeholder interactions (Kim *et al.*, 2022). It involves stakeholders' concerns (Moro *et al.*, 2022), which is crucial for a sustainable focus including transparent communication (Garcia-Muiña *et al.*, 2019; González-Sánchez, Settembre-Blundo, Ferrari & García-Muiña, 2020), and to serve each stakeholder's specific interests (Dwivedi *et al.*, 2023).

In addition, BMs for CM should be based on providing value through service beyond the product itself, allowing to maintain the product's value over long time (Tolio *et al.*, 2017). In such BMs, the product value is expanded, including added services, and it includes Product Service Systems (PSS) for both products and services (Chávez, Romero, Rossi, Luglietti & Johansson, 2019). Also, PSS business models allow to introduce sustainability criteria in business strategies to manage the pressure from buyers and the global market on sustainable concerns (Moktadir *et al.*, 2018).

Different PSS options for CM are available, such as product oriented services, use oriented services, and result oriented services (Matsumoto, Yang, Martinsen & Kainuma, 2016). Product oriented services aim to extend product life by maintenance, while the customer keeps the ownership. Use oriented services are based on sharing, pooling, and leasing the product, while the provider preserves the ownership. Result oriented services are focused on providing a service; the customer pays for a specific service condition without considering the means or devices that the provider needs to fulfill this condition. This service model supports product returning to an Original Equipment Manufacturer (OEM) or supplier; when the provider keeps the product ownership, they are motivated to extend product life (Matsumoto *et al.*, 2016).

However, the transition towards PSS BMs represents a challenging process for a company in terms of products and services design, manufacturing processes, production planning, and supply chain configuration and operation (Chávez *et al.*, 2019). A major identified challenge is to maintain value addition along the entire supply chain to satisfy stakeholders' requirements (Jensen *et al.*, 2019). This transition requires the configuration of a BM considering the business context to identify and manage its enablers and barriers (Urbinati *et al.*, 2021), promote innovation (Garcia-Muiña *et al.*, 2018) and develop competitive advantages in resource efficiency and customer value (Ramakrishna, Ngowi, Jager & Awuzie, 2020). Most of the developed BMs for CM have focused on recycling strategies (Islam, Iyer-Raniga & Trewick, 2022), due to the widespread emerging CE approach. As well, BMs have been adopting smart technologies to achieve increased performance and to provide innovative products while maximizing energy and resources efficiency (Atif *et al.*, 2021; Chowdhury, Haftor & Pashkevich, 2018)

The review of recent literature reveals that current approaches on CM implementation lack a concurrent perspective. Typically, they only consider partially the harmonization of BMs, RLs, and SAs. Some developed strategies focus solely on CM strategies, while others only partially discuss the integration of such strategies into a BM. Mostly, developed BMs neglect or scarcely address the social concerns of stakeholders when discussing sustainable strategies.

4.3.2 Remanufacturing barriers or challenges

Remanufacturing is an industrial practice that returns the performance and functionalities of a newly manufactured product to a used or EoL product (Bhatia & Srivastava, 2018). After returning the used product, performs the following processes in different sequences depending on their characteristics : inspection, cleaning, disassembly, repairing or refurbishing, reassembly, and final testing (Karvonen *et al.*, 2017). These operations can be repeated to achieve at each cycle a new full-service life, extending the product life cycle beyond the expected EoL (Russell & Nasr, 2019). In addition, each full-service life can be optimized by implementing artificial intelligence (AI) algorithms, e.g. as demonstrated by world's largest bearing manufacturer SKF® (SKF, 2020).

Remanufactured products have several advantages compared to new products, such as reduced cost and lower environmental footprint (Russell & Nasr, 2019). As well, remanufacturing contributes to product improvement (Haziri, Sundin & Sakao, 2019); due to the use of recovered data during remanufacturing processes about recurrent defects and features (Zhang *et al.*, 2020). New remanufacturing industrial plant realization contributes to job generation, creating positive social impacts in communities (Karvonen *et al.*, 2017), and it enables the growth of local business networks (Nascimento *et al.*, 2019). In addition, remanufacturing facilitates the implementation of other CE strategies, such as reuse, repair, recycle, refurbish and energy recovery (Monostori *et al.*, 2016).

Nevertheless, the adoption of remanufacturing is a complicated process that requires addressing multiple obstacles (Burmaoglu, Gungor, Kirbac & Saritas, 2023). It is generally adopted that uncertainty has a significant negative impact on the quantity, quality, and timing of used product returns, making uncertainty the primary internal barrier for remanufacturing systems (Milios & Matsumoto, 2019). Uncertainty directly affects production planning and scheduling, process efficiency, inventories, and even workers' security by the possibility of being in contact with polluted used products (Kurilova-Palisaitiene *et al.*, 2018). The lack of predictive information about the product's condition complicates operational and inventory planning, which is required for efficient process operation (Okorie *et al.*, 2018). As well, the (re)manufacturing system capacity can be not adequately balanced due to the unknown quantity of used products and the resulting generated waste volumes (Mejía-Moncayo *et al.*, 2021). In addition, many potential products for remanufacturing are complex or not specifically designed for remanufacturing, which causes disassembly issues. Furthermore, barriers to access product and process information forces manufacturers to use expensive reverse engineering processes, when operating in open-loop manufacturing-remanufacturing systems (Matsumoto *et al.*, 2016). Disassembly and repair operations also often require human intensive labor and development of novel processes (Renteria & Alvarez-De-Los-Mozos, 2019).

In general, the remanufacturing market is complex and largely unexplored on a global scale (Battaia, Dolgui, Heragu, Meerkov & Tiwari, 2018). There is also a lack of incentives towards

these routes for OEMs, because they identify remanufacturing as a high-risk operation, since higher profits can be obtained with new products and due to the potential cannibalization of new products by remanufactured products (Bressanelli *et al.*, 2018). Also, remanufactured products are not yet widely appreciated by customers due to an often-mistaken belief of their low quality (Bhatia & Srivastava, 2018). The definition of remanufacturing is also not adopted uniformly, which leads to confusion about its meaning and adds to the depreciation of consumers' perceptions on the quality of remanufactured goods (Chau *et al.*, 2021). From legal and political perspectives, legal barriers for recovering and trading of used products or their materials are present in multiple countries, and there is a lack of incentives to promote remanufacturing (Kurilova-Palisaitiene *et al.*, 2018). Novel and updated laws are necessary to promote sustainable initiatives as the CE (Burmaoglu *et al.*, 2023; Pham *et al.*, 2019).

Financial risks and the lack of financial sources also represents an obstacle for remanufacturing adoption (Yadav *et al.*, 2020), because this transition requires investing in technology for new processes, reverse logistics, data analysis and other elements depending on the adopted BM (Lobo, Trevisan, Liu, Yang & Mascarenhas, 2022).

Figure 4.2 summarizes the main barriers and challenges for a remanufacturing system as identified in the present literature review. The most significant influencing factors on system operation - uncertainty, informational barriers, product complexity and human intensive labor - are presented in figure 4.2, including their interaction with the remanufacturing system elements. Customer confidence directly affects the remanufacturing market, while financial risks, OEMs incentives and legal or political barriers impact all the dimensions of remanufacturing. The interactions among these factors make remanufacturing a practice prone to many changes. Smart systems based on I4.0 technologies can provide solutions for most of the above-mentioned barriers.

According to the literature, several studies are concentrating on the identification of the challenges and barriers as outlined above. However, a comprehensive approach to address these issues

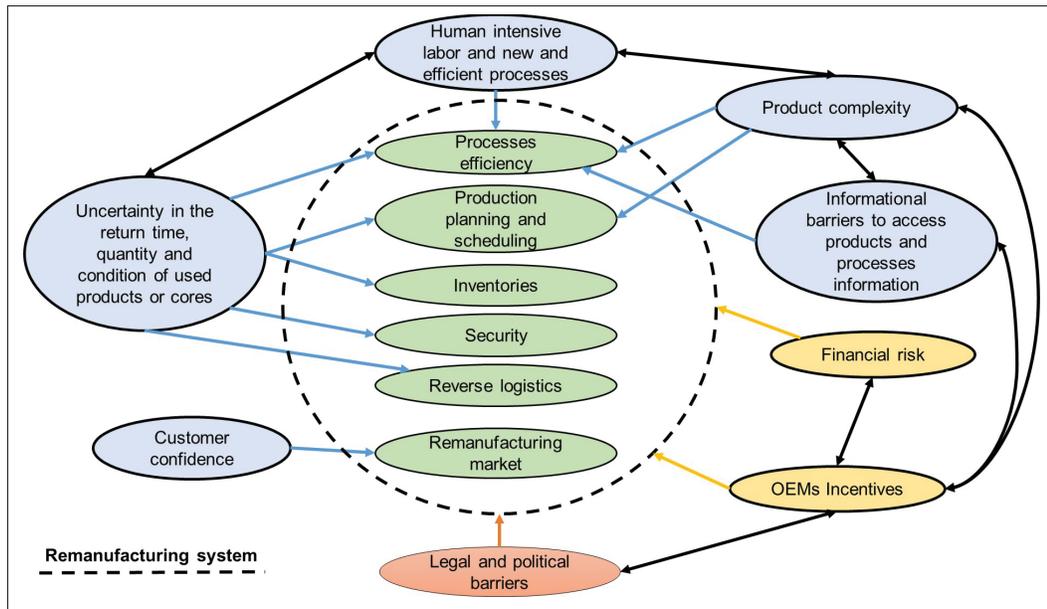


Figure 4.2 Interactions and relationships of the main remanufacturing's barriers and challenges with remanufacturing system elements

by jointly considering the role of BMs, SAs, remanufacturing operations, and production architecture is still missing.

4.3.3 Smart Manufacturing and Industry 4.0 in circular manufacturing

The fourth industrial revolution, also called I4.0 is a quickly growing and emerging concept (Rosa *et al.*, 2020), that comprises digitization and the Internet of Things (IoT) having a central role in connecting business and engineering processes for decentralized, efficient, flexible, and sustainable manufacturing (Bag *et al.*, 2021; Rosa *et al.*, 2020). Currently, industry 5.0 (I5.0) emerges as the evolution of I4.0 integrating sustainability and the wellbeing of humans as their goals (Dwivedi *et al.*, 2023; Leng *et al.*, 2022). I4.0 and Smart Manufacturing (SM) are mutually correlated concepts, and often used interchangeably to describe manufacturing paradigms aiming to optimize processes, reduce energy consumption (Ingarao, 2017), provide data for decision making (Linke, Garcia, Kamath & Garretson, 2019), automate processes

(Rocca, Rosa, Sassanelli, Fumagalli & Terzi, 2020), and give an improved business vision allowing to identify, quantify and use the value chain for innovation and sustainability.

I4.0 and SM have the potential to be key enablers of the CE concept and sustainable manufacturing (Culot *et al.*, 2020). These concepts support BM and servitization by identifying, quantifying, and maintaining product and service value along the life cycle (Piscitelli *et al.*, 2020), which can be achieved using smart or I4.0 technologies as outlined in figure 4.3 and described in this section.

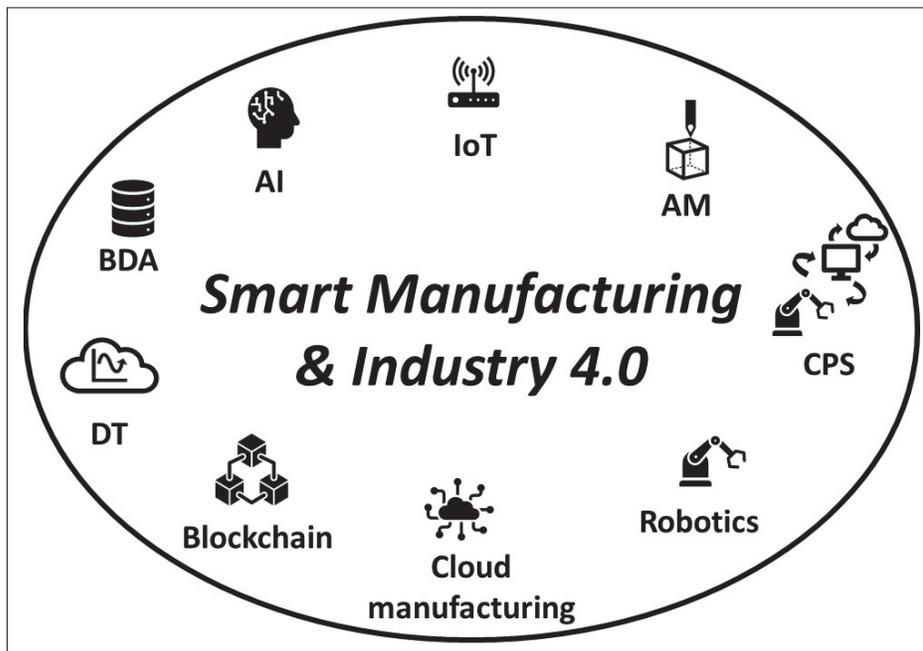


Figure 4.3 Smart manufacturing and Industry 4.0 technologies

The Internet of things (IoT) is a leading I4.0 technology with various applications in the reverse supply chain. Use cases can be found in the fields of inventory management using smart containers (Garrido-Hidalgo, Olivares, Ramirez & Roda-Sanchez, 2019), for used product parts recovering processes, such as for electric vehicle batteries (Garrido-Hidalgo, Ramirez, Olivares & Roda-Sanchez, 2020), or for the traceability of reusable building components (Ness, Xing, Kim & Jenkins, 2019). Recently, IoT and Cyber-Physical Systems (CPS) were jointly used in a smart waste collection system as described by Kerdlap, Low & Ramakrishna (2019), and

for optimizing the plastic extrusion process in terms of energy efficiency (Marilungo, Papetti, Germani & Peruzzini, 2017). In these initiatives, products could be traced and identified using IoT and radio frequency identification (RFID) tags (Delpla *et al.*, 2021).

CM has a focus on satisfying stakeholders' expectations through responsible, optimized, and reduced use of resources (Acerbi, Sassanelli, Terzi & Taisch, 2021; Acerbi & Taisch, 2020). Therefore, it is essential to establish clear communication channels with stakeholders (Asif *et al.*, 2018), and facilitate information exchange among them (Soldatos *et al.*, 2020). Information sharing platforms (Asif *et al.*, 2018; Liu *et al.*, 2022; Soldatos *et al.*, 2020), standard information protocols (Panza *et al.*, 2022; Pedrazzoli *et al.*, 2022), privacy (King, Timms & Mountney, 2023), information systems (Andersen, Bressanelli, Saccani & Franceschi, 2022), and cybersecurity (de Sousa Jabbour, Jabbour, Filho & Roubaud, 2018; Torbacki, 2021), emerge concurrently as enablers or barriers along the circular supply chain for stakeholders' communication and collaborative industrial processes (Yazan, van Capelleveen & Fraccascia, 2022; Yu, Yazan, Bhoohhibhoya & Volker, 2021b). As information integrity is crucial for these approaches, cybersecurity has become a topic of interest among stakeholders (Torbacki, 2021), due to the risk linked with informatics threats (Pedrazzoli *et al.*, 2022; Rodriguez-Corzo, Rojas & Mejía-Moncayo, 2018).

Traceability arises as one of the most significant issues to guarantee circularity and sustainability (Pedrazzoli *et al.*, 2022). Hence, different approaches based on blockchain technology (BCT) have been developed to provide confidence among stakeholders (Benitez-Martinez, Nunez-Cacho-Utrilla, Molina-Moreno & Romero-Frias, 2022; Mukherjee, Singh, Mishra & Bag, 2022; Shojaei, Ketabi, Razkenari, Hakim & Wang, 2021). BCT is an emerging technology including features that can support traceability and transparency in the supply chain (Bettín-Díaz, Rojas & Mejía-Moncayo, 2022; Cortés, Guzmán, Rincón-González, Torres-Casas & Mejía-Moncayo, 2019), CE strategies (Benitez-Martinez *et al.*, 2022; Khan *et al.*, 2021a; Kouhizadeh, Zhu & Sarkis, 2019), sustainability initiatives (Mukherjee *et al.*, 2022), quality assurance systems (Bettín-Díaz *et al.*, 2021), and other applications. An example of practical use of BCT is the digital material or product passport to provide supply chain stakeholders with necessary information about the

product circularity and its specifications (Faveto, Bruno, Lombardi & Panza, 2022; King *et al.*, 2023; Panza *et al.*, 2022; Yazan *et al.*, 2022).

Big Data Analytics (BDA) play a significant role as a smart sustainable manufacturing enabler (Eldrandaly *et al.*, 2022; Raut *et al.*, 2019). BDA has the potential to address CE challenges, such as operational risks, loss of ownership, users' willingness to pay, technology improvement, and return flow uncertainties (Bressanelli *et al.*, 2018). Artificial intelligence (AI) has also the potential to support sustainable CM systems by analyzing PLCI for product design Ferrero, Morris & Hapuwatte (2022), recognizing patterns (Çetin, Wolf & Bocken, 2021), tracking the industrial process (Bag *et al.*, 2021), supporting managerial decision-making process (Agarwal *et al.*, 2022; Çetin *et al.*, 2021), improving the potential for maintenance services, product reuse, and product remanufacturing (Ghoreishi & Happonen, 2020), waste treatment and transportation (Hala, Anass & Youssef, 2022), among others.

Although AI, BDA, and IoT have significant applications in CM some concerns remain about their implementation. For example, current use of BDA and AI are focused on increasing product consumption, which can generate negative environmental impacts (Yazan *et al.*, 2022). Also, the environmental impacts of these technologies should be analyzed because its high energy consumption (Fraga-Lamas, Lopes & Fernández-Caramés, 2021). In addition, concerns regarding user activity tracking and other potential privacy violations must be addressed (Cioffi, Travaglioni, Piscitelli, Petrillo & Parmentola, 2020).

Additive Manufacturing (AM) technologies support product customization and innovation in procedures, products, and services (Torn & Vaneker, 2019), as AM can manufacture complex parts, without cumbersome tooling, by adding materials layer-by-layer (Esmaeilian *et al.*, 2016). This manufacturing feature has a great potential for reparation, refurbishing, and remanufacturing processes (Ponis, Aretoulaki, Maroutas, Plakas & Dimogiorgi, 2021). AM can contribute to improve transport efficiency in supply chains (Burmaoglu *et al.*, 2023), and to decrease transport emission by implementing distributed manufacturing systems (Despeisse *et al.*, 2017; Moreno *et al.*, 2017).

The concept of cloud manufacturing is enabled by cloud computing technology (Esmaeilian *et al.*, 2016), where the hardware and software applications are offered as an online service. This contributes to a collaborative environment by an online communication, which is crucial to interconnect supply chain actors, leveraging industrial symbiosis in implementing CE strategies (Mathur, Deng, Singh, Yih & Sutherland, 2019). In addition, information systems and knowledge management perform important roles supporting operational and managerial decision-making processes (Acerbi *et al.*, 2021; Andersen *et al.*, 2022).

Robots could help to reduce intensive human labour in remanufacturing and other CE strategies by performing disassembly operations (Daneshmand *et al.*, 2023). However, this is a challenging task due to the complexity of the performed operations (Tolio *et al.*, 2017); human-robot interactions could be beneficial for a suitable CM system (Renteria & Alvarez-De-Los-Mozos, 2019). As well, robotization can manage variability in demand, products, quantity, and quality products in remanufacturing (Kerin & Pham, 2019). An example of such approach is a robotic cell following the automotive micro-factory concept proposed by Stavropoulos, Papacharalampopoulos, Athanasopoulou, Kampouris & Lagios (2022). Virtualization shows potential opportunities for workers training, reverse engineering processes, design processes for modular and repairable products, and efficient operations enabling the adoption of circular BMs (Antikainen, Uusitalo & Kivikytö-Reponen, 2018). Digital twins (DT) provide such virtual representation of the real world (Çetin *et al.*, 2021), having a significant potential to support remanufacturing, by providing a realistic approach to monitor product behaviour and deterioration, allowing to predict and intervene adequately in the manufacturing process (Wang *et al.*, 2020). Similarly, DT assists the CE products design process through a temporal representation of a product at different phases of its product life cycle (Ferrero *et al.*, 2022).

In summary, most of the current research contributions consider recycling case studies implementing industry 4.0 to address traceability, circularity, reverse logistic issues, and information sharing in CE. However, smart applications for remanufacturing are still rarely studied.

4.3.4 Smart architectures or frameworks in circular manufacturing (CM)

A smart architecture or framework describes the structure, components, and functionalities of a smart system to satisfy their goals. This section reviews the current SA approaches related to circular and sustainable manufacturing.

Yang *et al.* (2018b) demonstrated the support of Industry 4.0 for remanufacturing from perspectives of "Smart Life Cycle Data", "Smart Factory", and "Smart Service". Also, a smart remanufacturing cell was presented as a case study to address these perspectives, describing how to use the technology in each remanufacturing stage.

Asif *et al.* (2018), described the case study of Gorenje®, an OEM in the field of white goods and kitchen appliances. This study provides an ICT framework to enable the transition from conventional product sales models to service-based BMs.

Soldatos *et al.* (2020), introduced a CE digital platform that collects data in the circular supply chain from various stakeholders, such as manufacturers, demanufacturers, remanufacturers, recyclers, authorities, and others, to provide operational and value chain services.

Ma *et al.* (2020) proposed a data-driven smart manufacturing framework, using demand response for energy-intensive industries. Various demand response models were developed to reduce energy costs and to present the technical architecture for implementing the framework.

Blömeke *et al.* (2020) presented the "Recycling 4.0" framework, which was created by mapping smart manufacturing technologies and solutions that facilitate remanufacturing and recycling operations. This work presents a case study based on electric vehicles batteries to validate the developed approach.

Kerin & Pham (2020), introduced a conceptual smart remanufacturing framework, which describes the integration of different I4.0 technologies to support remanufacturing sustainability along product life cycles.

Bensassi *et al.* (2022) introduced an architectural platform for controlling and forecasting reverse flows in sustainable RL. They achieved system scalability, efficiency, reliability, autonomy, and adaptability by combining industry 4.0 and multi-agent and expert systems.

Bagalagel & ElMaraghy (2022), presented a conceptual framework based on washing machines with a modular configuration. This framework supports decision-makers in recognizing I4.0 technologies and in showing how these interact with each other along the full supply chain.

Panza *et al.* (2022), presented the Internet of Materials, a platform for eco-collaborative product development based on digital material passports. Here, the stakeholders in the value chain can track the materials along all lifecycle phases, enabled by digitization and material properties data transfers.

Stavropoulos *et al.* (2022) introduced a framework to identify and remanufacture automotive defective parts in a remanufacturing cell. This study discusses the detection of structural defects like the bents and damages that appear to the vehicle's components in the event of an incident.

There are common points in the functionalities among these developed architectures, such as to capture, store, process, analyze and provide support to (re)manufacturing operations or decision-making processes. I4.0 technologies play similar roles in these different approaches; the focus is mainly on stakeholders' information communication and its treatment. As well, there are concerns about cybersecurity and the negative use of stakeholders' information. However, other interactions with stakeholders are discarded and/or its relationship with sustainability is mainly addressed considering economic or environmental issues.

Two research scopes are identified among the current SAs approaches for remanufacturing. The first research scope focuses on specific tasks, such as energy consumption (Ma *et al.*, 2020), monitoring appliances use (Asif *et al.*, 2018), recycling operations (Blömeke *et al.*, 2020), planning and controlling reverse logistics (Bensassi *et al.*, 2022), traceability (Panza *et al.*, 2022), identifying defective parts (Stavropoulos *et al.*, 2022). The second provides a broader scope over the full system operations and supply chain actors (Bagalagel & ElMaraghy, 2022; Kerin & Pham,

2020; Yang *et al.*, 2018b). Approaches for this scope are currently only conceptual, because of its complexity, and the scarcity of industrial examples that allow to measure its performance and costs. In addition, there is a lack of hardware and software applications in the market for these issues, as described by Asif *et al.* (2018). The concept of remanufacturing cells, highlighted by Yang *et al.* (2018b) and Stavropoulos *et al.* (2022), has the potential to simplify remanufacturing facilities, thereby contributing to improve the performance of remanufacturing operations (Mejia-Moncayo, Rojas, Kenne & Hof, 2022).

4.3.5 Literature review discussion

The literature review revealed initial initiatives on addressing CM and sustainability, then it discussed the main remanufacturing barriers and challenges, followed by the introduction of I4.0 and smart manufacturing in the context of CM, and it finalized with discussing SAs for circular and sustainable manufacturing. It is important to highlight that the relationship between CM, I4.0 or smart technologies and sustainability is still an open discussion, which is supported by the elevated percentage of literature on this topic during the last five years.

Most of the works considered in the literature review have oriented their efforts to develop BMs, solve challenges associated with the supply chain, implement CE strategies, and use of I4.0 technologies applied to CE strategies. The literature also revealed that most studies concentrate their efforts on identifying or tackling specific remanufacturing barriers and challenges without taking a comprehensive strategy, also when proposing solutions based on I 4.0 technology implementation. Existing diverse strategies mostly concentrate on economic BMs and only partially explain the integration of BMs into CM systems, omitting to include the three dimensions of sustainability in their developments. Stakeholders' social concerns are frequently neglected or barely addressed when discussing sustainable strategies. Some of the studies present SAs or frameworks, but solely conceptual due to the complexity of the topic and the reduced number of industrial applications for remanufacturing. The proposed SA in the present study addresses these issues.

In general, the harmonization of CM strategies, BM, RL, and smart technologies is the core of a successful CM system implementation. This requires a well-balanced configuration of each system component to achieve the sustainable objectives, which represents a wide range of opportunities for developing hardware and software to support CM initiatives. The SA has a principal role establishing the links between BM and operations. It allows to identify and capture the value-added in used products, through recovering, processing, and analyzing the PLCI, while providing the information to the BM for implementing sustainable actions. However, there persists a lack of explaining how BMs interact with SAs, remanufacturing operations, and even production architectures in a CM context. Similarly, it is necessary to inform how to integrate supply chain actors, which is only partially considered in most analysis so far.

4.4 The proposed smart architecture for a sustainable remanufacturing system

The proposed smart architecture is presented in section 4.4.1, its main structure, its functionalities, and its capacity to address sustainability is discussed. Section 4.4.2 outlines the addressing of remanufacturing barriers and challenges by the proposed smart architecture. Section 4.4.3 discusses the smart architecture configuration along the supply chain actors. Section 4.4.4 introduces the case study based on a remanufacturing system for electric motors. Finally, in section 4.4.5 the full proposed smart architecture is discussed and evaluated.

4.4.1 Smart architecture

This study addresses the integration of I4.0, SM, and CM for the development of a conceptual smart architecture (SA) design for a sustainable remanufacturing system towards I5.0. Therefore, a SA has been conceived into a BM that is linked, in a three-layer structure, to the stakeholders and the operational layer, as indicated in figure 4.4. In this concept, the BM provides business rules and sustainable objectives, and the operational layer performs CM operations, while the proposed SA supports the operational layer and BM by addressing the system sustainability, remanufacturing barriers and challenges, while considering stakeholders interests.

Figure 4.4 presents the proposed conceptual SA, which includes three layers. The data recovery and process control layer automate and control the processes, and they recover information about product's life cycle, environmental footprint, and stakeholders among the supply chain actors through smart technologies. In a following layer, this information is processed in the information management cloud system, which integrates different functionalities focused on providing information to the operational layer for a sustainable operation.

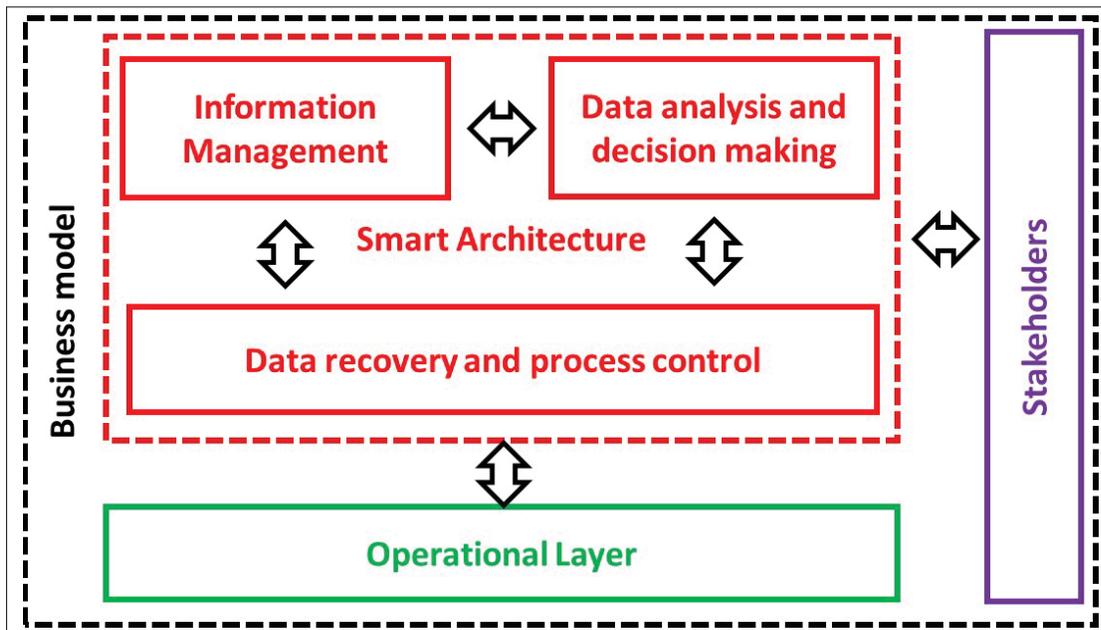


Figure 4.4 Schema of the proposed smart architecture layers integrated in business model with stakeholders and operational layer

The information management layer is a customized cloud application system for processing, sharing, and managing system data, and keeping it secure and available when needed. This system integrates the functionalities of an Enterprise Resources Planning (ERP), a Quality Management System (QMS), a Customer Relationship Management (CRM) system, an Environmental Management System (EMS), and a Product Lifecycle Management (PLM) system in order to achieve simultaneously economic, environmental, and social business objectives. The data analysis and decision-making layer performs data analysis to identify opportunities and forecast

scenarios to support decision-making processes at strategic, tactical, and operational business levels.

Tableau 4.1 Contributions to sustainability focus of the business model, smart architecture and operational layer

	Economic	Environmental	Social
Business model (BM)	To establish business objectives, rules, and strategies for identify, capture, and trade product value added along its life cycle.	To establish environmental objectives for the remanufacturing system, in terms of environmental impacts and circularity.	To establish social objectives and how to achieve it.
	To establish economic objectives and how to achieve it.	To establish how the system interacts with the environment.	To establish how the system address respect, justice transparency and how face discrimination.
	To identify system' enablers and drivers.		To establish how the system interacts with stakeholders.
Smart Architecture	To define and execute business strategies based on data analysis of product life cycle and operations information.	To measure, control and reduce operations emissions and consuming of renewable and non-renewable materials, energy, and water by smart process control and data analysis.	To establish transparent communication channels among stakeholders.
	To identify business opportunities, efficient processes, and prospective scenarios by data analysis.	To support product life cycle for extending EoL by establishing used product deteriorating condition.	To capture, process, analyze and use stakeholders' information ethically.
	Planning and executing of efficient operations minimizing costs and risks.	To establish environmentally friendly operational strategies and processes a long supply chain and product life cycle.	To provide trust information to stakeholders.
	To support design for remanufacturing.		To support products and processes quality assurance. To support responsible and equitable operations by providing information and developing strategies for achieving it.
Operational layer	To execute circular manufacturing operations minimizing cost and financial risks, a long supply chain.	To execute operations minimizing environmental impacts. To implement circular manufacturing strategies for reducing material and energy consuming by	To execute responsible and equitable operations respecting stakeholders, laws, and agreements, providing trust information, without discrimination.

The data analysis and decision-making layer performs different analysis using big data analytics (BDA), artificial intelligence (AI), simulation (Sim), digital twins (DT), virtual reality (VR), augmented reality (AR) and optimization (Opt). The resulting data feed the information management layer and business direction to support decision-making processes. Customers use or PLCI is analyzed using BDA, AI, and DT to establish products deteriorating conditions for reduced system uncertainty, and to extend product's EoL, and optimize operations performance. This information feeds planning and scheduling processes along supply chains, which reduces inefficiencies. As well, this data support product design by identifying recurrent quality or parts' deteriorating issues.

The BM integrates all remanufacturing system components and supply chain actors towards recovering and trading of the value added on new and used products. It also determines the system's sustainability level and provides guidelines to address remanufacturing barriers and challenges. Table 4.1 summarizes a set of sustainable objectives that allow to define the operation of a BM, SA and the operational layer to interact with the stakeholders and environment, while considering sustainability in terms of economic, environmental, and social objectives. These suggestions allow to guide the design process towards the proposed SA.

4.4.2 Smart architecture and remanufacturing barriers or challenges

One of the most significant remanufacturing challenges is the uncertainty in the return time, quantity, and condition of used products due to the lack of PLCI. The proposed SA recovers and uses the PLCI to minimize uncertainty by evaluating used products' deterioration, hence forecasting and planning return rate, inspection and production operations, and inventories. The economic, environmental, and social impacts are also determined, which contributes to achieve sustainable BM objectives.

Before starting CM operations, it is mandatory to address product complexity and the lack of data about products, and their processes. Image recognition and AI support reverse engineering process when this information is not available. These technologies can identify the best operation

candidates for product remanufacturing. Consequently, VR can be used to simulate the operation for labour or robotic system training. Product remanufacturability can be enhanced by integrating a PLM module including BDA, AI, DT, simulation, and optimization processes to develop modular product architectures that can be easily repairable, thus extending its EoL.

Tableau 4.2 Assessment of business model, smart architecture and operational layer features in their capacity to address remanufacturing barriers and challenges

Remanufacturing barriers and challenges	Business model	Smart Architecture	Operational layer
OEMs incentives	Establishing fair agreements or contracts with stakeholders. Establishing a PSS based on a results-oriented business model.	Identifying business opportunities by BDA, AI, simulation, and optimization.	
Legal or political barriers		Providing available, transparent, and trust information.	Performing fair operations fulfilling laws, contracts, and stakeholders' agreements.
Financial risk		Identifying, controlling, and mitigating financial risk by BDA, AI, simulation, and optimization.	
			Performing efficient circular manufacturing operations using CPS.
Uncertainty in the return time, quantity and condition of used products or cores		Performing data analysis by BDA, AI, DT, simulation, optimization, cloud systems, and software applications (ERP, QMS, CRM, EMS, and PLM) for planning and scheduling circular manufacturing operations.	Performing efficient and sustainable circular manufacturing operations using CPS.
Human intensive labor and new and efficient processes		Using CPS supported on smart sensors, controllers, RFID, robots, IoT, BDA, AI, DT, simulation, optimization, cloud systems, and software applications for recovering, processing, sharing, and analyzing PLCI, for establishing products deterioration conditions, location, quantity, return time, and for optimizing circular manufacturing operations towards sustainability.	
Product complexity		Product complexity can be tackled using PLM, BDA, AI, DT, simulation, and optimization for improving product design and its remanufacturability.	

Tableau 4.2 Assessment of business model, smart architecture and operational layer features in their capacity to address remanufacturing barriers and challenges. (Continuation).

Remanufacturing barriers and challenges	Business model	Smart Architecture	Operational layer
Informational barriers to access products and processes information		Performing reverse engineering processes using image recognition and AI to identify possible remanufacturing operations for products without OEM information. Using VR, AR, and DT for simulate and optimize processes or operations.	
Customer confidence	Establishing transparent communication among stakeholders. Providing trust information to stakeholders. Respecting stakeholders' agreements and contracts. Developing marketing strategies.	Establishing transparent communication among stakeholders involves using cloud services, social media, and cloud-based applications. Using BDA, social media, and CRM for identifying and executing marketing strategies. Using BCT and QMS to certify products and process quality. Using BDA, AI, and DT to provide online reports of product status, also to improve its performance and extend EoL.	Performing efficient and sustainable circular manufacturing operations, controlling quality products, and processes. Establishing transparent communication among stakeholders by providing trust information to stakeholders. Respecting stakeholders' agreements and contracts by performing fair operations.

Customer confidence is a market issue related to people's beliefs about the low quality or performance of remanufactured products. The present study proposes the use of a BCT system linked with the QMS module to provide trust about product quality and remanufacturability conditions by introducing features, such as a product passport. Here, the SA will generate a BCT certificate of the material or product quality condition and their warranty at suppliers' locations. Also, when the product is manufactured, the system will register its composition, properties, and quality of test results. Subsequently, when the product is remanufactured, another BCT certificate is generated, which registers inspection processes findings. The certificates will be uploaded to a BCT system linked with the QMS module that can be shared with customers to provide them with confidence on product quality. Simultaneously, the BM must provide the

conditions to develop good relationships with stakeholders by transparent communication, and conducting operations that respect the negotiated agreements.

The BM contributes principally to focusing on financial risk, OEMs incentives, legal or political barriers, customer confidence and uncertainty in the return time, and the quantity and the condition of used products by establishing the conditions for recovered used products, and by providing PLCI. Table 4.2 summarizes how the BM, SA, and operational layer address remanufacturing barriers and challenges.

4.4.3 Smart architecture along supply chain actors

The operational layer includes and connects all supply chain actors, such as suppliers, manufacturing, distribution, users, reverse logistics (RL), and remanufacturing thanks to the SA. In this layer, the SA can control, optimize, and automate manufacturing and remanufacturing processes, reduce energy consumption, and perform operations like inspection, disassembly, repair, assembly or testing parts or products. Also, it allows to classify in advance a used product by its condition ; establishing its inspection sequence before collection by a RL system. This enables to ordering of parts for repairing or refurbishing before the core material arrives.

Figure 4.5 outlines the proposed schematic overview of the materials and information flows for the sustainable manufacturing-remanufacturing system. It starting with raw material providers who can share the characteristics, place of origin, environmental impact and other information of the components or materials which they produce in the cloud. Similarly, manufacturing processes are controlled and automatized following I4.0 principles and tracking elements, e.g., RFID tags, are added to the products for their identification and traceability. Product or process information is captured and uploaded in the cloud and a record of the product identification, quality tests, components, and carbon footprint must be registered in the cloud system, where also a BCT certificate is generated including the quality information of the new or remanufactured product. This information, which considers the expected EoL defined by the product design process and deterioration predictive models, feeds the PLM module and DT to track the product life

cycle. Distribution and RL can use a similar schema and recover and share information about the warehousing and transport, such as vehicle type, route, fuel, or source of energy (type and consuming rate), warehousing conditions, time (warehousing and transport), and environmental footprint.

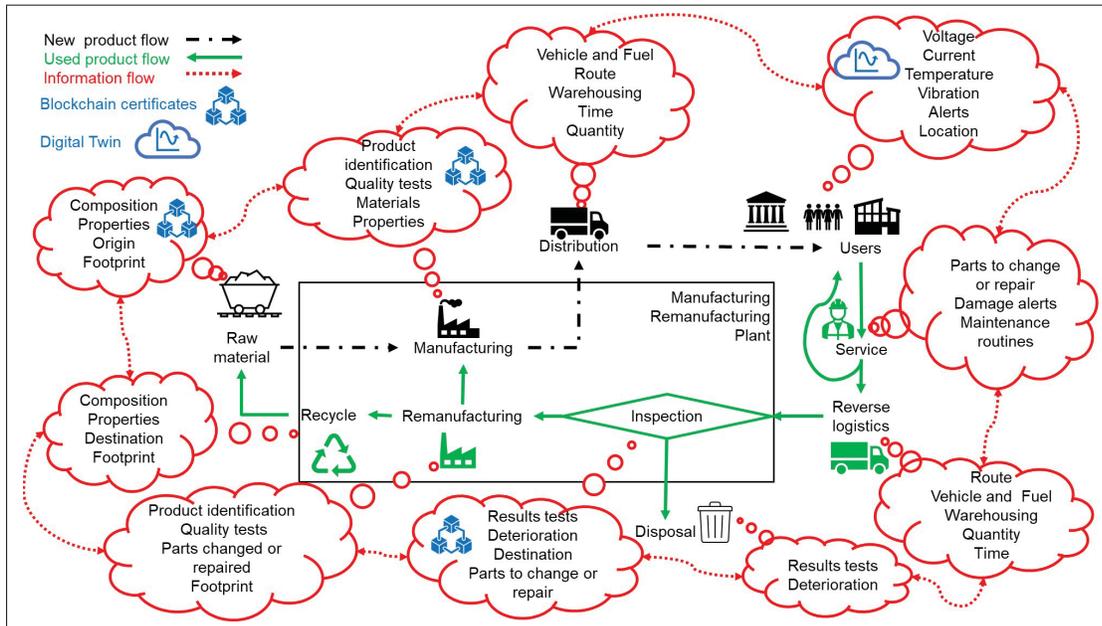


Figure 4.5 Schematic illustration of the products and information flow in the sustainable manufacturing-remanufacturing system

Once users have obtained the products, the process for capturing the information depends on product features. The PLCI can include the registration of specific variables like time, temperature, pressure, humidity, voltage, current, deformation, vibration, distance, location, acceleration, load, damage alerts, energy consumption, or other variables. In the developed SA approach, it is assumed that the product has CPS features, i.e., it is embedded with IoT and data acquisition to monitor PLCI, as presented in figure 4.6. The data is analyzed using BDA and AI feeding the DT to determine product deterioration and take preventive measures to extend product EoL through maintenance. The DT also aims to determine whether the product is a candidate for a new remanufacturing cycle, for recycling (by its high state of deterioration), or for disposing, which could represent a risk for health or security.

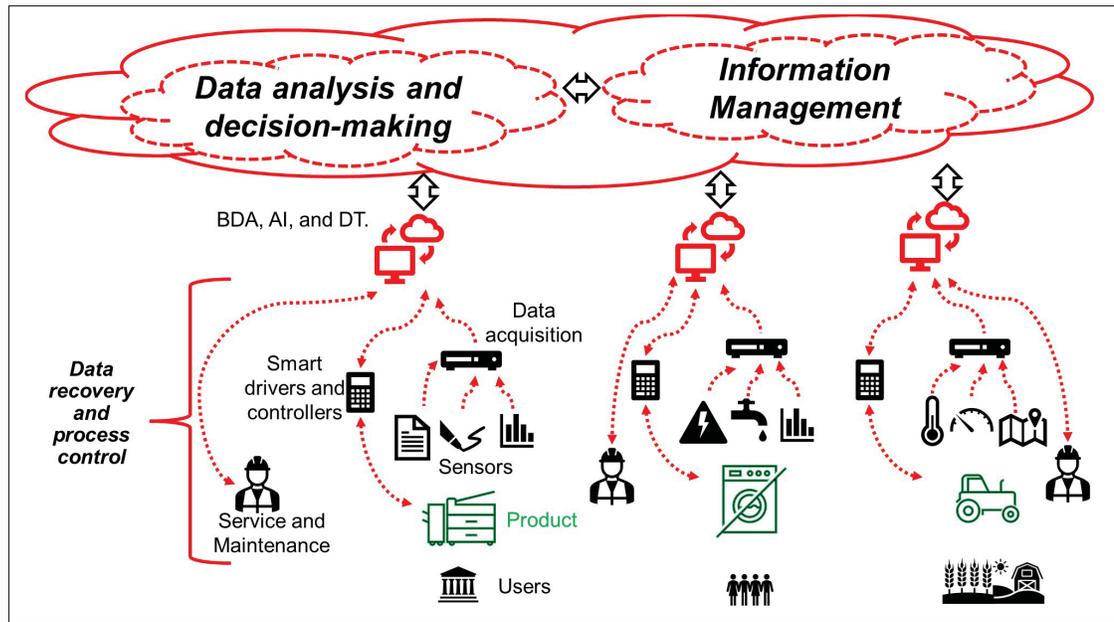


Figure 4.6 Schematic illustration of data recovery and process layer control for different remanufacturable products

When EoL or End of Use (EoU) occurs, a service recovers used products from a user location. Typically, RL or a third-party can transport it to the location in which it will be disposed, recycled, or remanufactured depending on a sustainability analysis that will assess its deterioration, location, or pollution state, and determine the resources needed for remanufacturing. At this point, the BM and SA have been reducing negative impacts of remanufacturing barriers and challenges by monitoring and controlling used products' life cycle. As such, the remanufacturing system receives used products with a controlled deterioration condition at scheduled rates, reducing the effects derived from uncertainty. To achieve such a systematic effort to reduce negative impacts, the remanufacturing plant should have a production architecture that can address random events, such as those proposed by Mejía-Moncayo *et al.* (2021). Cellular and reconfigurable features integrated into the remanufacturing system are proposed here. The reconfigurable and smart features are realized by implementing CPS workplaces connected by IoT. Each workplace can be self-configured, depending on the product reference or its condition using reconfigurable machines and devices that identify, handle, transport, and process used products or parts.

In the remanufacturing cells, the used product will be identified and transferred to be inspected following a standardized procedure. The inspection sequence can be optimized by using PLCI and maintenance reports to identify in advance which components have been failed, or must be recycled, disposed, or which are in good condition, confirming the expected deteriorating. Depending on these inspection results, used products can be disposed (when their materials are polluted), recycled when its deterioration is severe, or remanufactured when its deterioration satisfies the minimum condition for a sustainable result.

The selected products for remanufacturing are disassembled and damaged pieces are recycled. Remanufacturable products are cleaned, repaired, and refurbished. Once the parts have been processed, they are transferred to be assembled and tested on a manufacturing facility, closing one life cycle and starting another. This avoids duplication of equipment and facilities, that uses the same resources for new and remanufactured products.

4.4.4 Case study

An electric motor represents a widely used product and a promising candidate for remanufacturing with multiple applications. Considering BMs, it is possible to sell the motor operation time as a generic unit, in which the customer pays for the use of the electric motor under performance conditions established by a contract. The company keeps the ownership of the motors, performs the maintenance, recovers used motors, remanufactures, recycles, or disposes them at their EoL. This case study (see figures 4.7, 4.8 and 4.9) on the developed SA applies also to motor applications such as air compressors, fans, hydraulic pumps, air conditioning systems, heating equipment, equipment for small business, or other similar products.

Before the manufacturing processes start, the raw materials must be extracted and refined to obtain essential metals and polymers for electric motors parts manufacturing. Raw materials suppliers share traceable information of the supply chain from the extraction up to the manufacturing facility, including materials composition, properties, origin, ecological footprint, transport, and suppliers' information, and generate a BCT certificate as presented in figure 4.7.

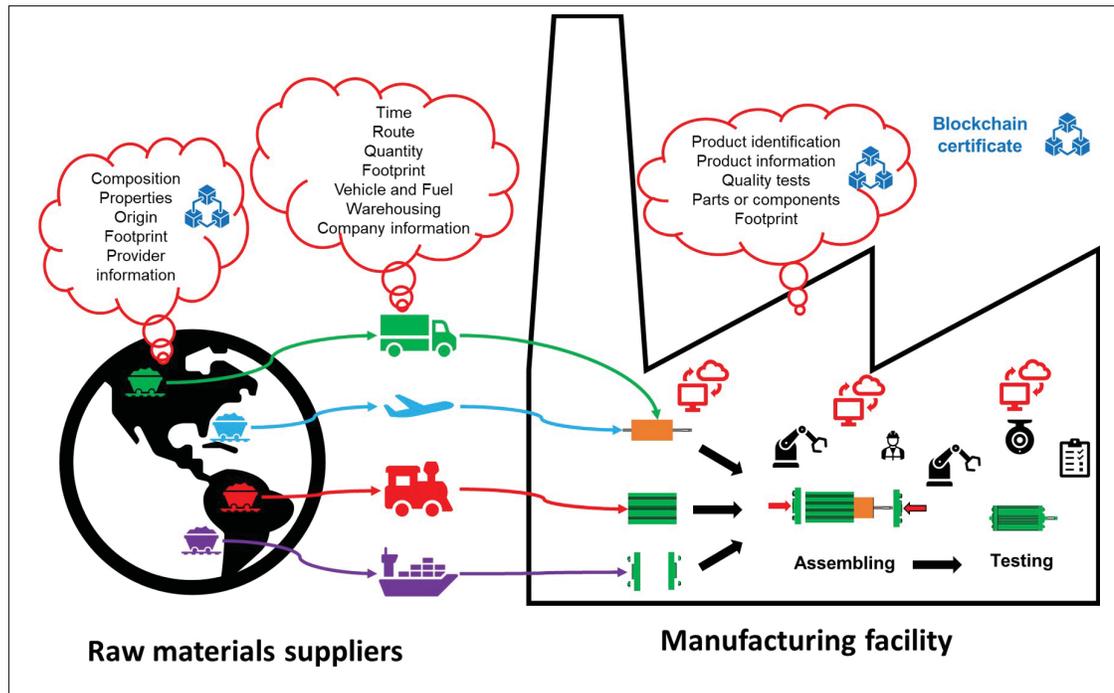


Figure 4.7 Schematic illustration of smart architecture recovering information of raw materials supply chain up to manufacturing facility

In a next step, when the materials are in the manufacturing facility, they are transformed into motor parts using manufacturing processes supported by a CPS. The manufacturing facility is configured like a smart factory, where CPSs perform, control, optimize, and register each production operation or process, while the processes are supported by information management, data analysis and decision-making layers for planning, controlling, optimizing, and improving operational performance. The CPS uses smart controllers and drivers, IoT sensors, imaging recognition technologies, automatic guided vehicles, CNC machining, AM, DT, among other equipment. In a final step, the motors are assembled by collaborative robots and human operators. When quality tests are performed to verify product features and performance, a BCT certificate is generated including the product information and tests results. Subsequently, the motor will be distributed, while registering the information related to the transport and warehousing, up to the customer's location.

Once the motor is in operation, an IoT smart controller and driver controls the electric motor and upload the data about motor status, use time, energy consuming, error alerts, rotating speed, temperature, vibrations, and location as schematically presented in figure 4.8. In parallel, maintenance routines will complement this information, including aleatory events, technical reports, and its status periodically stored information in RFID tags. This information is recovered for each motor in operation to establish its status, user consuming profile, deterioration, and ecological footprint. This information supports the optimization of motor performance, reduction of energy consumption, planning and scheduling manufacturing and remanufacturing operations, improvement of product processes design towards remanufacturability, identification of motor candidates for remanufacturing, recycling or disposal processes, and it provides information and engage stakeholders towards fair and confident relationships, prevents risks, addresses remanufacturing challenges, among others. These actions are enabled via deployment of BDA, AI, DT, simulation, optimization, and software applications of the information management layer. The results produce valuable knowledge about the different system aspects, which support decision-making processes to achieve sustainable objectives.

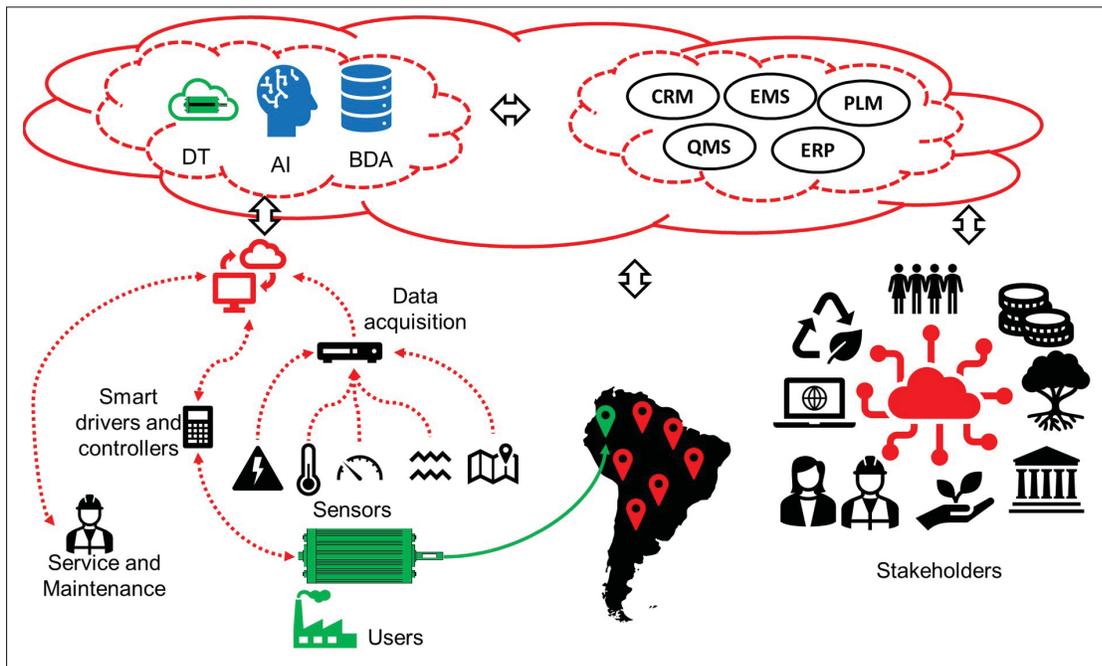


Figure 4.8 Schema of data recovery and process control for the electric motor case study

Once EoL or EoU service recovers and transports the motor to a remanufacturing facility, it will be identified by image recognition followed by inspection on a test bench. The inspection sequence was defined in advance by product life cycle data, hence reducing the operation time and helping to focus on the relevant items to confirm the deterioration rate and its feasibility to be remanufactured as is outlined in figure 4.9. These results are then used to generate a BCT inspection certificate, which includes the baseline of the remanufacturing process. In a next step, the motor will be disassembled, using a multi-axis clamping mechanism to hold the motor while a robot or human operator removes all joining elements and separates the parts. The system identifies and classifies each part through image recognition and separates them into remanufacturable, recyclable, or disposable parts. The parts for remanufacturing are cleaned, and then repaired or refurbished. Missing parts will be replaced, and they will be reassembled in a manufacturing facility. Finally, the motor will be tested before distribution for a new service cycle. The process details and the changed product components will be uploaded to the cloud and a new BCT testing certificate will be generated for secure data storage and remanufactured product validation.

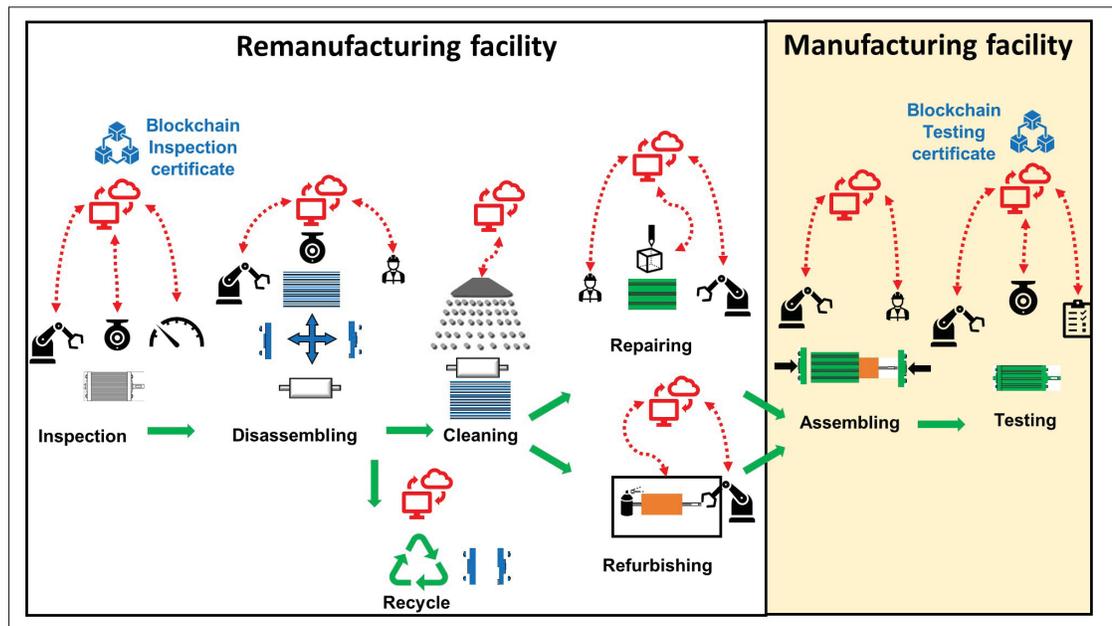


Figure 4.9 Schema of a smart remanufacturing and manufacturing facilities for the electric motor example

4.4.5 Smart architecture discussion

The proposed smart architecture (SA) represents a concurrent approach to I5.0 regarding BM, SA, and operations to address the different remanufacturing barriers and challenges with respect of the system components integration in a sustainable manner.

Table 4.3 presents a comparative analysis of the proposed architecture with other approaches in the literature along the following criteria : CES - Circular economy strategies ; BMf - Business model focus ; SCf - Supply chain focus ; RemB&C - Remanufacturing barriers or challenges ; RemOpe - Remanufacturing operations ; IR - Information recovery ; IM - Information management ; DA - Data analytics ; I4.0 - Industry 4.0 technologies ; SUCF - Stakeholder’s user or customer focus ; ECS - Economic sustainability ; ENS - Environmental sustainability ; SS - Social sustainability ; BM&SAoFI - Business model and smart architecture integration ; and SI - System integration.

Tableau 4.3 Comparison of the proposed smart architecture with similar approaches in literature

Authors	CES	BMf	SCf	RemBC	RemOpe	IR	IM	DA	I4.0	SUCF	ECS	ENS	SS	BM&SAoFI	SI
Asif <i>et al.</i> (2018)	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	
Bagalagel & ElMaraghy (2022)	✓		✓		✓	✓	✓	✓	✓	✓					
Bensassi <i>et al.</i> (2022)			✓	✓	✓	✓	✓	✓	✓	✓		✓			
Blömeke <i>et al.</i> (2020)	✓		✓		✓	✓	✓	✓	✓	✓					
Kerin & Pham (2020)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Ma <i>et al.</i> (2020)						✓	✓	✓	✓	✓	✓	✓			
Panza <i>et al.</i> (2022)	✓		✓			✓	✓		✓	✓	✓	✓			
Stavropoulos <i>et al.</i> (2022)					✓	✓	✓	✓	✓	✓					
Soldatos <i>et al.</i> (2020)	✓		✓			✓	✓		✓	✓					
Yang <i>et al.</i> (2018b)	✓	✓		✓	✓	✓	✓	✓	✓	✓					
This study	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 4.3 indicates the main similarities and differences among the approaches compared with this study. In general, the SAs have a focus supporting CE strategies, supply chain or reverse

logistic issues, or remanufacturing operations. The focus on BM, remanufacturing barriers and challenges, and the different dimensions of sustainability are partially addressed or even omitted. The different approaches share similar layers and functionalities such as information recovery (automatic or manual), information management, and data analytics, and also the use or application of I4.0 technologies is equivalent. Stakeholder integration, e.g. users or customers, is a common feature within all the contributions. However, social sustainability concerns and integration of the SA with the BM are mainly omitted or partially addressed.

This study implemented a holistic focus to create a multi-dimensional awareness and emphasis on stakeholders, integrating the systems components, and considering all the aforementioned criteria. This focus represents an advantage, because it provides an overarching vision on SAs for CM, thus nourishing the open discussion in this research field. However, this focus allowed currently only the development of a conceptual approach, because the scarcity of industrial examples and quantitative data that allows to evaluate its practical performance. As well, implementing the developed architecture requires a comprehensive analysis, because not all the technologies or features apply in all the cases. Even, in some cases the operational cost could be increased significant. Thus, future research must evaluate the economic, environmental, and social impacts of this proposal.

4.5 Conclusions

The present study aims to contribute towards the transition to a CE and I5.0 implementation. A SLR is conducted to address CM, remanufacturing barriers and challenges, smart and I4.0 technologies implementation for CM strategies, and smart architectures in the contexts of CM. The SLR contributes to understand their main concepts, applications, interactions, concerns and opportunities, and it feeds the development of a conceptual smart architecture for a sustainable remanufacturing system. The developed smart architecture seeks to address the gaps identified in the SLR, and it provides an overarching vision on the scope of such systems.

The proposed smart architecture includes the functionalities for efficient and sustainable operation, addressing remanufacturing system barriers and challenges, and supporting CBM for capturing and trading value-added used products. The architecture is integrated into a business strategy and has a layered structure configuration. A case study based on the proposed smart architecture for sustainable remanufacturing and focusing on electric motors was developed to demonstrate the architecture's functioning for recovery, processing, analyzing, and using PLCI along supply chain actors to perform, control, and optimize remanufacturing operations, and perform sustainable operations considering economic, environmental, and social impacts.

Three pillars of sustainability are developed in this study, describing the role of business models, the smart architecture, and its operations in a sustainable remanufacturing system. These principles can be applied and extended to other CM systems as well. The presented smart architecture also considers remanufacturing complexity through a comprehensive strategy to guarantee adequate economic, environmental, and social performance.

Smart architectures or frameworks for sustainable remanufacturing systems are an emerging research theme, with many research opportunities for the development of customized circular and sustainable technologies. Also, CM requires new standards, regulations, and BMs to enable its sustainable adoption. Future smart architectures should consider CM strategies requirements, and cultural or regional contexts. Current technology, software, and hardware are developed for linear manufacturing. Hence, the development of customized hardware and software to support CM can play an important role as an enabler of CM adoption, similarly as the development of new remanufacturing facilities or plants architectures.

Quantitative evaluation of economic, environmental, and social impacts of smart, digital, I4.0 architectures and technologies is a task and opportunity for future research. Finally, considering its scope and conceptual focus, it should be noted that this study has practical limitations on its real-time validation. Nevertheless, the analyzed case study in this work allows to provide a preliminary validation and example to illustrate its applicability and contributions towards more sustainable manufacturing strategies.

CRedit authorship contribution statement

Camilo Mejía-Moncayo : Conceptualization, Methodology, Investigation, Writing – review & editing, Writing – original draft, Data curation. **Jean-Pierre Kenné** : Supervision, Resources, Conceptualization, Writing – review & editing. **Lucas A. Hof** : Conceptualization, Supervision, Project administration, Resources, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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CHAPITRE 5

A RECONFIGURABLE CELLULAR REMANUFACTURING ARCHITECTURE : A MULTI-OBJECTIVE DESIGN APPROACH

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Abstract

Remanufacturing is a practice that postpones the product 'end-of-life' by returning the properties or features of a new product to a used product. Such a process represents an efficient circular economy strategy to extend product life, reducing its environmental footprint. However, remanufacturing systems must overcome distinct challenges related to information uncertainties about quantity and conditions of used products. Current strategies to address these issues include smart approaches towards smart remanufacturing systems. However, remanufacturing architectures must manage the negative effects on operations derived from the used product's deterioration and return rate variability, as well as remanufactured products demand fluctuations. This study contributes to address this issue by a Reconfigurable Cellular Remanufacturing Architecture that is integrated in a business strategy towards smart sustainable remanufacturing. The design process is based on a multi-objective optimization model that minimizes the grouping cost, the workload balancing cost, the investment cost, the makespan cost and the reconfigurable cost. A customized version of the well-known multi-objective evolutionary non-dominated sorting genetic algorithm II (NSGA2), a mono-objective genetic algorithm (GA-mo) and a GAMS model were implemented to obtain the potential architecture' configurations for an explanatory case study based on real-world industrial and random data, respectively. Two procedures to identify the best architecture were also considered. A sensitivity analysis is presented to illustrate the robustness of the proposed model. Managerial insights illustrate about solution methods,

and best architecture selection. Practical implications also are provided to offer useful options for practitioners.

Keywords : Remanufacturing, Uncertainty, Reconfigurable manufacturing, Cellular manufacturing, Multi-objective optimization, Smart manufacturing, NSGA2, Genetic Algorithm.

5.1 Introduction

Currently, global warming and other environmental negative impacts are part of the world discussion agenda where circular economy (CE) arises as a feasible strategy to face environmental issues. CE applies the natural principle in which the waste of a species is the food for another (Ellen-MacArthur-Foundation, 2013). This focus allows to recover the value added, materials, and energy in used products, by implementing CE strategies such as reuse, repair, refurbish, remanufacture, repurpose, or recycle.

One of the key CE strategies is remanufacturing that postpones the product end-of-life (EOL), returning the properties or features of a new product to a used product (Matsumoto *et al.*, 2016). In general, remanufacturing includes the return of a used product to an industrial facility in which it is inspected, disassembled, cleaned, refurbished, repaired (replacing parts as necessary), reassembled, and finally tested to ensure that the product is within its original design specifications (Russell & Nasr, 2019). It allows products to return to the market that would otherwise finish in a landfill (Ellen-MacArthur-Foundation, 2013).

In recent years, remanufacturing has become more important, as it represents an effective way to extend the life of products while reducing their environmental impact, as a remanufactured product requires less energy and materials compared to a new product (Russell & Nasr, 2019). Overall, remanufacturing presents important advantages as reduced labour, material, and energy costs, shorter production lead times, new market, and product development opportunities, and even an improvement in the business branding by customer engagement (Bulmuş, Zhu & Teunter, 2013). Numerous examples of products that are remanufactured can be mentioned, such as automotive parts (Saidani, Yannou, Leroy & Cluzel, 2020), photocopiers (Chaowanapong,

Jongwanich & Ijomah, 2018), technological devices (Tolio *et al.*, 2017), boilers (Toxopeus, Haanstra, van Gerrevink & van der Meide, 2017), and other products (Chaowanapong *et al.*, 2018; Kurilova-Palisaitiene *et al.*, 2018).

Despite the various benefits of remanufacturing, its adoption is a challenging process that requires overcoming significant barriers. Many of them relate to the lack of information about the used products' condition, their quantity, and return timing (Milios & Matsumoto, 2019), which generates uncertainty in the entire supply chain system. Then, this is translated into costly operations, due to the various inefficiencies in the collection and processing of used products, significant deviations on production plans, inventory, and even workers' security and pollution issues (Kurilova-Palisaitiene *et al.*, 2018). In fact, this uncertainty could be considered an upstream uncertainty, as it is related with the collection of used products that feeds the remanufacturing processes.

In the other direction, the remanufactured products' demand variability (Rizova, Wong & Ijomah, 2020) is the main cause of downstream uncertainty. Also, the customer acceptance of remanufactured products is another challenge (Chinen & Matsumoto, 2021), due to, prejudices about remanufactured products' inferior quality, or the absence of price advantages compared to a new product (Abbey, Kleber, Souza & Voigt, 2017). Hence, this reduces the demand for remanufactured products. In addition, the cannibalization of new products by remanufactured ones emerges among original equipment manufacturers (OEMs) as a risk to avoid. Indeed, the potential to reduce new products' sales is a factor that decreases the popularity of remanufactured products among OEMs (Okorie, Obi, Russell, Charnley & Salonitis, 2021). However, cannibalization could also increase remanufactured products' demand. Therefore, some OEMs prefer to make products including complex designs or they deploy other strategies to complicate remanufacturing to mitigate cannibalization (Matsumoto *et al.*, 2016). Table 5.1 summarizes the main sources and effects of uncertainty in remanufacturing, the systems' components affected by this process, and the closed loop supply chain (CLSC) actors involved in these upstream and downstream issues of uncertainty.

Tableau 5.1 Upstream and downstream remanufacturing uncertainty sources, its effects, and closed loop supply chain actors affected by it

Type	Source	Effects	CLSC actors affected
Upstream Uncertainty	Lack of information about the used products' condition, the quantity, and return timing	Costly operation.	Providers
		Inefficiencies in used product collection and processing.	Manufacturing
		Deviations on production plans and inventory.	Remanufacturing
		Workers' security issues.	Distribution
		Materials pollution issues.	Service
Downstream Uncertainty	The prejudices about the quality or performance of remanufactured products negatively impact customer acceptance.	Remanufactured products' demand variability.	Reverse logistics
	Cannibalization of new products by remanufactured		

The remanufacturing uncertainty problem includes two dimensions ; 1) the lack of product life cycle information, resulting in upstream and downstream uncertainty as illustrated in figure 5.1, and 2) the physical variability of used products. Currently, the first dimension (1) is addressed by approaches based on industry 4.0 (I4.0) technologies, towards implementing smart remanufacturing (SR) systems Bagalagel & ElMaraghy (2022); Kerin & Pham (2020); Mejía-Moncayo *et al.* (2023b). Such systems use a smart architecture to recover, analyze and process product life cycle information along the CLSC to support business models, address remanufacturing challenges, and reduce remanufacturing uncertainty (Kerin & Pham, 2019).

Indeed, SR emerges as a business strategy in which a circular business model, a smart architecture and the operational level must work concurrently to tackle uncertainty (Bagalagel & ElMaraghy, 2022; Kerin & Pham, 2020). Although smart technologies mitigate information uncertainty, physical variation persists among used products that represent the second (2) uncertainty dimension. This includes the physical implications of performing transport, handling, storage, and production of the targeted products for remanufacturing. These operations have a direct correlation with the production architecture, an issue that has rarely given attention in current literature when uncertainty has been addressed, despite its importance.

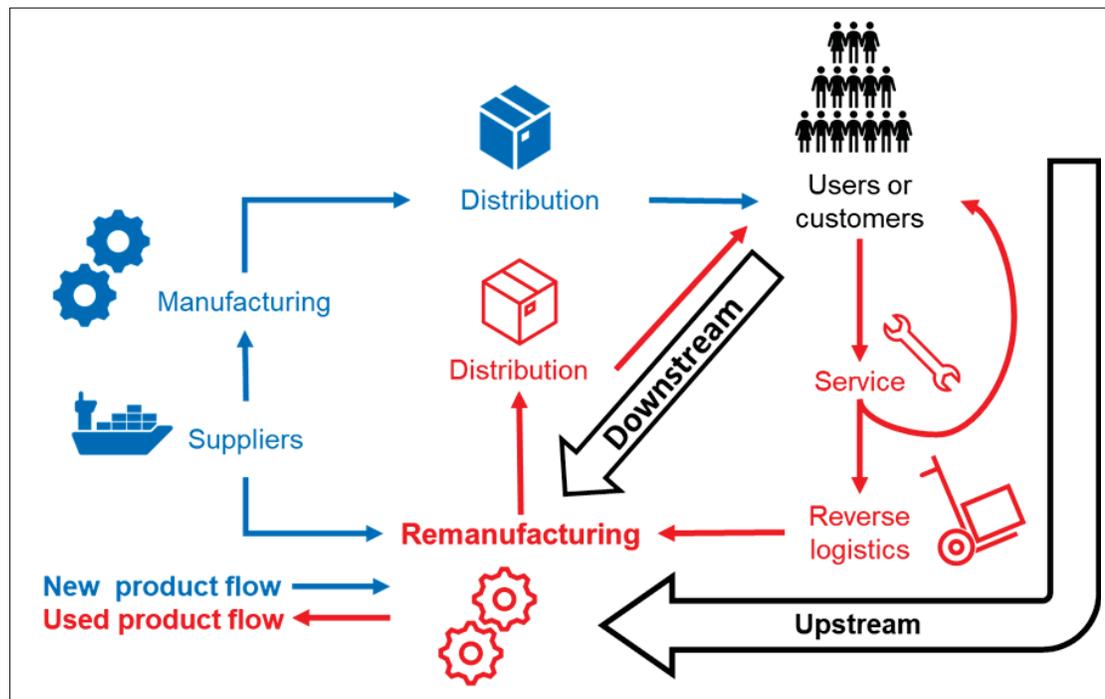


Figure 5.1 Upstream and downstream remanufacturing uncertainty in a closed loop supply chain system

The present study contributes to address this gap by proposing a hybrid manufacturing architecture that incorporates cellular and reconfigurable features to address remanufacturing uncertainty. Therefore, a multi-objective optimization model is formulated to configure the proposed architecture, and three solution methods were implemented. This approach also contributes to understand the multi-criteria nature of the proposed architecture design process. In addition, the

architecture also represents the physical framework of a smart and sustainable remanufacturing system as part of the proposed business strategy to tackle uncertainty. Finally, this study presents managerial insights and practical recommendations to guide its implementation in real-world scenarios.

The presented study is organized as follows ; section 2 presents the research methodology, section 3 introduces the literature review, and section 4 describes the proposed architecture. Then, the developed mathematical model is introduced in section 5. Section 6 presents the study's results and discussion, including a sensitive analysis and managerial insights, to finalize with the conclusions in section 7.

5.2 Research methodology

To achieve the defined main objective, this study implements a research methodology including four (4) major steps as described in figure 5.2, that has been specifically designed for the proposed hybrid architecture.

The first step (Step 1, see Figure 5.2) in the process to develop a hybrid remanufacturing architecture consists of conducting a literature review regarding uncertainty and cellular or reconfigurable systems in remanufacturing. The systematic literature review process was performed using the Scopus database in two stages. In a first stage, the current approaches to address remanufacturing uncertainty were identified. Hence, the main causes and effects of uncertainty on remanufacturing and their relations with smart and I4.0 technologies could be identified. Then, in a second stage, cellular and reconfigurable manufacturing strategies in remanufacturing were explored. As a result, the features to tackle the negatives effects of uncertainty could be provided.

The objective of the second step (Step 2, see Figure 5.2) was to establish the architecture's features. This development process considers the results obtained by the systematic literature review (Step 1), which identified how uncertainty affects the remanufacturing system and its components. This helps in recognizing the need to integrate the hybrid architecture into a

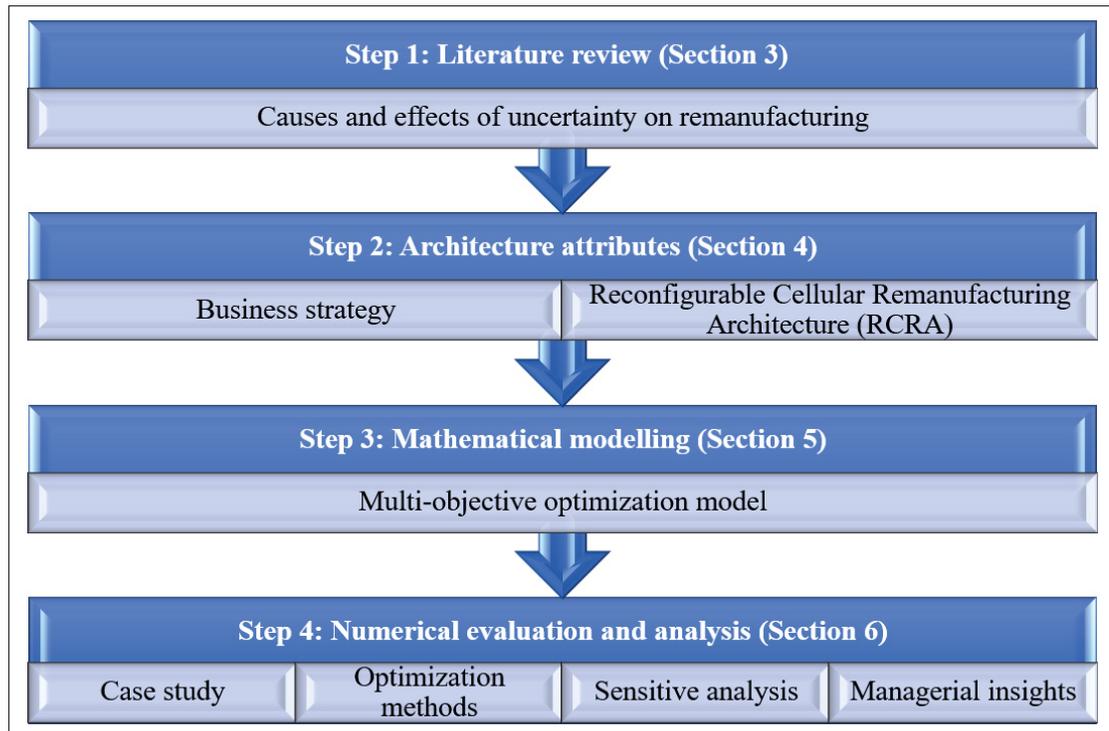


Figure 5.2 Research methodology steps

business strategy that tackles uncertainty concurrently. The proposed Reconfigurable Cellular Remanufacturing Architecture (RCRA) attributes include cellular and reconfigurable features integrated in the business strategy.

The third step (Step 3, see Figure 5.2) comprised mathematically modelling of the proposed architecture configuration as a multi-objective optimization model. Considering that uncertainty affects simultaneously many system components including different purposes, a multi-criteria approach seems the best option to model the architecture's design problem. Such a strategy also allows identifying the effect of each single problem in the architecture configuration.

In a fourth step (Step 4, see Figure 5.2), the mathematical model to design the proposed hybrid RCRA architecture was evaluated numerically by three methods; 1) a customized version of the well-known multi-objective evolutionary algorithm non-dominated sorting genetic algorithm II (NSGA2) (Deb, Pratap, Agarwal & Meyarivan, 2002); 2) a mono-objective genetic algorithm

(GA-mo) and; 3) a GAMS model using CPLEX solver, where the latter two methods were using weighted factors as goal programming to get the Pareto frontier. The numerical evaluation of the two genetic algorithms was performed running MATLAB R2021a (Appendix-A describes these genetic algorithms solutions coding and their main operators and functions), and the NEOS-Solver (Czyzyk, Mesnier & More, 1998) was used to obtain the results of the GAMS-CPLEX approach.

A case study was developed for the numerical evaluation using information from a Colombian motorcycle assembler company and random data. It should be noted that the data and achieved results were used for explanatory purposes and will not be used as a reference for real-world implementation. The case study considers a set of 10 remanufacturable products that can be remanufactured in some of the 10 different defined workplaces. Each product has 4 versions and its own operation time in the workplaces for processing, and a potential return rate for 10 periods. The case study also considers a cycle time for each product and costs for the optimization model objectives. A sensitive analysis was performed to illustrate the behaviour of the proposed model, and two procedures are considered to select the best solution. The first approach takes into account the minimum value of the sum of the five objective function values (f_i) denoted by equation (5.1) :

$$\min[f1 + f2 + f3 + f4 + f5] \quad (5.1)$$

The second method implements an analytic hierarchy process (AHP) (Saaty, 1987). The selected solution can be used as the first version of the remanufacturing system facility layout (Romero-Duque, Mejía-Moncayo & Torres-Martínez, 2015). Managerial insights were proposed to guide decision-makers in the selection of solution method and procedures to select the best architecture configuration. The proposed manufacturing architecture is explained in the next section by an illustrative case study.

5.3 Literature Review

Formulating a hybrid manufacturing architecture that addresses uncertainty in remanufacturing requires state-of-the-art information about the current approaches to address this issue and the possible features that will be integrated into such systems. Therefore, the following section present a brief review of the fundamental aspects relates to current focus on remanufacturing uncertainty based on I4.0 and smart systems, cellular manufacturing, and reconfigurable manufacturing. Finally, literature review discussion synthesizes the main findings and contributions of this study.

5.3.1 Current approaches to remanufacturing uncertainty

Evidently, the upstream and downstream uncertainty in remanufacturing has the attention of academics and practitioners. Many of them have focused their efforts on developing approaches based on smart or I4.0 technologies to recover, process and analyze product life cycle information (Kerin & Pham, 2019). This information is then used to reduce uncertainty and minimize their negative effects (Daneshmand *et al.*, 2023).

Upstream uncertainty is addressed from a technological perspective, considering the traceability of products along their life cycle. As such, internet-of-things (IoT) allow to track products or materials within closed loop supply chains (CLSCs), which is currently explored by industry, e.g., for the recovering of electric vehicle batteries (Garrido-Hidalgo *et al.*, 2020), or the tracking of electronic products to establish its deterioration condition (Delpla *et al.*, 2021). In addition, blockchain technology (BCT) is used in traceability applications to provide confidence among customers, as BCT allows to guaranteeing the immutability of information (Bettín-Díaz *et al.*, 2021; Matenga & Mpofu, 2023; Niu, Xu & Chen, 2022).

Big data analytics (BDA) contributes to address downstream uncertainty by developing marketing strategies concentrated on users' willingness to buy remanufactured products, and it also allows to establish used products' return (Bressanelli *et al.*, 2018). The adoption of artificial intelligence (AI) provides predictive models about product deterioration contributing to develop more

accurate production plans, inventory, service or maintenance operations that extend a product's EOL, hence increasing the system performance (Acerbi *et al.*, 2021; SKF, 2020).

Indeed, these technologies contribute to reduce both upstream and downstream uncertainties and support remanufacturing on operational, tactical, and strategic levels. This is enabled by a smart architecture that allows the harmonic integration of the remanufacturing operations and business model for a smart sustainable remanufacturing system (Mejía-Moncayo *et al.*, 2023b). In such system, a hybrid remanufacturing architecture that allows to manage the operational challenges related to used products' variability is required. Cellular and reconfigurable manufacturing have associated features and advantages that could prove useful for this purpose.

5.3.2 Cellular and reconfigurable manufacturing systems

Cellular manufacturing systems can be defined as the decomposition of an aggregate manufacturing system into small units or cells (especially machines, tools, and operators), which are consequently easier to manage and control (Mejía-Moncayo, Rojas & Mura, 2018; Mejía-Moncayo & Battaia, 2019). These cells are established by the cell formation (CF) process (Papaioannou & Wilson, 2010). CF groups machines or workplaces that share products or parts, that also share similarities in their materials, manufacturing processes, design, or even other criteria among them (Mejía-Moncayo, Rojas & Dorado, 2017). In the transition to remanufacturing, an OEM should have a set of candidates' products to be remanufactured distributed along different references, versions, or configurations (Mejía-Moncayo *et al.*, 2022). A CF process could contribute to generate product families based on their similarities on product features, configurations, manufacturing or remanufacturing processes, versions, or even deterioration level. These product families share a great similarity among their members. This allows to group them, up to an amount that could be made economically feasible for the adoption of remanufacturing. The methods to develop product families or manufacturing cells are thoroughly studied in literature (Papaioannou & Wilson, 2010), and they can be implemented in a remanufacturing context i.e., by Ant Colony Optimization (Mejía-Moncayo *et al.*, 2022), or mixed integer programming (Aljuneidi & Bulgak, 2017).

However, remanufacturing cells approaches are few explored in the literature, although they have the potential to provide modularity to the system, facilitating its reconfigurability.

A Reconfigurable Manufacturing System (RMS) can change its structure to adjust production capacity and functionality to the changes in market or regulatory requirements (Koren *et al.*, 1999). RMS is possible thanks to reconfigurable and modular machines, devices, and software designed or customized to process a specific product or part family (Bortolini, Galizia & Mora, 2018), which include machining systems, fixture systems, assembly systems and material-handling systems (Bi, Lang, Shen & Wang, 2008). RMSs seek to achieve a self-adaptive system that provides the throughput of dedicated manufacturing systems (DMS), the adaptability of flexible manufacturing systems (FMS), and the modularity and scalability of cellular manufacturing systems (CMS) (Bortolini *et al.*, 2018; Koren & Shpitalni, 2010). RMS or adaptive manufacturing emerges as a promising way to enable sustainability and address the challenges of circular strategies as remanufacturing (Andersen *et al.*, 2023).

Commonly, RMSs are configured to manage downstream uncertainty, mainly derived from demand variations. In a remanufacturing context, RMSs must address simultaneously upstream and downstream uncertainty. Cyber physical systems (CPS) connected by IoT (Napoleone, Macchi & Pozzetti, 2020; Yao *et al.*, 2019), can provide the features for system self-configuration depending on the system needs (Andersen *et al.*, 2023). The integration of such technologies in a RMS has the potential to enhance the adaptability, flexibility, resilience, sustainability of smart remanufacturing system (Brunoe, Andersen & Nielsen, 2019).

Disassembly and repair operations require intensive manual operations (Tolio *et al.*, 2017), which could be reduced in a RMS for remanufacturing processes using robots (Eguia, Lozano, Racero & Guerrero, 2011), or reconfigurable technology (Daneshmand *et al.*, 2023). Additive manufacturing (AM) also can increase flexibility and adaptability to perform reparation operations for different levels of deterioration, contributing to manage scarcity of spare parts (Ponis *et al.*, 2021). Similarly, reconfigurable machines also allow to optimize the part repair processes, i.e., it was demonstrated that a reconfigurable joint turning-milling machine tool successfully machined

a fraction of 90% among all processes on repaired work pieces through rapid machining (Fan, Zhang, Jin, Yuan & Guo, 2010). Yet, in the literature, only few approaches address cellular and reconfigurable remanufacturing. The focus of current approaches is mostly on optimization models that minimize operational cost (Aljuneidi & Bulgak, 2017; Telegraphi & Bulgak, 2021; Gen, Lin & Zhang, 2009). Aljuneidi & Bulgak (2017) introduced a mixed integer linear programming (MILP) model based on a cell formation problem for manufacturing-remanufacturing cells (Eguia *et al.*, 2011). Telegraphi & Bulgak (2021) presented a mixed integer mathematical model for designing a hybrid manufacturing-remanufacturing system considering alternative process routings and contingency. The research interests in cellular and reconfigurable manufacturing, and optimization of these studies, are also included in the present study.

5.3.3 Literature review discussion

Table 5.2 presents a comparison of different existing approaches in the literature related to uncertainty, cellular manufacturing, and reconfigurable manufacturing in the context of remanufacturing or circular manufacturing. This comparison demonstrates a clear focus on using smart or I4.0 technologies to address remanufacturing uncertainty by recovering, analyzing, and processing product life cycle information. These approaches mainly emphasize on addressing the lack of information about used products' conditions, return timing, and demand. Some also consider the potential of deploying smart technologies in remanufacturing and CE operations, such as disassembly and repair. Despite the significant impact of uncertainty on its performance, the production architecture is not given sufficient attention. In fact, a joint focus is needed, that also includes the product manufacturing architecture to address uncertainty challenges.

Cellular manufacturing systems are few explored in a remanufacturing context, while reconfigurable manufacturing has received more attention due to its potential applications in disassembly or repair operations. The few research studies that consider both cellular and reconfigurable manufacturing are based on optimization models. The present study contributes to transitioning to smart remanufacturing by the design and development of a hybrid architecture able to address

Tableau 5.2 Comparison of different approaches in the literature addressing remanufacturing uncertainty, reconfigurability and cellular manufacturing

Authors	Rem-CM	U	S-I4.0	CM	RM	O	MO
Abbey <i>et al.</i> (2017)	✓	✓					
Aljuneidi & Bulgak (2017)	✓			✓	✓	✓	
Andersen <i>et al.</i> (2023)	✓	✓	✓		✓		
Brunoe <i>et al.</i> (2019)	✓	✓	✓		✓		
Bressanelli <i>et al.</i> (2018)	✓	✓	✓				
Chinen & Matsumoto (2021)	✓	✓					
Eguia <i>et al.</i> (2011)	✓		✓		✓		
Daneshmand <i>et al.</i> (2023)	✓		✓		✓		
Fan <i>et al.</i> (2010)	✓				✓		
Kurilova-Palisaitiene <i>et al.</i> (2018)	✓	✓					
Telegraphi & Bulgak (2021)	✓			✓	✓	✓	
Kerin & Pham (2019)	✓	✓	✓				
Kerin & Pham (2020)	✓	✓	✓				
Mejía-Moncayo <i>et al.</i> (2021)	✓	✓		✓	✓	✓	
Mejia-Moncayo <i>et al.</i> (2022)	✓			✓		✓	
Mejía-Moncayo <i>et al.</i> (2023b)	✓	✓	✓				
Milios & Matsumoto (2019)	✓	✓					
Tolio <i>et al.</i> (2017)	✓	✓	✓				
This study	✓	✓	✓	✓	✓	✓	✓
Table criteria : Rem-CM - Remanufacturing or Circular manufacturing, U - Uncertainty, S-I4.0 - Smart or I4.0, CM - Cellular manufacturing, RM - Reconfigurable manufacturing, O - Optimization, MO - Multi-objective.							

remanufacturing uncertainty on an operational level. Such architecture serves as a physical framework for a smart sustainable remanufacturing system. The proposed architecture integrates cellular manufacturing paradigm strategically to reduce the complexity of the system by breaking it down into smaller remanufacturing cells. Then, these cells incorporate smart reconfigurable features that allow them to control upstream and downstream uncertainty. A multi-objective optimization approach is used in the architecture's design process for its configuration and to provide a discrete approach to its facility layout design.

5.4 Reconfigurable Cellular Remanufacturing Architecture

The proposed reconfigurable cellular remanufacturing architecture (RCRA) plays a crucial role in the business strategy to address uncertainty, as is illustrated in figure 5.3. The RCRA serves as the productive framework or physical structure of a smart sustainable remanufacturing system. The business strategy also incorporates concurrently a smart architecture and a circular business model. A business model defines the system's interaction with stakeholders, and establishes the agreements that allow to engage the customers and returned used products, while the smart architecture is focused on recovery, processing, and analyzing products life cycle information. In this way, the uncertainty is minimized to a level that can be effectively managed by the production architecture as presented in figure 5.3.

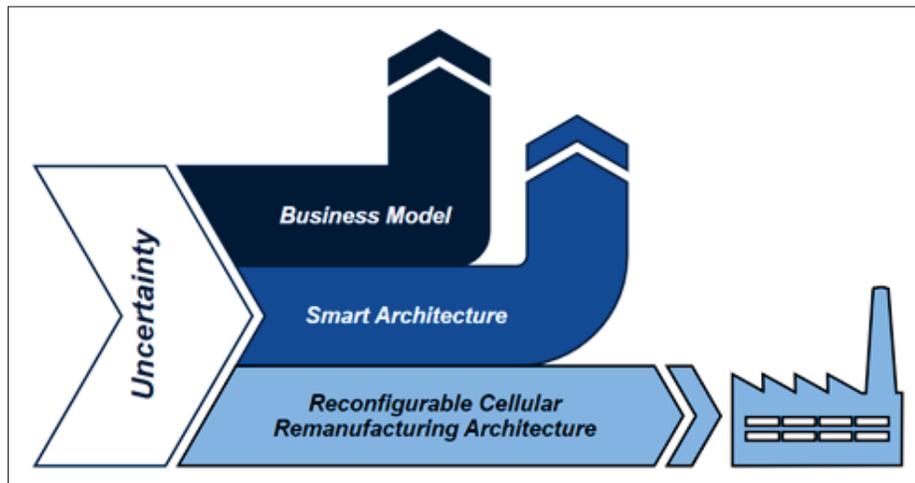


Figure 5.3 Overall business strategy, including a joint business model, smart architecture and reconfigurable cellular remanufacturing architecture approach, to address remanufacturing uncertainty

Once the business strategy is established, the uncertainty effects must be verified on the remanufacturing system to establish RCRA features. The variations in used products conditions have a significant effect on system complexity, processes capacity, operational times, production rate, production scheduling, and inventory. When adopting remanufacturing approaches, it is highly probable to face sets of used products having different configurations and state of deterioration, as described by the explanatory case study based on electric motors introduced in

figure 5.4. Here, these motors have four different configurations defined by their materials and applications, four types of product deterioration, and each group of motors has its own potential return rate and operation times, which fluctuate from one version to another. Fortunately, the motors share similar processes and spare parts, enabling to group them into product families. However, the problem still presents complexities.

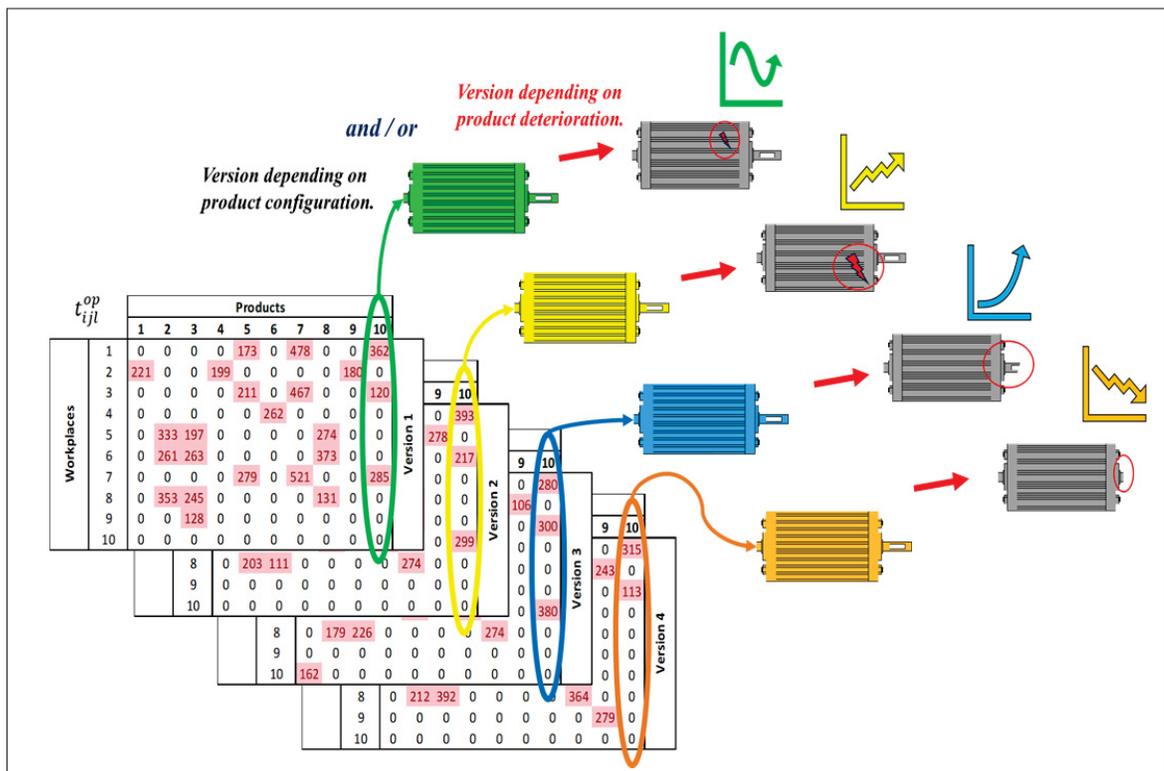


Figure 5.4 Example of variation on return rate and operation times for electric motors by their versions and / or deterioration conditions

Considering the aforementioned characteristics, the to be developed architecture should be simple, agile, flexible, and economically feasible. In RCRA, cellular manufacturing contributes to simplify the system from a complex and aggregated process to a set of mini plants or cells with a reduced size and complexity. Hence, it becomes possible to define remanufacturing cells and product families, which share the same workplaces and product versions, assigned to one cell in which the product will be remanufactured completely. All cells need to be able to swiftly self-configure their processes, operations, machines, or workplaces. Furthermore, each

cell includes smart workplaces with reconfigurable machines or devices that identify, handle, transport, and process products for remanufacturing. The success of the proposed architecture depends on the efficient interaction of the smart remanufacturing cells that can balance their workloads, changing their production capacity by adding or removing (turning On or Off) devices, machines, workplaces or even labour to maintain a continuous production rate.

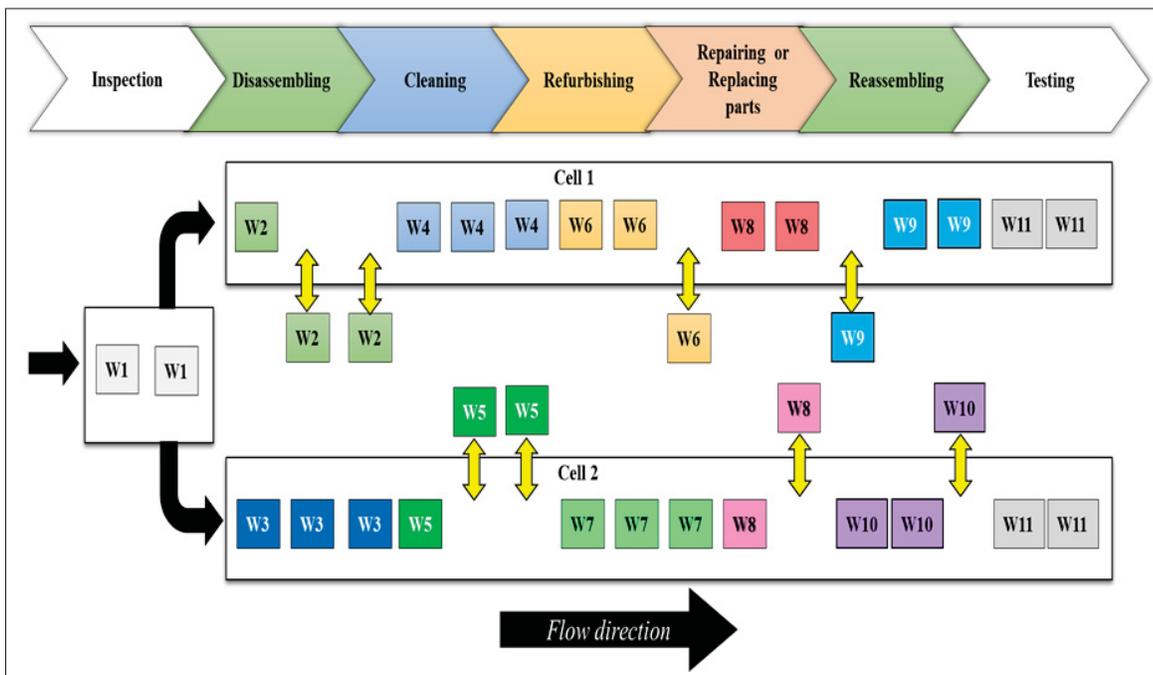


Figure 5.5 Schema of proposed remanufacturing architecture

Figure 5.5 presents a general schema of the proposed RCRA, illustrating on the top a generic sequence of the principal remanufacturing processes, followed by two reconfigurable remanufacturing cells, referred to as Cell 1 and Cell 2.

For a better understanding of the smart remanufacturing cells, figure 5.6 presents a schematic example based on electric motors. Here, once the motor has arrived in the inspection workplace, an IoT connected image recognition system recognizes the motor and starts the inspection process, as shown in figure 5.6. A robotic arm mounts the motor on the test bench for measuring the variables, which define its deteriorated condition. Based on these test results, the motor continues for further processes, such as disassembling, repairing, reusing, recycling, or disposal.

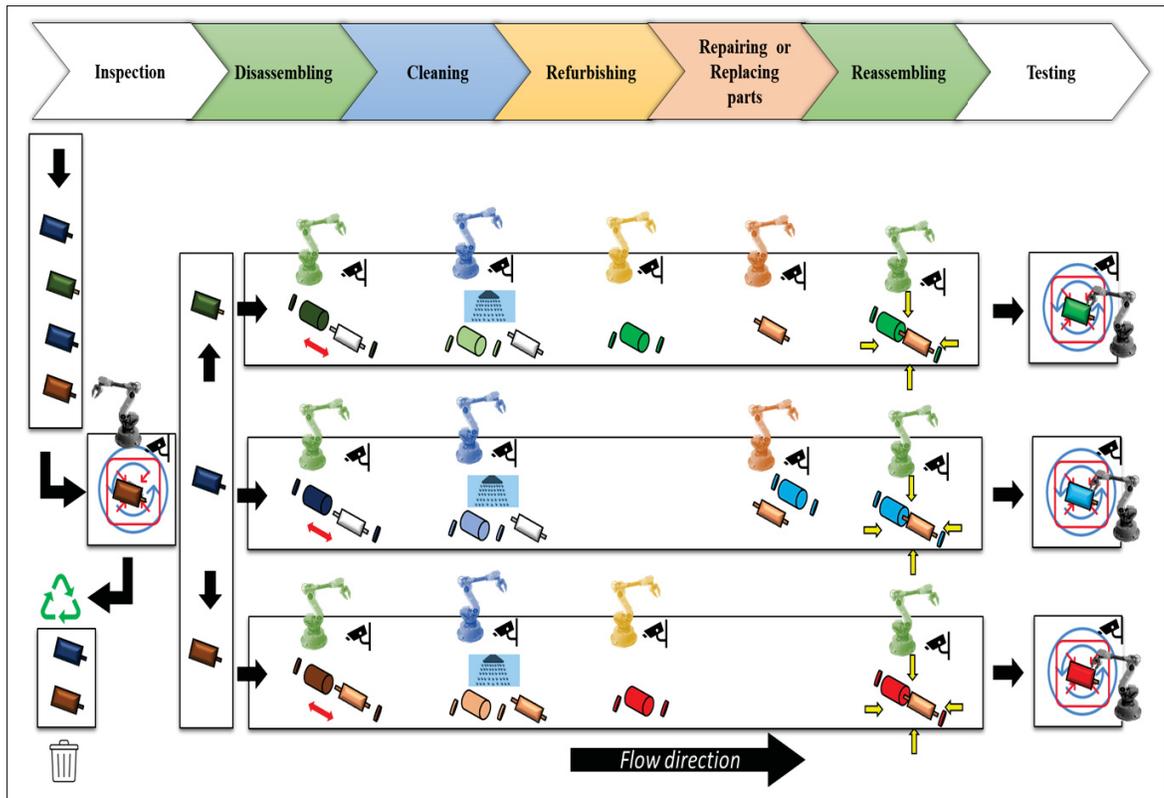


Figure 5.6 Schema of the proposed remanufacturing architecture for electric motors

When product life cycle information is available, it will support these processes by establishing the properties for verification in advance for each used product, hence improving the inspection sequence efficiency.

In the disassembling workplaces outlined in figure 5.6, a multi-axis clamping mechanism holds the motor, while a robotic arm separates the parts. For this example, the motors are disassembled and cleaned in a next step. Repairs can include material adding or removing processes, such as coating or polishing, besides other treatments such as straightening to return the part to its original shape, changing components or other operations to return a component to the original part condition. Refurbishing operations can be executed as well, aiming to improve the performance or appearance beyond original condition, as a product update. Figure 5.6 illustrates an example where one cell performs reparations and refurbishing operations, and other cells

conduct only reparations and others only refurbishing, depending on the deterioration condition of the motors, e.g., the frame receives a coating for corrosion protection, which improves its original characteristics (refurbishing), and the stator is repaired. Missing parts will be replaced, and they will be reassembled. It is important to note that the remanufacturing cells manage its capacity to keep workloads balanced. Finally, the motors will be evaluated on its quality.

Once the RCRA architecture has been defined, its configuration needs to be established. This challenging task requires assigning products and workplaces to each cell, setting the number of workplaces to keep workloads balanced, reducing makespan, while keeping reconfigurability and investment costs at a feasible level. Therefore, in section 5, a multi-objective optimization model is introduced.

5.5 Mathematical model

The formulated multi-objective optimization to configure RCRA's features to address remanufacturing system uncertainty is presented in this section. The proposed mathematical model aims to achieve jointly the following objectives :

- Minimizing the grouping cost to assign products to families and workplaces to cells, where each cell processes entirely its own product family ;
- Balancing the workloads by establishing the number of workplaces required to process each product version. This allows to minimize the waste of time, reduce work in process, keeping a continuous production rate, and contributes to the system flexibility and reconfigurability ;
- Minimize the investment cost to achieve economically feasible solutions ;
- Minimize the makespan to provide the best possible service to customers ;
- Minimize the reconfigurability cost by developing production sequences that require less effort to pass from one product to another.

5.5.1 Nomenclature

The model indices are defined as follows :

- m : number of machines or workplaces
 n : number of products
 mc : maximum number of cells
 np : number of periods
 nl : number of product versions
 i : machine or workplace index ($i = 1, \dots, m$)
 j : product index ($j = 1, \dots, n$)
 k : cell index ($k = 1, \dots, mc$)
 p : period index ($p = 1, \dots, np$)
 l : allowed product versions index ($l = 1, \dots, nl$)

The model parameters are defined as :

a_{ijl} : is the incidence book, defined as follows :

$$a_{ijl} = \begin{cases} 1 & \text{if workplace } i \text{ can process version } l, \text{ of product } j \\ 0 & \text{otherwise} \end{cases}$$

R_{pjl} : return rate of version l , of product j for the period p

t_{ijl}^{op} : operation time of version l , of product j in machine or workplace i

t_j^c : cycle time for product j

C^g : grouping cost.

C^{wb} : workload balancing cost.

C_i^{wp} : investment cost of workplace i .

C^m : makespan cost.

$d_{ii'}^{wp}$: Hamming distance among the incidence book rows.

$d_{jj'}^p$: Hamming distance among the incidence book columns.

wp_{ik}^{max} : maximum quantity of workplaces i by cell k .

t_k^{cell} : maximum completion of processing time by remanufacturing cell k .

The decision variables are defined as :

$$X_{ik} = \begin{cases} 1 & \text{if machine or workplace } i \text{ belongs to cell } k \\ 0 & \text{otherwise} \end{cases}$$

$$Y_{jk} = \begin{cases} 1 & \text{if product } j \text{ is produced in cell } k \\ 0 & \text{otherwise} \end{cases}$$

$$W_{pjj'k} = \begin{cases} 1 & \text{in period } p, \text{ if product } j \text{ is processed before of product } j', \text{ in the cell } k \\ 0 & \text{otherwise} \end{cases}$$

Z_{ijl} : quantity of workplaces of type i to produce version l , of product j .

5.5.2 Objective function

The definition of the proposed architecture is a multi-criteria problem, which is summarized in the following multi-objective function (equation (5.2)) :

$$\text{Minimize } \{f_1 \wedge f_2 \wedge f_3 \wedge f_4 \wedge f_5\} \quad (5.2)$$

The first objective function f_1 (equation (5.3)), emulates the similarities among products and workplaces as Hamming distances for the definition of cells and product families. The first term of equation (5.3) corresponds to the Hamming distance among the incidence book rows $d_{ii'}^{wP}$ (equation (5.4)). The minimization of this term allows grouping the workplaces into cells, where the low Hamming distance value is linked with high similarity among the workplaces that share the products to be processed. Similarly, the second term of equation 5.3 corresponds to the Hamming distance among the incidence book columns $d_{jj'}^P$ (equation (5.5)). The minimization of this term allows grouping the products into families. The low Hamming distance value is linked to a high similarity among the products that share workplaces in which they are processed. The third term of equation (5.3) aims to avoid the product movements between two different cells.

$$f_1 = C^g \sum_{k=1}^{mc} \sum_{i=1}^m \sum_{i'=1}^m X_{ik} X_{i'k} d_{ii'}^{wp} + C^g \sum_{k=1}^{mc} \sum_{j=1}^n \sum_{j'=1}^n Y_{jk} Y_{j'k} d_{jj'}^p + C^g \sum_{j=1}^n \sum_{i=1}^m \sum_{p=1}^{np} a_{ijl} \left(1 - \sum_{k=1}^{mc} X_{ik} Y_{jk} \right) \sum_{l=1}^{nl} R_{pjl} \quad (5.3)$$

$$d_{ii'}^{wp} = \sum_{j=1}^n \sum_{l=1}^{nl} \left\| \left(a_{ijl} \sum_{p=1}^{np} R_{pjl} \right) - \left(a_{i'l} \sum_{p=1}^{np} R_{pjl} \right) \right\| \quad (5.4)$$

$$d_{jj'}^p = \sum_{i=1}^m \sum_{l=1}^{nl} \left\| \left(a_{ijl} \sum_{p=1}^{np} R_{pjl} \right) - \left(a_{i'jl} \sum_{p=1}^{np} R_{pjl} \right) \right\| \quad (5.5)$$

The second objective f_2 (equation (5.6)) aims to minimize the workload balancing cost. This is achieved by minimizing the difference between the operation time t_{ijl}^{op} and the cycle time t_{jp}^c . This difference can be increased or reduced by Z_{ijl} , the number of workplaces i for the l^{th} version of each product j . This objective f_2 allows the system to manage the return rate variations and to introduce reconfigurable features.

$$f_2 = C^{wb} \sum_{l=1}^{nl} \sum_{p=1}^{np} \sum_{k=1}^{mc} \sum_{j=1}^n \sum_{i=1}^m a_{ijl} R_{pjl} \left(t_{ijl}^{op} - t_j^c Z_{ijl} \right) \quad (5.6)$$

In order to control the initial project budget, and to avoid expensive solutions, objective function f_3 , represented by equations (5.7) and (5.8), considered the investment cost of workplaces i assigned to the different cells k .

$$f_3 = \sum_{k=1}^{mc} C_i^{wp} \max [wp_{ik}^{max} : i = 1, \dots, m] \quad (5.7)$$

$$wp_{ik}^{max} = \max [X_{ik} \max [a_{ijl} Z_{ijl} : l = 1, \dots, nl] : j = 1, \dots, n], \quad \forall i, k \quad (5.8)$$

Production scheduling relates directly to the remanufacturing system's performance, flexibility, and adaptability. This study proposes to model production scheduling by the makespan cost objective function f_4 presented in equation (5.4). Here, makespan is defined as the maximum completion time by cell t_k^{cell} , which is calculated by equations (5.10) and (5.11).

$$f_4 = C^m * \max [t_k^{cell}] \quad (5.9)$$

$$t_j^{max} = \max_{Z_{ijl} > 0} \left[\frac{t_{ijl}^{op}}{Z_{ijl}} : i = 1, \dots, m \wedge l = 1, \dots, nl \right] \quad \forall i, j, l \rightarrow Z_{ijl} > 0 \quad (5.10)$$

$$t_j^{cell} = \sum_{p=1}^{np} \sum_{j=1}^n t_j^{max} Y_{jk} \sum_{l=1}^{nl} R_{pjl} \quad \forall p, j, l \quad (5.11)$$

The reconfigurability cost objective function f_5 is incorporated into the model to measure the cost of changing the cells' configuration from one product to another (equation 5.12).

$$f_5 = C^{wb} \sum_{p=1}^{np} \sum_{j=1}^n \sum_{j'=1}^n \sum_{k=1}^{mc} C_{jj'} W_{pjj'k} \quad (5.12)$$

5.5.3 Model constraints

The model is subjected to the following constraints, as described in this section. To define cells and product families, the model must guarantee that each machine or workplace i has to be assigned to at least one cell k , as is described in equation (5.13). This allows that different cells comprise the same type of machines to avoid movements between cells. In equation (5.14), the model restricts that each product j must belong to a single product family, which at the same time must belong to a single cell k . Equation (5.15) guarantees to have workplaces i needed to process the different versions of product j .

$$\sum_{k=1}^{mc} X_{ik} \geq 1, \forall i \quad (5.13)$$

$$\sum_{k=1}^{mc} Y_{jk} = 1, \forall j \quad (5.14)$$

$$\sum_{k=1}^{mc} X_{ik} Y_{jk} - a_{ijl} \geq 0, \forall i, j, l \quad (5.15)$$

To achieve feasible solutions in terms of production scheduling and reconfigurability, the solutions must fulfil certain conditions as described below. Equation (5.16) restricts production sequences to occur only among products belonging to the same product family. Similarly, equation (5.17) helps to make the number of assignments in the production sequence in accordance with the number of products in the cell. Equations (5.18) and (5.19) guarantee that all products serve at least one time as origin or destiny in the production sequence. Finally, the domain constraints for the decision variables are described in equations (5.20) to (5.22) .

$$W_{pj'jk} + W_{pj'jk} - Y_{jk} Y_{j'k} \leq 0, \forall p, j, j', k \quad (5.16)$$

$$\sum_{j'=1}^n Y_{jk} - \sum_{j=1}^n \sum_{j'=1}^n W_{pj'jk} \leq 1, \forall p, k \quad (5.17)$$

$$\sum_{j'=1}^n W_{pj'jk} \leq 1, \forall j, k, p \quad (5.18)$$

$$\sum_{j=1}^n W_{pj'jk} \leq 1, \forall j', k, p \quad (5.19)$$

Domain constraints for decision variables are defined as below :

$$X_{ik}, Y_{ik}, W_{jj'p}, \in \{0, 1\} \quad (5.20)$$

$$Z_{ijl} \in \mathbb{Z} \quad (5.21)$$

$$f_1, f_2, f_3, f_4, f_5 \geq 0 \quad (5.22)$$

Section 5.6 presents the numerical evaluation of the proposed multi-objective model by the three methods (NSGA2, GA-mo, and GAMS-CPLEX) considered in this study.

5.6 Results and discussion

This section starts with the numerical evaluation of the explanatory case study (see figure 5.4 and 5.5) in section 5.6.1. Then the model's sensitive analysis is presented in section 5.6.2. Section 5.6.3 details the procedures for the selection of the best architecture configuration. Managerial insights are subsequently presented in section 5.6.4, and concludes with the model's and case study's discussion 5.6.5.

5.6.1 Numerical evaluation

This section presents the results of the numerical evaluation of the multi-objective optimization model to design the RCRA, by the customized version of NSGA2, the GA-mo, and the model implemented in GAMS using CPLEX solver. The obtained results include 60, 78, and 9 solutions for NSGA2, GA-mo and GAMS-CPLEX, respectively. The solutions illustrated in figure 5.7 represent the best Pareto frontier achieved by the three methods solving the explanatory case study (section 4). Each graph presents a three-dimensional representation of three of the five

objective function' values. Each solution represents a feasible architecture configuration for the case study. For each product version, the solution provides the required workplaces to fully process each product version. The number of workplaces, production sequences, and investment cost were established considering cells configuration, workload balancing, makespan, and reconfigurable cost.

The optimal Pareto frontier is embodied by the GAMS-CPLEX solutions (red) and therefore serves as a valuable reference point. Unfortunately, this set only has 9 solutions because different weighted factors converge to the same solution, reducing the size of the Pareto frontier. In addition, the case study presents numerous singularities points during its solution, which affected CPLEX solver. The Pareto frontier can be increased by adding 18 solutions obtained by GA-mo, because these solutions are non-dominated by the GAMS-CPLEX solutions. In fact, this shows the potential of GA-mo to achieve Pareto optimal solutions. Therefore, figure 5.7 exposes the clear proximity between GA-mo (green) and GAMS-CPLEX (red) solutions, while NSGA2 (black) solutions are widely distributed. This behaviour becomes even more clear when the data distribution is analyzed by box plot graphs. Figure 5.8 unmistakably demonstrates the proximity among GA-mo and GAMS-CPLEX solutions, and the long distance to NSGA2 solutions for each objective function. Also, its dispersion is greater compared to the two other methods. Indeed, figures 5.8-a and 5.8-e also show the difference among f_1 and f_5 scales to the other objectives. Such differences push global optimization approaches to minimize the objectives with higher values, while sacrificing the lowest. This reason explains why GA-mo and GAMS-CPLEX solutions are densely located in the same space, while NSGA2 solutions are more widely spread.

5.6.2 Sensitivity Analysis

A sensitivity analysis was conducted to verify the changes in model decision variables by the variation in model parameters, which often are unknown in initial design stages, or which can change with time. The performed analysis comprised the verification of the decision variables X_{ik} , Y_{jk} , $W_{pjj'k}$ and Z_{ijl} evolution, when varying one parameter at a time in a weighted range compared to its original values between 25% and 350%.

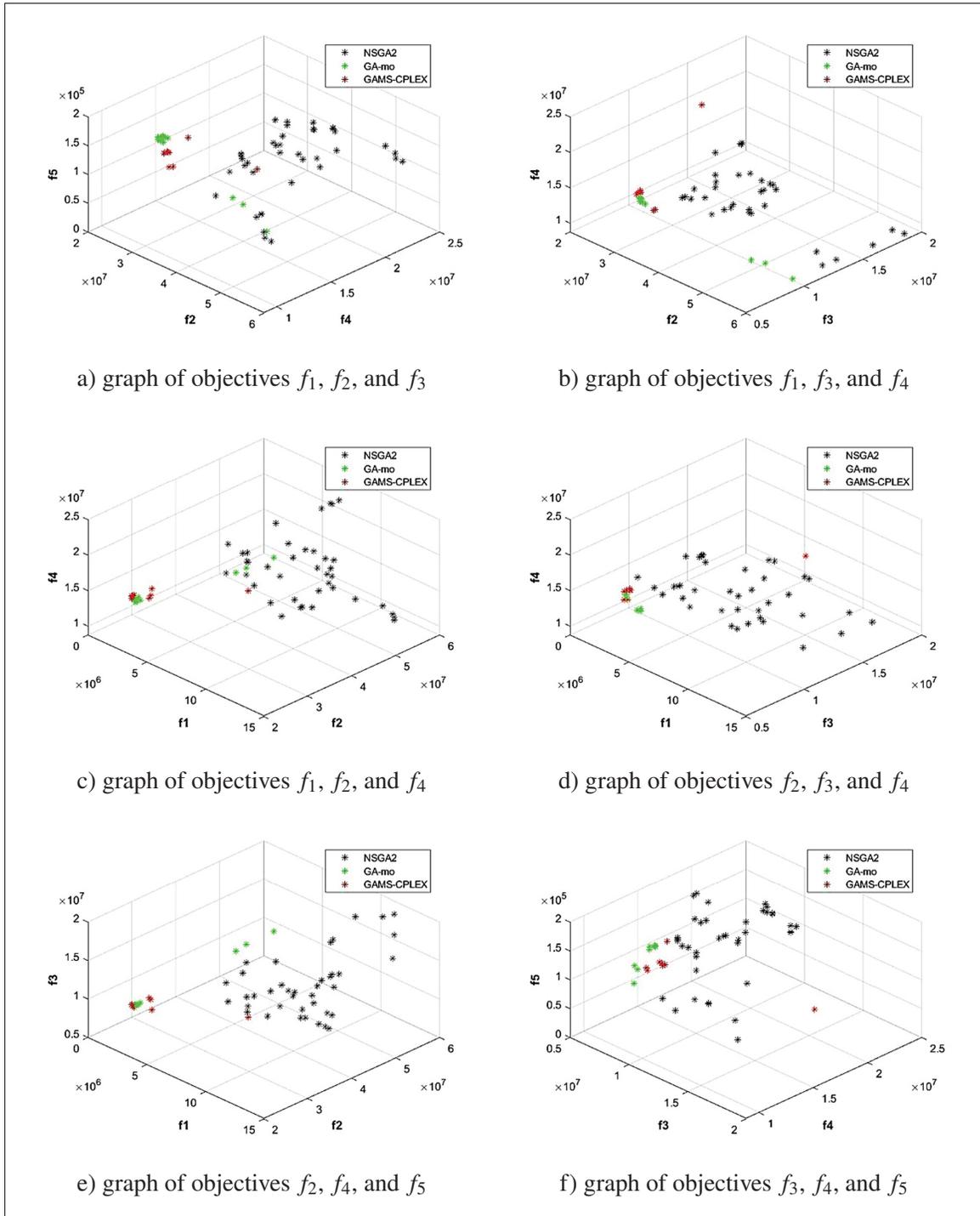


Figure 5.7 Solutions to the introduced case study achieved by NSGA2 (in black), GA-mo (in green), and GAMS-CPLEX (in red)

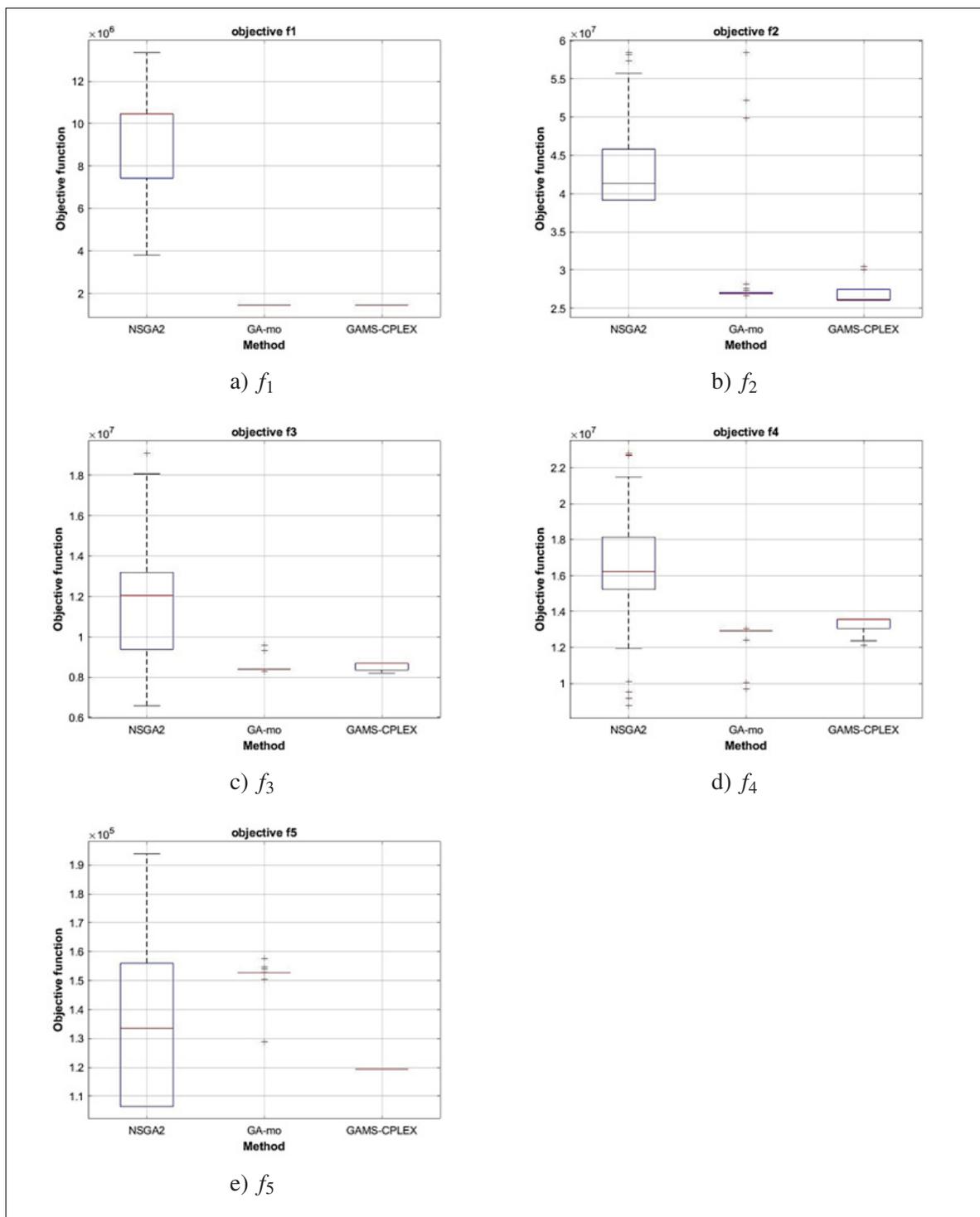


Figure 5.8 Box plot graphs of the objective function values by optimization method (NSGA2, GA-mo, and GAMS-CPLEX), for each objective

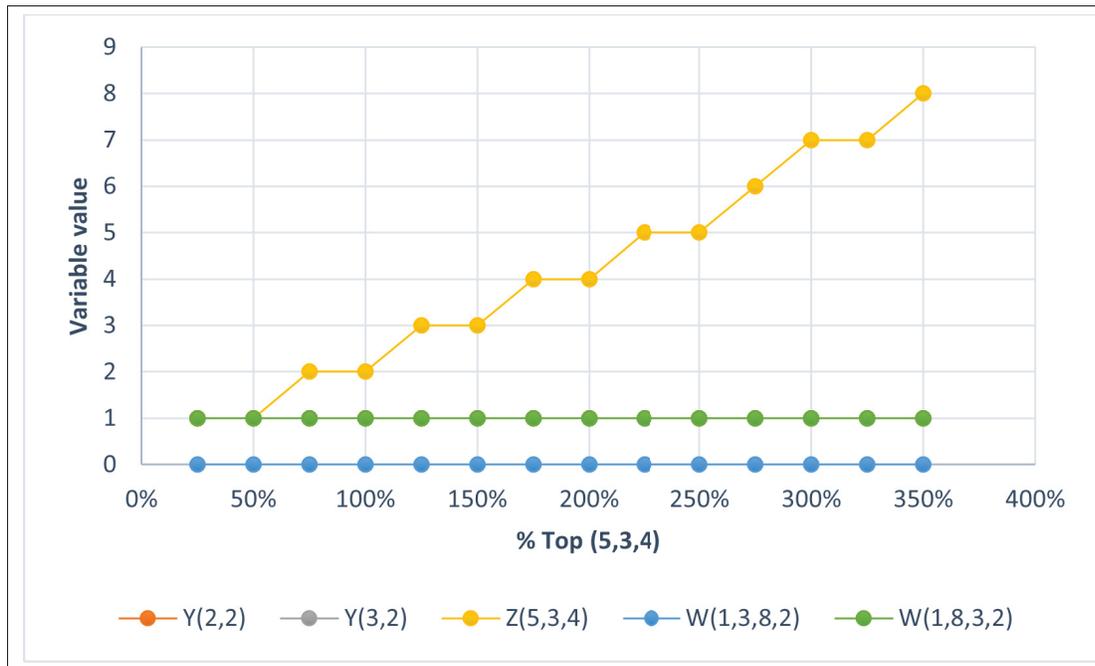


Figure 5.9 Sensibility of decision variables by time of operation Top (5,3,4) variation from 25% up to 350% of its original value

Figure 5.9 shows that Z_{ijl} grows when t_{ijl}^{op} experiments increase greater than of 25% or more. Contrary to this behaviour, Z_{ijl} decreases its value up to a stable value when t_j^c grows as illustrated in figure 5.10. The other decision variables maintain their values despite the changes in operational time and cycle time. This analysis identified that Z_{ijl} is sensible to the changes in values of operational time t_{ijl}^{op} and cycle time t_j^c . Managerial insights, presented in section 6.4, will address how to determine the best solution method and architecture.

5.6.3 Procedures for the selection of best architecture configuration

Considering the multi-objective nature of the remanufacturing architecture configuration problem addressed in this study, the selection of the best solution emerges as an important issue. Thus, two procedures were considered; the first is to select the solution whose sum of its objective function values is the minimum (see equation (5.1)), and the second procedure seeks to implement an analytic hierarchy process (AHP) (Saaty, 1987). For the first procedure, for each individual

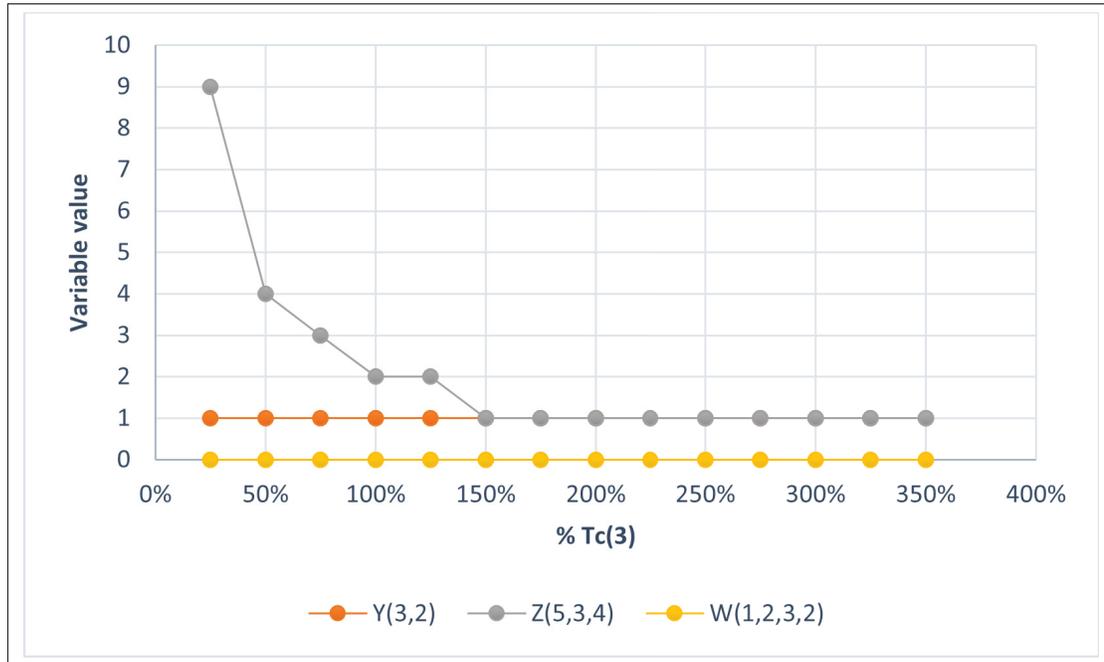


Figure 5.10 Sensibility of decision variables by cycle time Tc(3) variation from 25% up to 350% of its original value

solution, the sum of its five objective function values was calculated and then those with the minimum value were selected. For the second procedure, the AHP method was implemented to identify a solution that balanced the different objective functions and priorities of decision makers.

The objective functions' priority was established as the following sequence : f_1, f_2, f_4, f_5, f_3 , where f_1 is more important than f_2 and so on, continuing up to the last term. Based on this ranking, the evaluation matrix was established, and its eigenvector was determined. Then, the objective function values were normalized, dividing by the maximum value per function, and a similar process was performed to get the five eigenvectors. The priority P_{x-y} of solution S_x over S_y is assigned depending on the difference between the evaluation matrix values of the two solutions ($V_x - V_y$), e.g., when $V_1 - V_2 = 0.24$; this value is greater than 0.2 and lower or equal to 0.3. Then considering the lower solution S_2 , the priority of S_2 over S_1 is $P_{2-1} = 3$, while the priority of S_1 over S_2 , is $P_{1-2} = 1/3$ as presented in table 5.3. This relation was established

considering the AHP procedure defined by Saaty (1987). Finally, combining the priority and solutions' eigenvectors, the global best solution was selected.

Tableau 5.3 Priority selection criteria P_{y-x} and P_{x-y} between two solutions S_x and S_y for the AHP procedure implemented, based on the difference between the evaluation matrix values $(V_x - V_y)$, (when $V_y < V_x$)

Difference	P_{y-x}	P_{x-y}
$0 \leq V_x - V_y \leq 0.1$	1	1
$0.1 < V_x - V_y \leq 0.2$	2	1/2
$0.2 < V_x - V_y \leq 0.3$	3	1/3
$0.3 < V_x - V_y \leq 0.4$	4	1/4
$0.4 < V_x - V_y \leq 0.5$	5	1/5
$0.5 < V_x - V_y \leq 0.6$	6	1/6
$0.6 < V_x - V_y \leq 0.7$	7	1/7
$0.7 < V_x - V_y \leq 0.8$	8	1/8
$0.8 < V_x - V_y \leq 0.9$	9	1/9
$0.9 < V_x - V_y \leq 1$	10	1/10

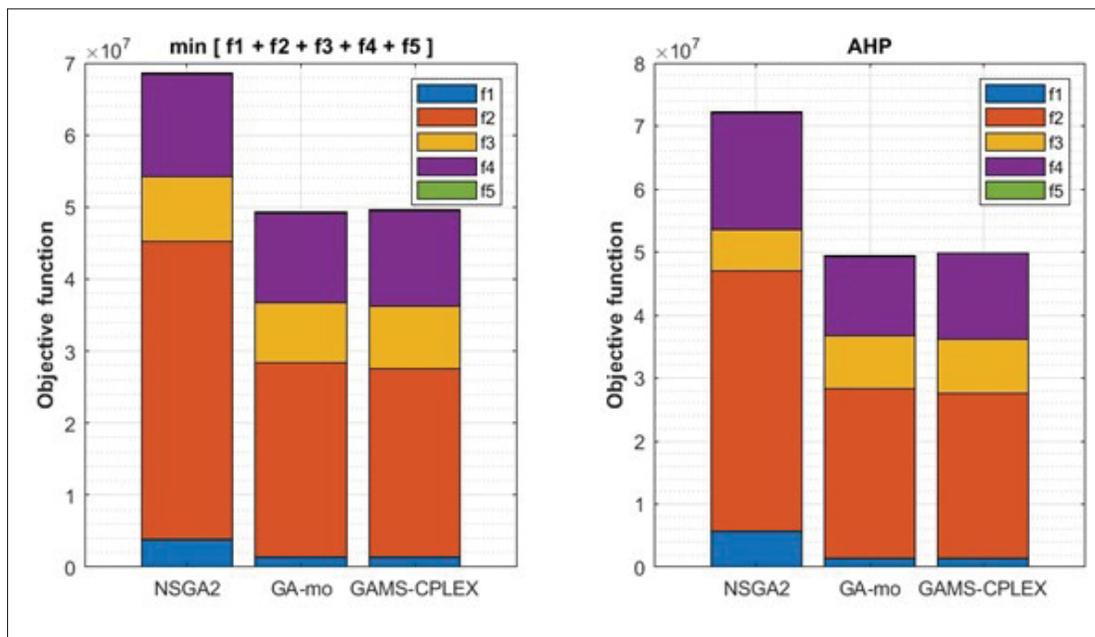


Figure 5.11 Comparison of the total cost of best solutions obtained by NSGA2, GA-mo, and GAMS-CPLEX considering the sum of objective function values and AHP

Figure 5.11 and table 5.4 provide a global approach to the best solutions' performance. The lowest values for each objective and the sum of them are highlighted by bold fonts in Table 5.4. These solutions, considering the sum of its objective function values, are less expensive than AHP solutions. Also, there are reduced differences in values between the solutions using the same solution method for the two procedures, as shown in table 5.4. For both procedures, NSGA2 solutions get the highest total cost, while GA-mo are the lowest. This demonstrates the benefit of GA-mo over the other solution methods.

Tableau 5.4 Comparison of best solutions obtained by NSGA2, GA-mo, and GAMS-CPLEX considering the sum of objective function values and AHP

	$\min [f_1 + f_2 + f_3 + f_4 + f_5]$			AHP		
	NSGA2	GA-mo	GAMS-CPLEX	NSGA2	GA-mo	GAMS-CPLEX
f_1	\$ 3.793.016	\$ 1.439.605	\$ 1.444.659	\$ 5.607.864	\$ 1.439.605	\$ 1.439.605
f_2	\$ 41.370.619	\$ 26.936.641	\$ 26.121.000	\$ 41.370.619	\$ 26.936.641	\$ 26.061.456
f_3	\$ 9.102.500	\$ 8.401.600	\$ 8.682.700	\$ 6.573.700	\$ 8.401.600	\$ 8.682.700
f_4	\$ 14.242.429	\$ 12.428.169	\$ 13.292.710	\$ 18.485.162	\$ 12.428.169	\$ 13.566.894
f_5	\$ 164.240	\$ 152.710	\$ 119.300	\$ 176.330	\$ 157.710	\$ 119.300
Total	\$ 68.672.803	\$ 49.358.725	\$ 49.660.369	\$ 72.213.674	\$ 49.363.725	\$ 49.869.955

Figure 5.12 exposes the best remanufacturing architectures for the three solution methods, considering the sum of the objective function values. GA-mo and GAMS-CPLEX present similar configurations that differ in one workplace number (5), and the order of remanufacturing cells. On the other hand, NSGA2 has an architecture in which cells 2 and 3 are almost equal, duplicating its workplaces.

The best architectures selected through the AHP process have been depicted in Figure 5.13. GA-mo and GAMS-CPLEX have configurations that differ only in two workplaces type ; (5) and (9). The NSGA2 solution provides an attractive option for addressing issues of space scarcity and cost as a primary concern. Its compact design and low investment cost make it a potentially valuable option. The results in table 5.3 provide evidence that GA-mo gets the least expensive alternatives compared to the other available options. In general, the analyzed configurations exhibit a compact configuration that reduces both the complexity of the system and the required area for production processes, which is well-aligned with the goals of this study.

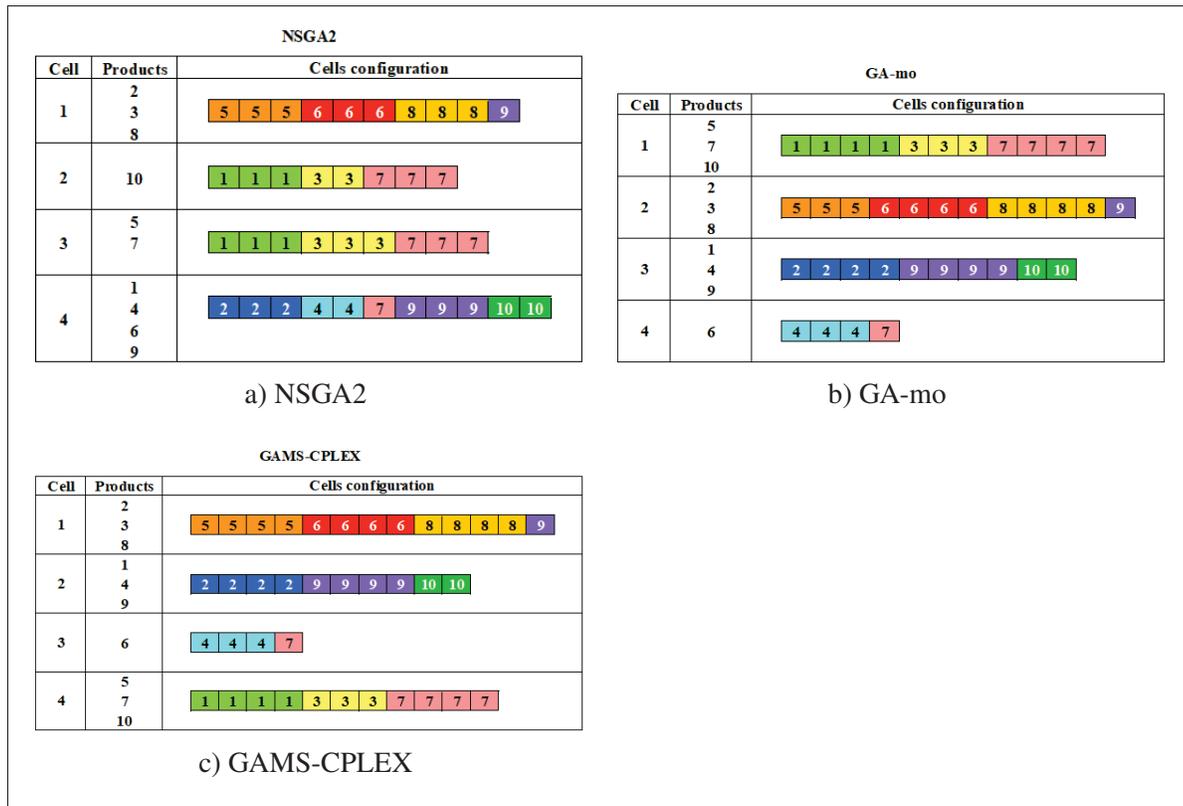


Figure 5.12 Best architectures considering the sum of objective function values obtained by optimization method (NSGA2, GA-mo, and GAMS-CPLEX)

Once the best architectures have been established, it is crucial to thoroughly analyze each architecture configuration on agreement with the five objective functions. Considering the objective function f_1 , GA-mo has the best solutions achieving the lowest costs, as is shown in table 5.3. The GAMS-CPLEX solution, when AHP is considered, displays similar performance to GA-mo, making it an interesting solution to evaluate. For objective function f_2 , GAMS-CPLEX has the best performance, mainly for the AHP architecture.

Generally, investment costs (objective function f_3) are among the most important selection criteria in engineering projects, hence NSGA2 achieves the lowest value in such case. The proposed architecture also demonstrates the potential of NSGA2 to provide diverse alternatives that expose the different edges to the analyzed problem. However, it is important to note that indeed the initial investment could be amortized, while this is not possible for the other objectives.

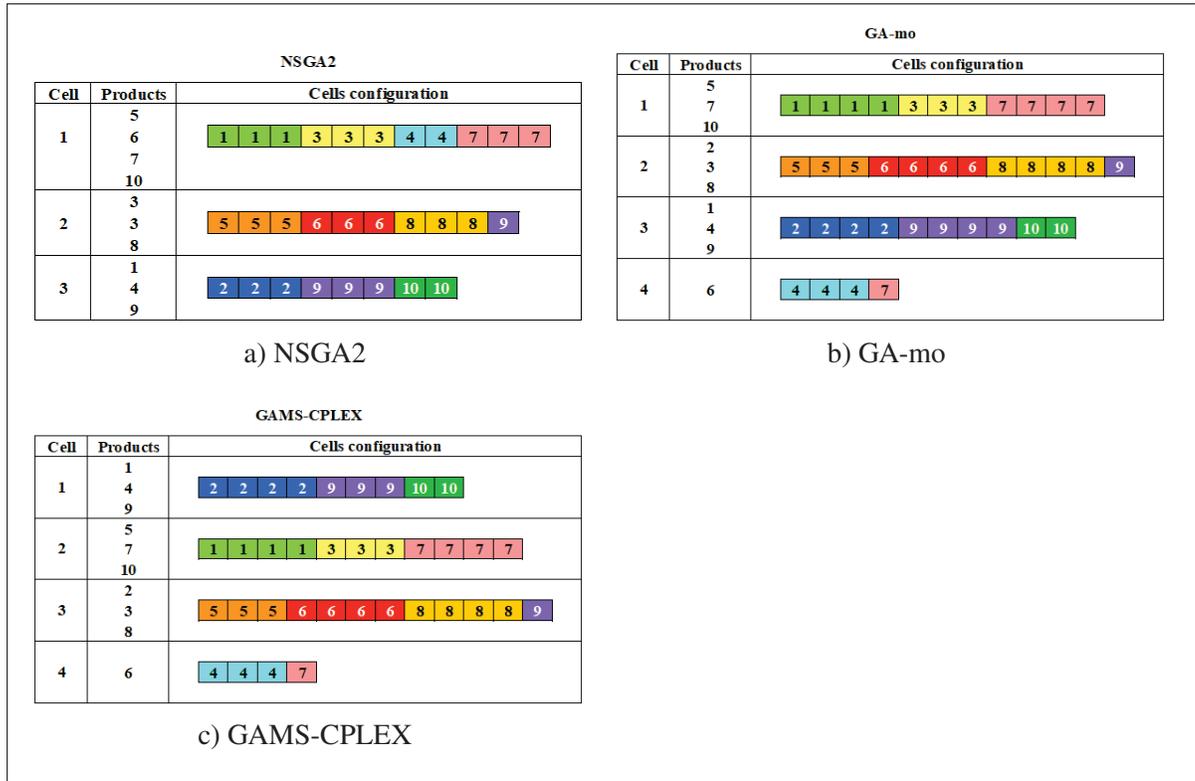


Figure 5.13 Best architectures considering AHP procedure obtained by optimization method (NSGA2, GA-mo, and GAMS-CPLEX)

The lowest makespan (objective function f_4) values were achieved via GA-mo, which is the most effective option here, and proves that the GA-mo architecture has the highest potential to meet customer demands quickly and efficiently. Meanwhile, GAMS-CPLEX presents the lowest reconfigurable cost f_5 , or a set of production sequences that require shorter transition times between products.

Finally, it can be concluded that RCRA configurations are feasible to integrate the features that reduce system' complexity by an arrangement of cells, balance the workloads, minimize the investment, reduce makespan for quick customer answer, and provide production sequences that reduce the effort to pass from one product to another. Once the case study has been evaluated, is the turn to introduce managerial insights.

5.6.4 Managerial insights

For practitioners exploring the transition to remanufacturing, two questions emerge at this point ; (1) which solution method (NSGA2, GA-mo, or GAMS-CPLEX) to apply in a given industrial context ; and (2) once obtaining the set of solutions, which procedure of the two to establish the best architecture configuration is preferred ?

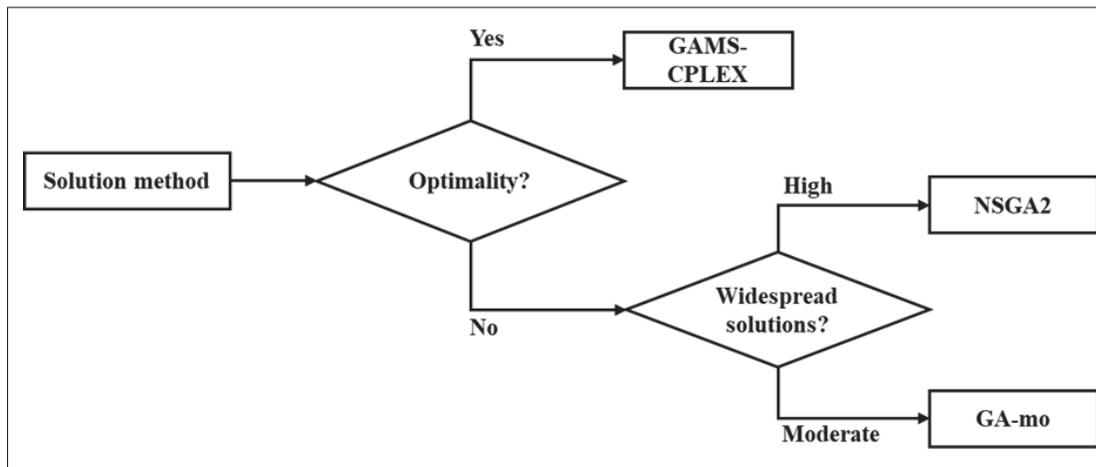


Figure 5.14 Decision tree to select the solution method for multi-objective optimization model

To address the first question (1), the decision tree presented in figure 5.14 supports to decide which method is best to apply. If the optimality of the solutions or architecture configurations are essential, the clear answer is to select GAMS-CPLEX. This method provides optimal solutions ; however, the diversity of the solutions are penalized in this case. If optimality is not the dictating factor, genetic algorithms emerge as good candidates. Indeed, if the design process requires diverse or widespread solutions NSGA2 should be selected, otherwise GA-mo. It is important to highlight that NSGA2 and GA-mo produce feasible solutions, however their performance depend on their configuration. Besides using optimization strategies, the proposed architecture could also be implemented by an iterative process that addresses the five objective functions of the model by using traditional, not optimization-based, methods.

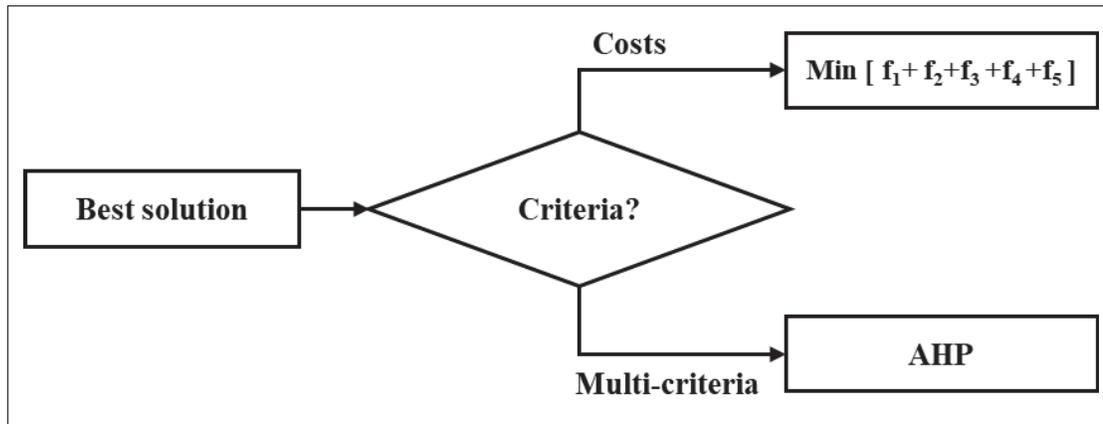


Figure 5.15 Decision tree to select the most appropriate procedure to establish the best architecture configuration

Once the solution has been obtained, the second question (2) emerges. The decision tree presented in figure 5.15 aids to decide which criteria to apply. If the cost of the implementation is the main criteria, the best architecture configuration must be selected at its minimum objective function values. However, if there are more criteria to consider in the implementation project, such as sustainability or the involvement of multiple decision-makers, the AHP process will be the best candidate. Certainly, AHP allows to integrate different points of view to identify an alternative that seeks agreement among the decision-makers.

5.6.5 Discussion

A RCRA was introduced as a concurrent approach integrated into a business strategy to address remanufacturing uncertainty and other challenges in smart sustainable remanufacturing. This strategy recognizes the need to address uncertainty as a multidimensional problem including a multi-objective optimization model in the design process. Hence, the design process can achieve a diverse set of feasible architecture configurations. Each configuration provides the type and quantity of workplaces for each remanufacturing cell, its product family, and their production sequences for each period. This represents the essential elements to start the design and development of a new remanufacturing facility.

However, it should be noted that this study has a limitation caused by the use of randomized data in the case study. Therefore, the data and results of the case study can only serve as an explanatory example of the proposed architecture. Considering the potential challenges in obtaining all the model parameters at an early stage of the design process, it is recommendable to start by the Incidence book a_{ijl} , operations times t_{ijl}^{op} and cycle times t_j^c ; because they are essential for the model. This is because they have a great influence on the decision variables, as shown in sensitive analysis. Even the incidence book and grouping distances can be obtained from the operation time matrix. Other model parameters as the costs related with each objective (C^g , C^{wb} , C_i^{wp} , C^m , or $C_{jj'}^r$) could be neglected in an initial design phase, assigning a value of “1” to them in the model (see section 5), and then solve the model to obtain a first approach for the proposed architecture. Also, the return rate (R_{pjl}) could be forecasted. After that, the costs related with each objective (C^g , C^{wb} , C_i^{wp} , C^m , or $C_{jj'}^r$) must be established in the industrial context of the company. In fact, grouping costs can be established considering the transport and handling of used products during the remanufacturing processes. The workload balancing cost quantifies the wasted time, and the workplaces costs include the equipment, tools, smart technology, installation, maintenance, labour, and other operational cost associated to the workplace during its useful life. Additionally, the makespan cost can be estimated considering it as an opportunity cost related to quality service, or it could be considered by the makespan time only. The reconfigurability cost quantifies the setup time and needed resources for the remanufacturing cell reconfiguration to process products sequentially. Finally, it will be useful to evaluate the performance and economic feasibility of each remanufacturing cell before its implementation.

5.7 Conclusions

A reconfigurable cellular remanufacturing architecture (RCRA) is introduced in this study to address the research gap related to the negative effects of upstream and downstream uncertainty in remanufacturing architectures. The proposed architecture configurations demonstrate the advantages of RCRA, due to their implementation feasibility, and their configuration suitability for efficiently minimizing all five objective functions; grouping cost f_1 , workload balancing cost

f_2 , investment cost f_3 , makespan cost f_4 , and reconfigurability cost f_5 . Indeed, RCRAAs reduce the system' complexity by transitioning from an aggregated system to a distributed system divided in individual remanufacturing cells. Such a strategy favors the control of the remanufacturing system by reducing the impact of information uncertainty. Then, each cell can fully process its own product family, and reconfigurable features allows to increase or decrease the cell's capacity. This contributes to manage and control the fluctuations in remanufactured product demand, return rate, and product conditions towards maintaining a continuous production rate.

The three solution methods - NSGA2, GA-mo, and GAMS-CPLEX - provide feasible solutions, each method presenting specific advantages; NSGA2 provides widespread solutions, while GA-mo obtains faster sub-optimal results, and GAMS-CPLEX results in optimal solutions.

Managerial insights were also introduced to support the selection process of the model solution method and the procedure to identify the best architecture configuration. It was concluded that the procedure using AHP allows to incorporate multiple decision criteria and decision makers perspectives, which represent an advantage over the objective function values sum minimizing based procedure. This is consistent with the multicriteria focus of the design process based on a multi-objective optimization model. Practical implications of the proposed model are discussed that contribute to its adoption and offer the industrial context related to model parameters.

Future research is needed to consider the sustainable and technological evaluation of the proposed architecture, and to include sustainable criteria in the objective functions' model, such as water and energy consumption, and health and safety.

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Data availability The codes and case study data are available in https://github.com/cmm14art/art_rcra_case_study.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CHAPITRE 6

TOWARDS REMANUFACTURING 5.0 : A SMART SUSTAINABLE APPROACH FOR END-OF-LIFE ELECTRIC VEHICLE LITHIUM-ION BATTERY REVALORIZATION

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Abstract

Remanufacturing is a value retention strategy to return used products to a state comparable to new ones, requiring less energy and materials than new products. Despite its benefits, its implementation faces intrinsic barriers and occasionally fails to address social concerns or stakeholder requirements. These gaps are addressed in this study by introducing Remanufacturing 5.0 (R5.0) as an implementation of Industry 5.0 principles in remanufacturing. R5.0 uses smart systems for enabling sustainability, integrating a human-centered approach, and enhancing system resilience. This is explained through an illustrative case study that simulates an R5.0 system for end-of-life (EOL) lithium-ion batteries (LIBs) from electric vehicles (EV) in Quebec, Canada. R5.0 includes a smart architecture that helps to integrate stakeholders, sustainable goals, system resilience, product life cycle information, and operations. A machine-learning-based approach helps to reduce uncertainty in lifespan. A multi-objective optimization model balances economics, environmental, and social concerns while establishing vehicle routing and recovery-processing scheduling of EoL EV LIBs. Finally, a sensitivity analysis is performed to demonstrate system robustness, and the advantages and limitations of R5.0 are discussed.

Keywords : Industry 5.0, Remanufacturing, Reverse Logistics, Sustainability, Lithium-ion Batteries.

6.1 Introduction

Remanufacturing emerges as a key product value retention strategy within the circular economy (Russell & Nasr, 2023), which contributes to mitigating resource depletion and pollution (Afari *et al.*, 2025; Haque *et al.*, 2024). Through a series of industrial processes, remanufacturing brings a product back to a condition that is comparable to a new product (Kerin & Pham, 2020). Remanufacturing and recycling are integrated in a closed-loop supply chain (CLSC) as described in figure 6.1. The CLSC begins with the extraction of raw materials. Suppliers transform raw materials into components. These are used to manufacture new products, which are then distributed to the users. After end-of-life (EoL) the product is recovered by reverse logistics (RL). Then, an inspection or a quality assessment is performed, and depending on the degradation, pollution, and risks connected with the product, it can be disposed of or disassembled for recycling or remanufacturing, closing the loop (Mejía-Moncayo *et al.*, 2025b).

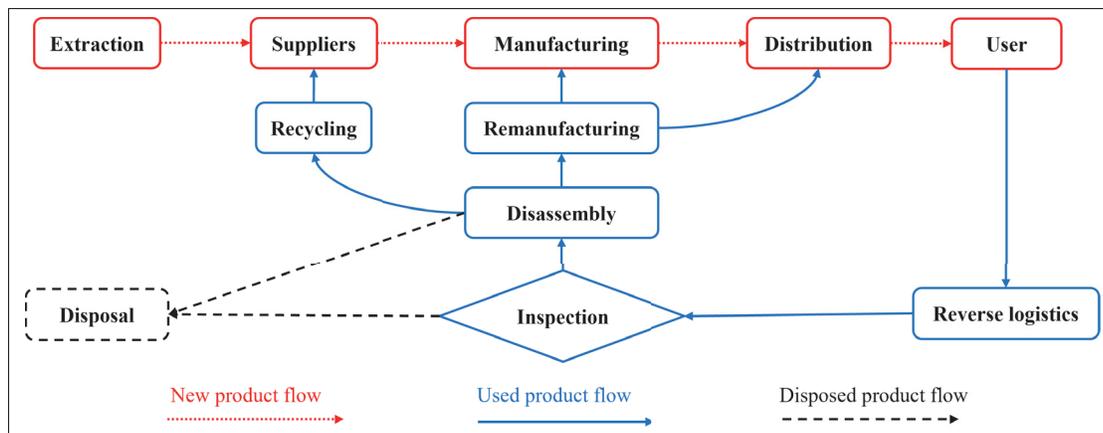


Figure 6.1 Schematic overview of the generic remanufacturing's closed-loop supply chain (CLSC)

Remanufacturing offers substantial benefits for sustainability in all three dimensions : economic, environmental, and social (Haque *et al.*, 2024). It reduces the environmental impact by preserving valuable resources. It helps the environment by reducing the need to extract, process, and transport materials for new products (Afari *et al.*, 2025). Furthermore, it supports job creation and stimulates economic expansion (Haque *et al.*, 2024).

However, implementing remanufacturing presents inherent challenges that have limited its scale and efficiency. These include uncertainty about the quantity, quality, and return times of used products; the complexity of disassembly and reassembly processes; and a notable lack of product life cycle information (PLCI) (Mejía-Moncayo *et al.*, 2023b). In addition, there are barriers related to customer trust, financial risks, and the reluctance of original equipment manufacturers (OEMs) to share data or view remanufacturers as competitors (Chau *et al.*, 2021).

Despite the economic and environmental benefits of remanufacturing for sustainability, an imbalance between the economic, environmental, and social dimensions persists (Tsalis *et al.*, 2022). The economic dimension prevails over the others, while environmental aspects are included thanks to government regulations (Gusmerotti *et al.*, 2019). However, the social dimension is often omitted or only partially considered in circular economy applications (Kaya *et al.*, 2023). In addition, this dimension is typically approached with a focus on the strategic level of the organization (Henaó *et al.*, 2021), due to the difficulty in establishing links with operational variables.

Industry 4.0 (I4.0) emerges in this context as a crucial enabler to overcome these barriers and optimize remanufacturing operations in a sustainable way (Lobo *et al.*, 2022). I4.0, characterized by the digitalization and smart interconnection of machines and processes that improve operational efficiency, reduce costs, and provide direct environmental benefits (Bag, Yadav, Wood, Dhamija & Joshi, 2020). In addition, it digitizes and optimizes supply chain processes (Rahman, Yaqot & Menezes, 2023; Sun, Yu, Solvang & Govindan, 2024) and remanufacturing facilities (Mejía-Moncayo *et al.*, 2021), promising even greater efficiency and sustainability. However, Industry 4.0's emphasis on minimizing human involvement in operations has reached its limit, as technology cannot replicate the adaptability and resilience inherent in human beings. Furthermore, sustainability issues cannot be resolved solely through technology.

Industry 5.0 (I5.0) involves the integration of smart or I4.0 technologies, combined with a focus on sustainability, human-centricity, and system resilience (Castillo *et al.*, 2025; Bongomin *et al.*, 2025). This focus leverages the capabilities of I4.0 to achieve comprehensive sustainability, where

economic, environmental, and social objectives are concurrently addressed. This study introduces Remanufacturing 5.0 (R5.0) as an implementation of I5.0 principles in remanufacturing.

However, remanufacturing has intrinsic barriers. An imbalance persists across the economic, environmental, and social dimensions in the operational decision-making process. Stakeholders' requirements are unaddressed or in conflict, and addressing system resilience is challenging. This raises concerns for decision-makers about the adoption and implementation of R5.0 which leads to the following research questions (RQ) :

RQ1 : How to implement I5.0 principles in remanufacturing systems ?

RQ2 : How to address uncertainty about the quantity, quality, and timing of used products in an R5.0 system ?

RQ3 : How to integrate and balance economic, environmental, and social concerns in operational decision-making in R5.0 ?

RQ4 : How can stakeholders' requirements be integrated into R5.0 ?

This study addresses these questions through an illustrative case study that simulates an R5.0 system for electric vehicle (EV) lithium-ion batteries (LIBs) at their EoL in Quebec, Canada.

The presented study is organized as follows : section 6.2 introduces the literature review, which provides R5.0 context and the different concepts addressed by the proposed case study. Section 6.3 presents the research methodology, describing the case study, system components, simulation process, and lifespan forecasting. Then, the developed optimization model is presented in section 6.4. Section 6.5 presents the study's results and discussion, to finalize with the conclusions in section 6.6.

6.2 Literature review

The literature review begins by introducing smart sustainable remanufacturing. Then explains the concepts explored in the case study. The operations and main concerns of reverse logistics for EoL EV LIBs are illustrated. Subsequently, end-of-life strategies for EV LIBs, including

recycling, reuse, and remanufacturing, will be reviewed. The EV LIB fire and explosion risk during transportation is addressed. Finally, the role of I4.0 in RL of EV LIBs is presented.

6.2.1 Smart sustainable remanufacturing

Smart sustainable remanufacturing integrates smart systems to overcome the intrinsic challenges of remanufacturing and achieve sustainable goals. This is instrumentalized through smart architectures as is described in the following paragraphs.

Smart or I4.0 technologies drive sustainable remanufacturing, cyber physical systems (CPS) enabling real-time monitoring, data integration, and process simulation (Govindan, 2024). Digital twins (DT) are critical to managing the EoL of products, predicting their remanufacturability (Delbari & Hof, 2024), and recovering PLCI to minimize uncertainty in planning and operations (Kim *et al.*, 2024; Mejía-Moncayo *et al.*, 2021). Internet of Things (IoT) facilitates the continuous collection of data on the condition, performance, and operational and environmental parameters of products throughout their entire lifecycle (Brusa, Gastaldi, Guglielmino & Marchitto, 2024; Chau *et al.*, 2021). IoT improves supply chain visibility and communication between stakeholders and it is vital for the efficient procurement of used products (Kerin & Pham, 2020). Its applications include inventory management and traceability, essential for the recovery of EoL products (Brusa *et al.*, 2024).

Artificial intelligence (AI) and big data analytics (BDA) enable advanced information processing, pattern recognition, and informed managerial decision-making (Govindan, 2024; Wang *et al.*, 2020). Combining AI with life cycle assessment can increase accuracy in predicting environmental impact (Kerin & Pham, 2020). Additive manufacturing, or 3D Printing allows to reproduce complex, lightweight, and durable parts to repair complex components. Such additive fabrication methods contribute to reducing the use of materials, increasing design flexibility, and shortening production times (Chau *et al.*, 2021).

Different approaches have introduced smart architectures or frameworks that integrate I4.0 technologies to support sustainability (Kerin & Pham, 2020), platforms to design RL networks

(Sun *et al.*, 2024), control reverse flows sustainably in RL (Bensassi *et al.*, 2022), frameworks that show the interaction of I4.0 technologies along the supply chain (Bagalagel & ElMaraghy, 2022) or RL (Rodrigues, de Carvalho Gomes, Peres, de Faria Correa & Baierle, 2025), the tracking of materials using digital passports (Panza *et al.*, 2022), and the identification and remanufacturing of defective automotive parts (Stavropoulos *et al.*, 2022). Smart architectures or frameworks enable the integration of I5.0 technologies. These frameworks allow to control, optimize, and execute remanufacturing operations, communicate between supply chain actors, and support sustainable business models (Mejía-Moncayo *et al.*, 2023b). Thus, the smart architecture represents the core of a remanufacturing 5.0 system. The next section introduces RL for EoL EV batteries.

6.2.2 Reverse logistics for end-of-life electric vehicles batteries

EV LIBs RL is the integral process of planning, implementing, and controlling the efficient and cost-effective flow of used or unwanted batteries from the point of consumption to the point of origin or reprocessing, with the purpose of recovering value and ensuring their correct disposal (Jauhar, Singh, Kamble, Tiwari & Belhadi, 2024; Mohiuddin, Bai & Mo, 2025). Key activities within EV LIBs RL include the collection of EoL LIBs, their transport, storage, sorting, and performance testing. Subsequently, the batteries may undergo disassembly, remanufacturing, reuse, or recycling (Akram & Abdul-Kader, 2021; Azadnia, Onofrei & Ghadimi, 2021). Non-recoverable materials are destined for proper disposal (Wang, Meng & Azib, 2024).

RL starts at collection points, which are usually car dealerships or service shops. These centers receive batteries removed from users, either by replacement or scrapping of the vehicle, and send them to consolidation centers or centralized hubs (Mohiuddin *et al.*, 2025). In these facilities, initial tasks such as testing, sorting, packaging, and temporary storage are carried out (Wang, Feng, Woo, Wood & Yu, 2023). Tests assess LIBs' health status; those with good performance can be repaired or reconditioned for reuse. Batteries with lower performance are recycled (He *et al.*, 2024). Batteries are disassembled to recover high-performance components, such as battery management systems, which can be reused. Valuable materials such as cobalt, nickel, lithium,

and manganese are extracted from modules in recycling centers using hydrometallurgical or pyrometallurgical processes (Akram & Abdul-Kader, 2021; He *et al.*, 2024). These recovered materials can be reincorporated into the production of new batteries. The remaining waste is sent to waste treatment centers for safe disposal.

The EV LIBs RL success depends on efficient network design, robust task scheduling that considers market dynamics and regulations, and vehicle routing optimization that balances cost, safety, and environmental sustainability (Azadnia *et al.*, 2021; Mohiuddin *et al.*, 2025). Efficient management of the RL network requires the development of production planning models that consider the spatial distribution of collection, recycling, reuse, and production facilities. (Scheller, Schmidt & Spengler, 2023). The purpose of these planning models is to meet both internal grid demand, e.g., for remanufacturing, and external demand, e.g. sale of recycled materials or reused batteries, while minimizing total costs, carbon emissions or maximizing profits (Akram & Abdul-Kader, 2021; He *et al.*, 2024). These models are often formulated as linear or mixed-integer programming problems and are solved with optimization software (Saha & Jin, 2024; Scheller *et al.*, 2023).

Vehicle routing is a fundamental logistical operation to connect the different nodes of the network, especially during the collection phase. The transport of EoL batteries is a critical aspect, as it can account for up to 41% of the total cost of recycling and has a significant impact on human health due to local pollutant emissions (Slattery, Dunn & Kendall, 2021). To optimize this phase, optimal transportation routes are designed from collection points to processing facilities to minimize distance, time, cost, carbon emissions, and safety risks (Mohiuddin *et al.*, 2025).

The transportation of LIBs is subject to strict regulations, as they are classified as hazardous materials (Slattery *et al.*, 2021). This requires special safety protocols, certified packaging for damaged batteries, and proper documentation, adding complexity and cost to logistics. Therefore, routing models must incorporate these constraints to ensure regulatory compliance (Kamath, Moore, Arsenault & Anctil, 2023). In addition, such routing decisions should harmonize cargo

consolidation (Slattery *et al.*, 2021). Because a sufficient number of batteries at collection points leads to a balance between transportation and storage costs (Alfaro-Algaba & Ramirez, 2020).

6.2.3 End-of-life strategies for electric vehicle batteries

Recycling, reuse or repurposing, and remanufacturing represent the most utilized EoL strategies for EV LIBS. Recycling makes it possible to take advantage of the materials of used batteries by reprocessing them into new materials comparable in quality to the original material (Picatoste, Justel & Mendoza, 2022). A battery is considered for recycling if its capacity has degraded by more than 30% (Sharmili, Nagi & Wang, 2023). Recycling also serves to prevent the extraction of new raw materials and the subsequent emission of greenhouse gases (GHG) (Arshad *et al.*, 2022). There are three conventional methods of recycling, including pyrometallurgy, hydrometallurgy, and direct physical recycling.

The reuse of batteries is implemented when they still have more than 80% of their original capacity (Azadnia *et al.*, 2021). They can also be used in another EV or a new product with a different function (repurposing), such as energy storage for solar panels or as mobile energy storage units (Saba, Ullah & Tariq, 2024). However, there are concerns about the reliability of used batteries and challenges due to irregular degradation of the cells (Azadnia *et al.*, 2021; Sharmili *et al.*, 2023).

Remanufacturing is implemented when a battery's capacity has degraded by 20% to 30%. The defective or obsolete cells or modules are replaced to restore the batteries' original performance (Akram & Abdul-Kader, 2021). Although remanufacturing can reduce the cost of manufacturing by up to 40% (Sharmili *et al.*, 2023), its implementation has been limited due to the risks and complexity of disassembly (Han, Yun & Li, 2023).

6.2.4 Electric vehicle batteries fire and explosion risk

The transport and storage of batteries present unique and complex fire hazards (Huang, Hu, Yong, Mao & Bai, 2022; Jiang, Ren, Xu, Zheng & Wu, 2025). The presence of high-capacity LIBs

amplifies the risks of fire and explosion in confined spaces with limited ventilation and restricted firefighting capacity (Jiang *et al.*, 2025). The most common cause of EV fires is the thermal runaway of the LIBs. This phenomenon refers to an overheating event in which exothermic chain reactions take place that exceed refrigeration (Sun, Bisschop, Niu & Huang, 2020).

Internal short circuit is the most common cause of thermal runaway and can be divided into three categories : 1) caused by mechanical abuse, 2) electrical abuse, or 3) thermal abuse (Feng *et al.*, 2018). When an LIB is exposed to external impacts or extreme operating conditions, it can rupture and eject sparks, flammable gases, and toxic fumes that can ignite and lead to sustained combustion, jet flames, or a gas explosion (Sun *et al.*, 2020). Figure 6.2 illustrates the main causes of thermal runaway, and the sequence of events after cell failure.

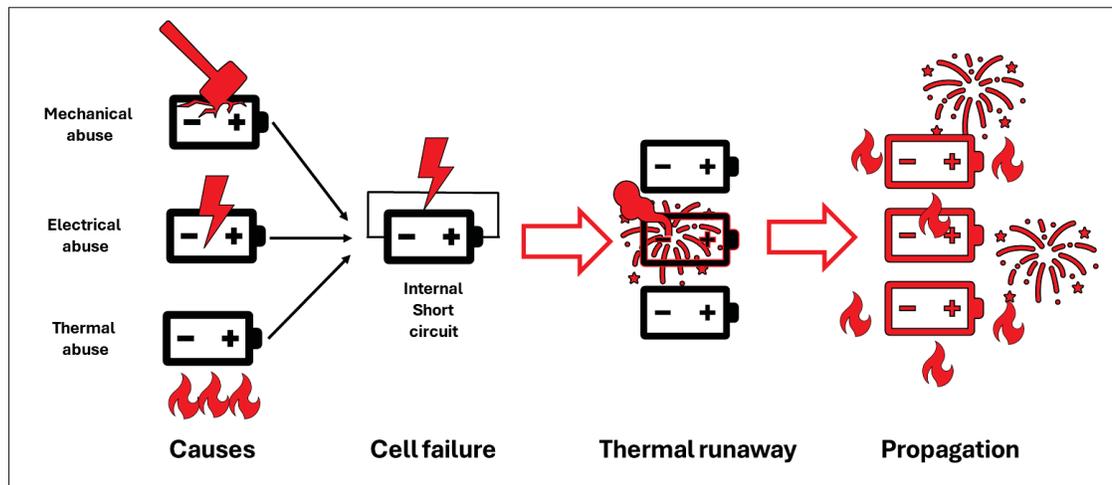


Figure 6.2 Schematic description of thermal runaway causes and process

Risk assessment is crucial to establishing the severity of an LIB incident. Chrysler LLC developed a methodology called Hazard Modes & Risk Mitigation Analysis (HMRMA) to assess the risk of advanced batteries. This methodology is based on quantifying risk, including all detection, control, and protection devices, and serving as a tool in the design process at all levels of the vehicle (Ashtiani, 2008).

The hazard risk number (HRN) is calculated as the product of the hazard severity (S), the probability level (L), and the hazard control number (HCN) (Ashtiani, 2008; Huang *et al.*, 2022).

An HCN of 0.0 means total prevention, while 1 means no control scheme has been used (Ashtiani, 2008). HRN, S, and L thresholds are set to manage fire risk. Huang *et al.* (2022) introduced a fire risk assessment method for LIBs during transportation and storage by combining fault tree analysis (FTA), HRN, and fuzzy logic. FTA helps find eight failure paths and nine basic events in battery fires. HRN is calculated using likelihood, severity, and hazard control. Fuzzy logic evaluates these indexes using several sub-factors. Battery safety relies on thresholds for synthesis, failure paths, and event severity (Huang *et al.*, 2022).

6.2.5 Industry 4.0 in reverse logistics for electric vehicle batteries

I4.0 technologies are emerging as essential tools to overcome the challenges of LIBs RL. DTs can play an important role in optimizing EV batteries lifespan (Saba *et al.*, 2024). LIBs have smart systems for managing their operation as a smart product. This integrates with EV systems as a CPS for controlling its operation (Meng, Xu, Peng, Youcef-Toumi & Li, 2022). They enable advanced analysis of batteries, monitoring performance degradation, health status, and state of charge by tracking complex interactions in real-time (Marcos, Scheller, Godina, Spengler & Carvalho, 2021; Saba *et al.*, 2024). A DT uses real-time data from sensors, cloud computing resources, and algorithms to calculate health metrics and forecasting tasks, reducing uncertainty about battery health (Saba *et al.*, 2024). Machine learning (ML) helps determine the failure rate of electric vehicle fleets and predict battery return volumes for a circular economy model, based on cell aging and deterioration. (Kampker *et al.*, 2023).

The integration of simulation and optimization is critical to addressing uncertainty in RL (Garside, Ahmad & Muhtazaruddin, 2024). Genetic algorithms (GA) and tabu search (TS) are applied to optimize RL (de Oliveira Neto *et al.*, 2023). Simulation is a powerful tool for modeling and analyzing complex and dynamic processes in remanufacturing and RL, being used in the design of RL networks and supply chain risk management (Monferdini, Pini, Tebaldi, Bigliardi & Bottani, 2024; Yu & Sun, 2024).

6.2.6 Literature review analysis

Table 6.1 presents the main focus identified in the literature for the different approaches to smart sustainable remanufacturing. This table shows a substantial connection between remanufacturing, recycling, sustainability, and I4.0 technologies. I4.0 is used in remanufacturing in many of the analyzed documents to enhance system performance sustainably. In other approaches, smart architectures are introduced in order to support system operation through the integration of its various systems, as well as the recovery, processing, and analysis of product lifecycle information.

In the literature consulted, few studies address Industry 5.0 in remanufacturing. The relationship between Industry 5.0, smart architectures, and RL also has received limited attention. These topics represent little-explored research areas. Optimization and ML applications are being integrated into the design and management of R5.0 systems as emerging methodologies.

Tableau 6.1 Focus of different approaches in the literature addressing topics related to smart sustainable remanufacturing

Authors	Rem	Rec	I4.0	I5.0	SA	RL	Sus	Opt	ML
Bagalagel & ElMaraghy (2022)	✓		✓						
Bensassi <i>et al.</i> (2022)			✓		✓	✓	✓		
Brusa <i>et al.</i> (2024)			✓				✓		
Chau <i>et al.</i> (2021)	✓	✓	✓			✓	✓		
Delbari & Hof (2024)	✓	✓	✓	✓					
Govindan (2024)	✓		✓						✓
Kerin & Pham (2020)	✓	✓	✓		✓	✓	✓		
Kim <i>et al.</i> (2024)	✓	✓	✓				✓		✓
Mejía-Moncayo <i>et al.</i> (2023b)	✓	✓	✓	✓	✓	✓	✓		
Mejía-Moncayo <i>et al.</i> (2024)	✓		✓				✓	✓	
Panza <i>et al.</i> (2022)			✓			✓	✓		
Stavropoulos <i>et al.</i> (2022)	✓		✓			✓	✓		
Sun <i>et al.</i> (2024)	✓	✓	✓			✓	✓	✓	
Wang <i>et al.</i> (2020)	✓	✓	✓		✓				
This study	✓	✓	✓	✓	✓	✓	✓	✓	✓
Table criteria :									
Rem - Remanufacturing, Rec - Recycling, I4.0 - Industry 4.0, I5.0 - Industry 5.0,									
SA - Smart architecture, RL - Reverse logistics, Sus - Sustainability,									
Opt - Optimization, ML - Machine learning.									

Tableau 6.2 Focus of different approaches in the literature addressing topics related to the electric vehicle battery case study

Authors	Rem	Rec	Bat	F&E	RL	CO ₂	Opt	ML	VR	Sc
Akram & Abdul-Kader (2021)	✓	✓	✓		✓	✓				
Alfaro-Algaba & Ramirez (2020)	✓		✓				✓			
de Oliveira Neto <i>et al.</i> (2023)					✓	✓	✓	✓	✓	
Garside <i>et al.</i> (2024)							✓		✓	✓
Han <i>et al.</i> (2023)	✓							✓		
He <i>et al.</i> (2024)			✓		✓	✓	✓			
Huang <i>et al.</i> (2022)			✓	✓						
Jauhar <i>et al.</i> (2024)			✓	✓						
Jiang <i>et al.</i> (2025)			✓	✓						
Kamath <i>et al.</i> (2023)	✓	✓				✓				
Mohiuddin <i>et al.</i> (2025)			✓	✓						
Monferdini <i>et al.</i> (2024)			✓	✓						
Saba <i>et al.</i> (2024)			✓						✓	
Saha & Jin (2024)		✓	✓		✓		✓			
Scheller <i>et al.</i> (2023)			✓		✓		✓			✓
Sharmili <i>et al.</i> (2023)	✓	✓	✓		✓					
Tohir & Martín-Gómez (2023)			✓	✓						
Wang <i>et al.</i> (2023)		✓	✓		✓		✓			
Wang <i>et al.</i> (2024)			✓					✓		
Yu, Bai, Xiong & Liao (2021a)	✓		✓			✓				
This study	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Table criteria :										
Rem - Remanufacturing, Rec - Recycling, Bat - Batteries or LIBs, F&E - Fire and explosion risk, RL - Reverse logistics, CO₂ - CO ₂ emissions, Opt - Optimization, ML - Machine learning, VR - Vehicle routing, Sc - Scheduling or production planning.										

The different approaches addressed in the literature review associated with the EV LIB case study are presented in Table 6.2. This table has several under-explored subjects in the existing literature, including LIB remanufacturing, which is hindered by disassembly issues. Recycling is presented as a strategy connected to remanufacturing. The risk of fire and explosion at different stages of the battery life cycle is a topic that receives significant attention in the literature. ML and optimization are used to improve battery performance and predict how long they will last. CO₂ Emissions are addressed in relation to the battery life cycle and RL. Vehicle routing and production scheduling in the EV LIBs context appears as an under-explored field.

The main objective of this study is to introduce R5.0, an implementation of I5.0 principles in remanufacturing. For this purpose, all topics related to smart sustainable remanufacturing and EoL EV LIBs shown in Tables 6.1 and 6.2 are addressed in this study. R5.0 is explained through an illustrative case study that simulates an R5.0 system for EoL EV LIBs in Quebec, Canada. The simulation addresses uncertainty in quantity, quality, and timing of used products. It considers stakeholder requirements, balances economic, environmental, and social concerns, and enhances system resilience.

6.3 Research methodology

This study implements a research methodology focused on answering the research questions through an illustrative case study, which includes three (3) main steps : 1) the establishment of the components of the R5.0 system, 2) the simulation of the R5.0 system, and finally 3) the numerical evaluation of the case study, as is illustrated in figure 6.3. The case study is introduced in section 6.3.1, and the methodological steps are described in sections 6.3.2 to 6.3.4.

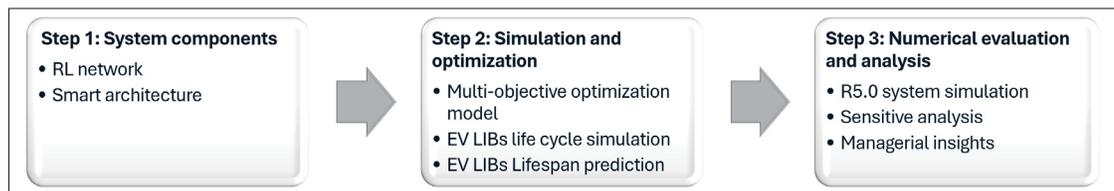


Figure 6.3 Research methodology

6.3.1 Case study

EV lithium-ion battery (LIB) are candidates for the implementation of circular economy strategies such as recycling and remanufacturing (Sharmili *et al.*, 2023). EV LIBs are components with a high retained value, making them economically attractive (Sharmili *et al.*, 2023). Their materials are scarce in nature, and their extraction is expensive. Furthermore, improper disposal at the end of their useful life can be highly polluting (Chen *et al.*, 2023). Therefore, implementing a value recovery strategy is the best option for EV LIBs (Call2Recycle, 2025).

The province of Quebec currently has an LIB value chain able to close the loop of EoL EV LIBs (Propulsion-Québec, 2025). This includes mining and ore concentrate, refining, active materials, battery components, cells, modules and assembly, vehicle integration, reuse of batteries, and recycling (Propulsion-Québec, 2025). This value chain represents an important enabler of EV LIB remanufacturing in Quebec.

Considering the abovementioned, this study presents an illustrative case study simulating an R5.0 system for EoL EV LIBs in Quebec, Canada. The proposed case study considers LIB deterioration along its life cycle, reverse logistics (RL), recycling, and remanufacturing. The LIB's life cycle is simulated, and its lifespan is forecasted by a ML approach, feeding a multi-objective optimization model. The total cost, CO_2 emissions, and LIB fire and explosion risk during transportation are minimized for establishing recovery-processing scheduling and vehicle routing for EoL EV LIBs, as is schematized by figure 6.4.

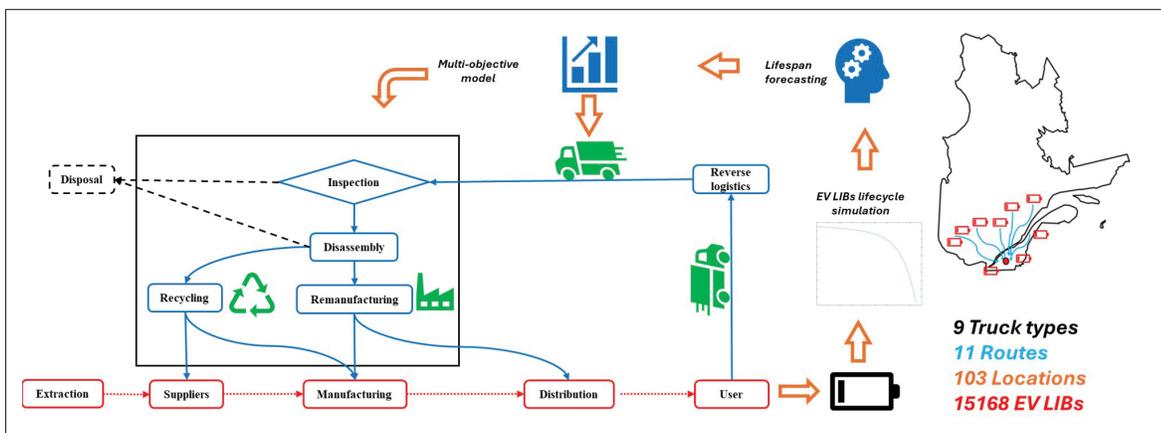


Figure 6.4 Schema of the system simulated by the proposed case study

6.3.2 R5.0 System Components

In order to illustrate the components and operations of the R5.0 system, this section introduces the proposed RL network or operational layer and smart architecture for the case study.

6.3.2.1 Reverse logistics network

The proposed RL network for this case study includes the collection points or consolidation centers in each city, the transporters, and the processing plant where the EoL EV LIBs are stored and subsequently recycled or remanufactured, as illustrated in figure 6.5. This network corresponds to the used product flow in blue, as is shown in figure 6.1.

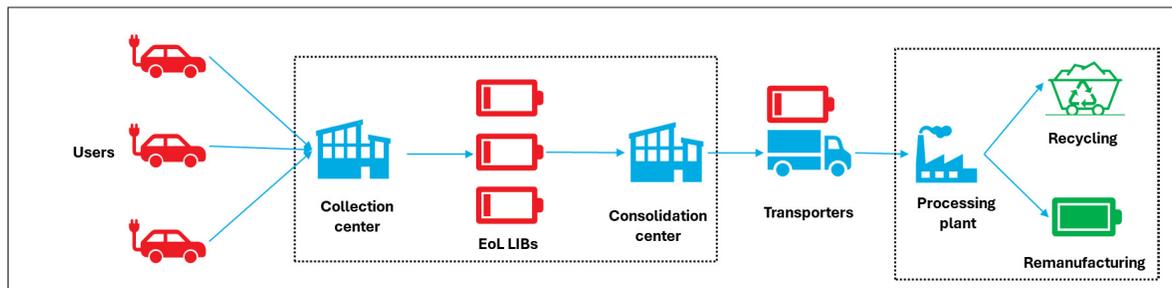


Figure 6.5 Schema of reverse logistics network

In this study, Saint-Bruno, Quebec, was selected as a potential site for a remanufacturing plant, given the proximity to Lithion Technologies (Lithion-Technologies, 2025); a company that currently recycles LIBs by hydrometallurgical processes. Thus, the proposed RL system should recover the LIBs distributed along the province to transport them to this location. These batteries belong to 15.168 private EVs registered in Quebec from 2011 to 2022 (?).

6.3.2.2 Smart architecture

Figure 6.6 presents the smart architecture for the EoL EV LIBs case study in Quebec, based on Mejía-Moncayo *et al.* (2023b). It is important to begin with defining the stakeholders who establish the system's requirements and/or objectives. In this case, three stakeholders are considered : investors, the community or users, and workers. The objectives include an economic objective f^{eco} , an environmental objective f^{env} , and a social objective f^{soc} .

Stakeholders can interact directly or indirectly with the smart architecture through a portal that allows them to consult or verify the results against the established objectives. EV users can check their vehicle's consumption or performance, receive alerts, or be subject to study based

on the data the vehicle collects. While workers will interact continuously with the company's management systems through its applications.

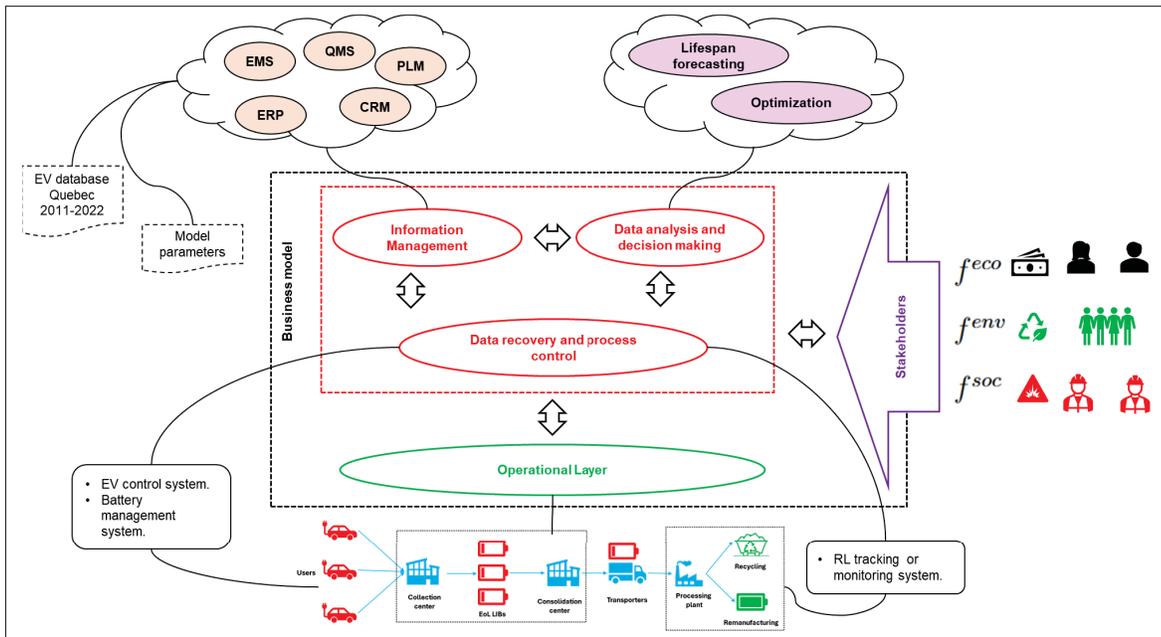


Figure 6.6 Schema of the smart architecture for the R5.0 system

The operational layer comprises the batteries and electric vehicles, collection or consolidation centers, transporters or trucks, and processing facilities. Each of these interacts with the smart architecture through the data recovery and process control layer. This includes the smart systems that support operations and interact with the other architecture layers. In EVs, these are their control systems, and in the battery, it is their management system. The RL for its part, uses vehicle tracking or monitoring systems and the company's management systems interface, through which tasks are assigned and progress is reported.

The information management layer includes the company's management systems and their respective applications. Information concerning the battery lifecycle, truck CO_2 emissions, costs, and risk assessments associated with battery transport is extracted from the information management layer to feed the data analysis and decision-making layer. This latter layer includes a lifespan forecasting and optimization model, which, after processing, transfers their results as collection sequences, collection routes, and production schedules for recycling

and remanufacturing. Finally, a circular business model provides the conditions for integrating R5.0 into the value chain.

6.3.3 Optimization, simulation and lifespan forecasting

Once the system components were established, the R5.0 system was simulated in Matlab R2024b (Step 2, see figure 6.3). This step includes a multi-objective optimization model, the EV LIBs life cycle simulation, and the implementation of a predictive model based on ML to forecast lifespan.

Multi-objective optimization model

The proposed multi-objective optimization model aims to integrate sustainable objectives into the management of the R5.0 system. These include minimizing the total cost (f^{eco}), CO_2 emissions (f^{env}), and LIB fire and explosion risk during transportation (f^{soc}), while establishing the recovery scheduling for EoL EV LIBs and vehicle routing. The proposed model is described in detail in section 6.4.

EV LIBs life cycle simulation

The process conducted for the simulation of the life cycle of the batteries is described in Figure 6.7. For this purpose, this study used a database of 124 commercial lithium iron phosphate/graphite cells subjected to different load conditions from the study performed by Severson *et al.* (2019). To simulate different battery types in Quebec's electric vehicles, this study assumes one cell's behavior represents the entire battery. This assumption does not represent reality; however, it allows us to generate the data needed to simulate the proposed system. This means the collected data and findings are for explanation only, not for real-world implementation.

The modeling of the life cycle of the batteries was performed using the discharge capacity as a function of the number of cycles. The development of the model began with the cleaning and interpolation of each curve data, as presents figure 6.7. Only 106 of the original 124 cells' curves were used; the rest were omitted because of missing data or because they generated

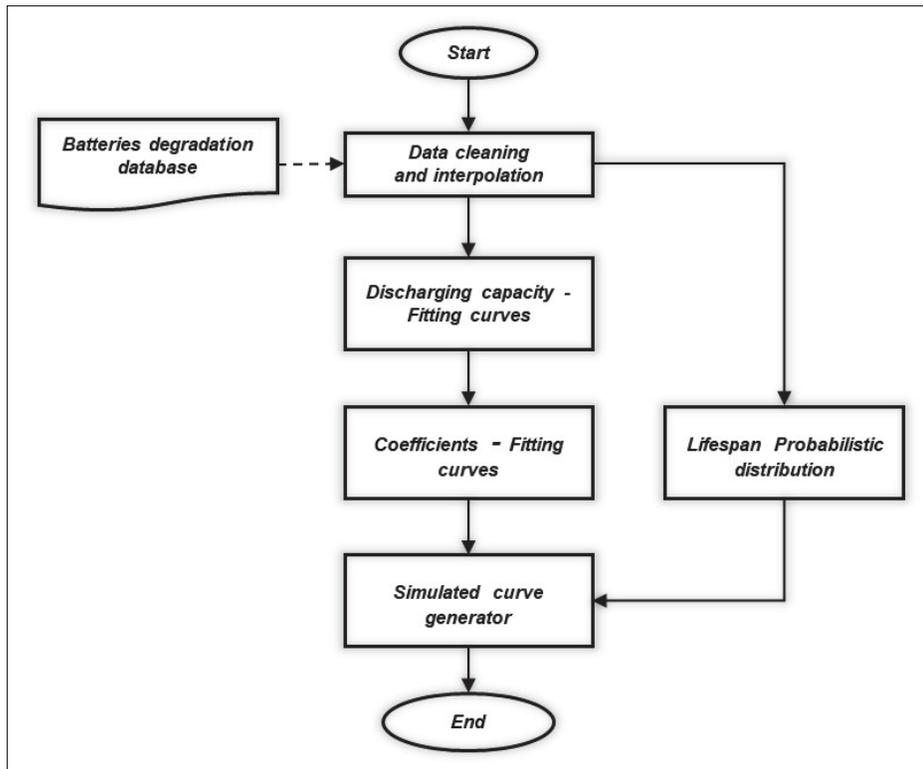


Figure 6.7 Flow diagram of the process performed to simulate EV LIBs life cycle

mathematical singularities during the simulation. Then, as is shown in figure 6.8 the original curves were fitted to the equation 6.1, which best fits the curves' data :

$$y = ae^{bx} + ce^{dx} \quad (6.1)$$

Where, y is the discharge capacity, x is the number of cycle, a , b , c and d are coefficients of the equation 6.1. Figure 6.8 features the original curves in black and fitted in red. This process achieves for all curves R^2 values near to 1 as presented in figure 6.9.

Then, the curves of coefficients a , b , c and d , as function of lifespan in cycles, were fitted to equation 6.2 (see coefficients - fitting curves in figure 6.7). In this way, each coefficient a , b , c or d , was modeled as a function of n , as presented by the equation 6.2 :

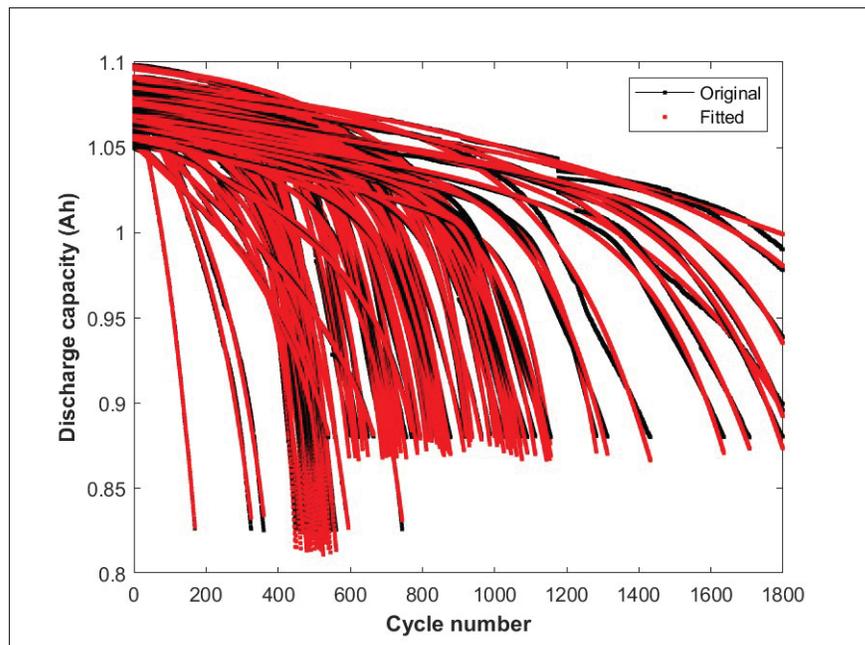


Figure 6.8 Experimental and fitted curves of discharging capacity

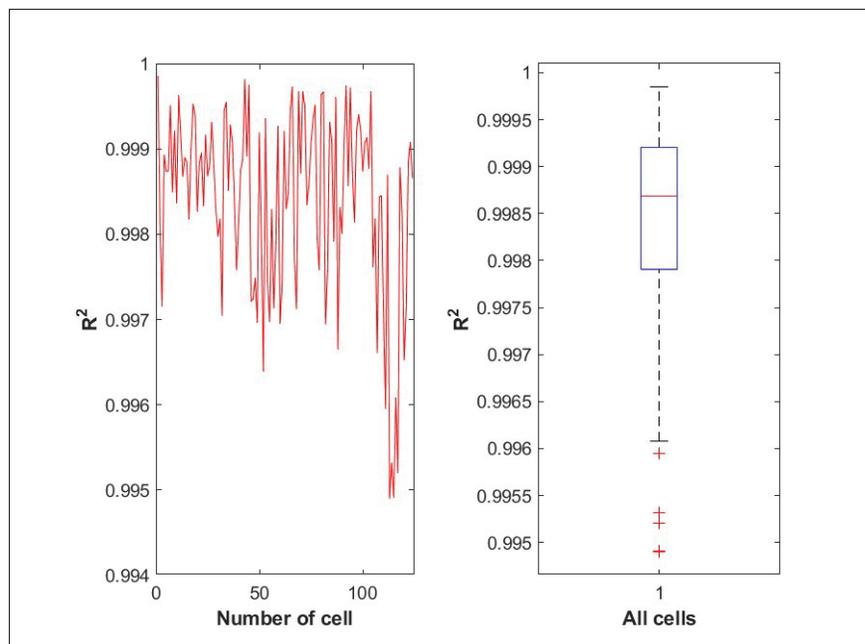


Figure 6.9 Coefficient of determination R^2 of fitted curves from figure 6.8

$$z(n) = \alpha e^{\beta * n} + \gamma e^{\delta * n} \tag{6.2}$$

Where, z is the coefficient a, b, c or d , n is the lifespan in number of cycles for each original cell, α, β, γ and δ are coefficients of the equation 6.2.

The curves in figure 6.10 present fitted curves of coefficients α, β, γ and δ . R^2 coefficients of α, γ and δ curves are greater than 0.86, evidencing that the model fits the data well. While the dispersion of values of β produces a tolerable R^2 of 0.5846.

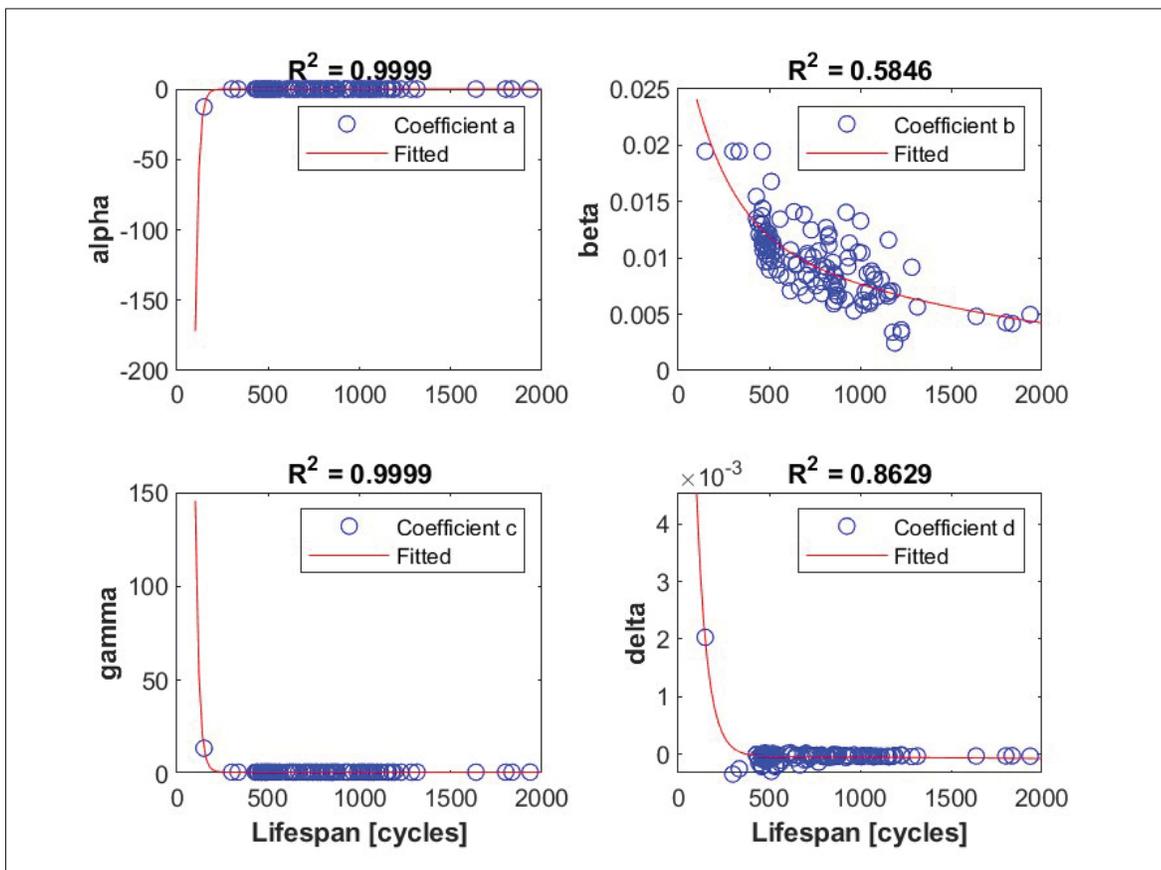


Figure 6.10 Fitted curves of coefficients α, β, γ and δ of model equation 6.2

Lifespan in number of cycles of original cells was fitted to a *lognormal* distribution or *Galton* distribution (see Lifespan probabilistic distribution in figure 6.7). The distribution is presented in figure 6.11. The coefficients of simulated curves were generated from the expected lifespan,

which is based on this distribution. Then, the expected lifespan was used to generate the coefficients α , β , γ , and δ of each simulated curve of discharge capacity, following the model of equation 6.1. These processes were synthesized in a simulated curve generator function in Matlab (see figure 6.7).

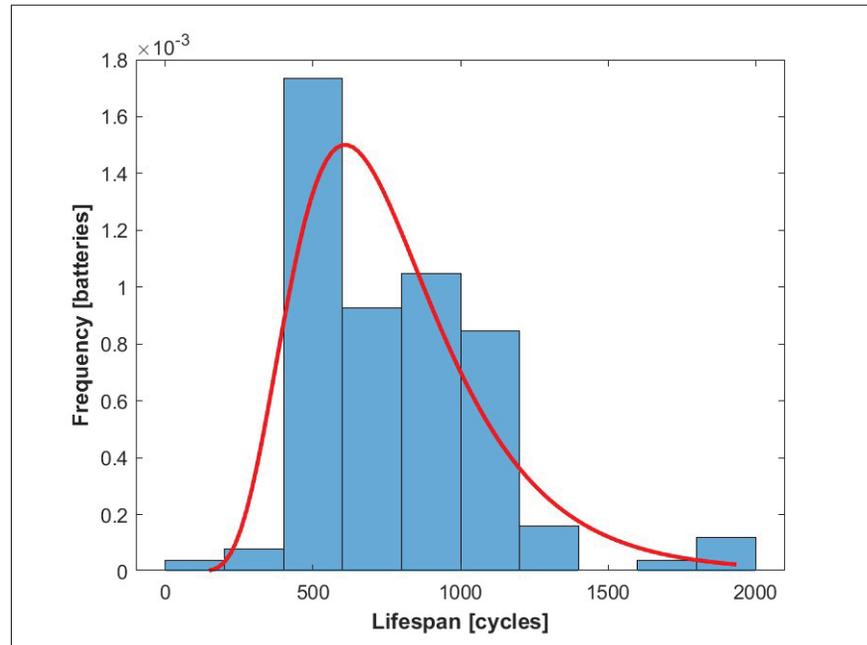


Figure 6.11 Histogram and probability distribution of cell lifespan in number of charging cycles, from the original database (Severson *et al.*, 2019)

EoL EV LIBs lifespan forecasting

The battery lifespan forecasting was performed using a neural network with 10 hidden layers, as described in figure 6.12. The input data is a vector of 55 components. The input vector includes the following components : *skewness*, *kurtosis*, $\frac{\sigma}{\mu}$, $\frac{\sigma^2}{\mu}$, $\frac{Max-min}{400}$, and 50 equally separated points in the curve, extracted from the first 400 cycles of each simulated curve of discharge capacity.

The training of the neural network was carried out using a Bayesian regulation algorithm. In each training, 70% of the data was used to train the neural network, 15% for validation and 15%

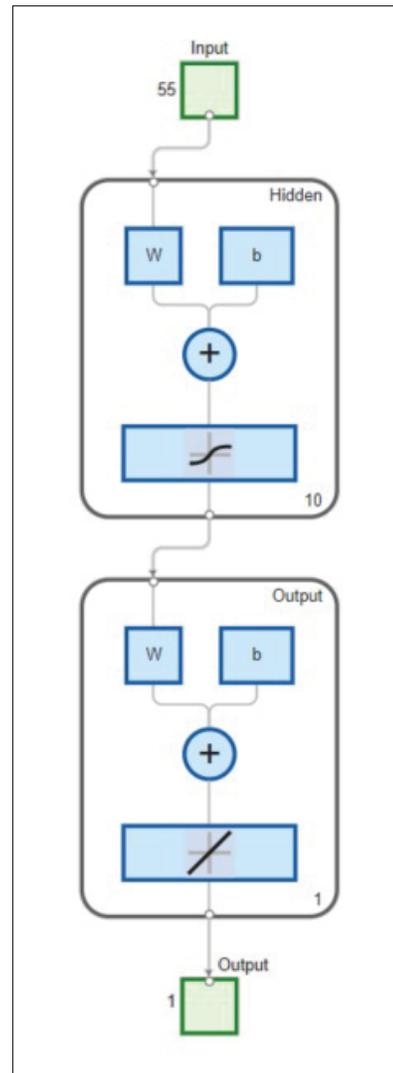


Figure 6.12 Neural network for forecasting lifespan of simulated EV LIBs

for testing. This process was carried out initially with the batteries degradation database (see figure 6.7), and then the simulated data of the batteries whose lifespan had already occurred were added after each scheduling cycle of R5.0 system.

6.3.4 Numerical evaluation and analysis

Figure 6.13 describes the numerical evaluation process of the case study performed in Matlab R2024b. The case study data and their sources are provided as complementary materials.

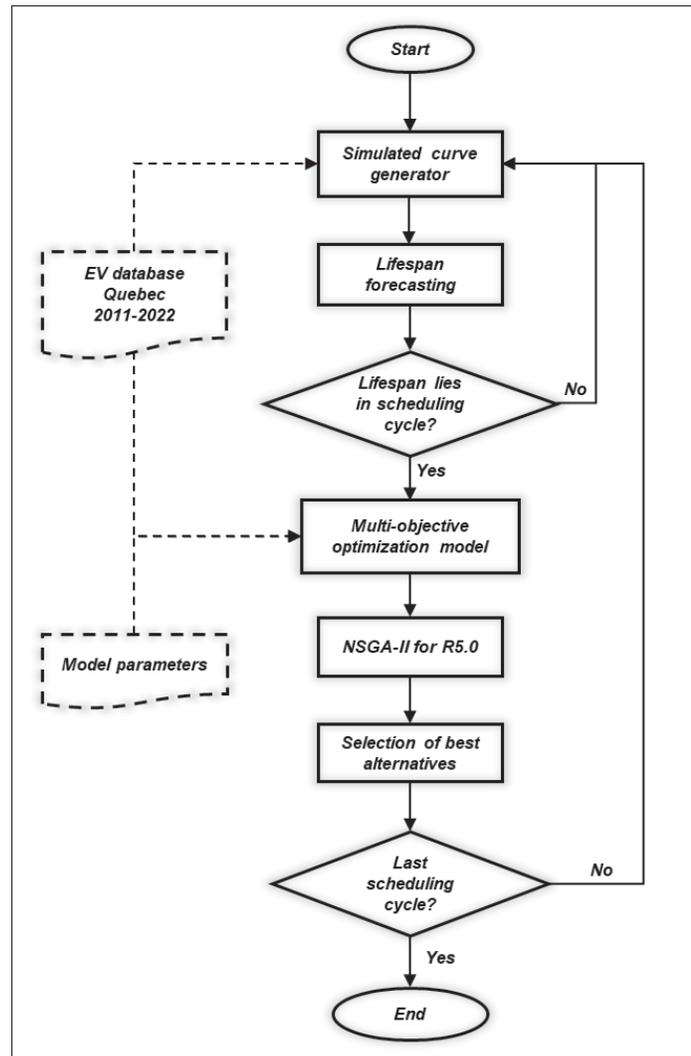


Figure 6.13 Flow diagram of the numerical evaluation of the proposed case study

Simulated curve generator

Numerical evaluation begins by generating simulated data (see figure 6.13). This task follows the order and quantity established in the Québec EV registry (only battery-powered EVs for private use were considered, incomplete registrations were omitted). Each EV record was randomly assigned an introduction week, as the record only includes the year. In each scheduling cycle, simulated curves data are generated for the EV LIBs introduced in that period.

Lifespan forecasting

Once simulated curves are generated, EV LIBs lifespan forecasting is performed, and those values in the scheduling period are included in the optimization model calculations; otherwise, it continues to the next scheduling cycle as is shown in figure 6.13.

Multi-objective optimization model

The batteries selected for the scheduling cycle are integrated into the multi-objective optimization model (see figure 6.13). The information corresponding to these is extracted from the records of EVs in Quebec, and the model parameters are loaded. This model is solved by employing a customized version of the NSGA2 multi-objective algorithm. This solution method based on Pareto optimality gives each objective the same importance without its value range.

NSGA2 for R5.0

The implemented version of NSGA2 follows the structure and procedures of the original version proposed by Deb *et al.* (2002), with customization of the encoding of variables and reproduction operators. A binary tournament was implemented for the selection of the parents. In the reproduction processes, simple crossing was used and the mutation was carried out by generating random numbers to reconfigure the vectors.

Selection of the best solution

Once solutions are achieved, the selection of the best alternatives is conducted (see figure 6.13). Then, if it is the last scheduling cycle, the process ends; otherwise, it continues to the next scheduling cycle. The selection of the best solution considers 10 alternatives. The first three include the solutions, which obtain the minimum value in one of the three objectives f^{eco} , f^{env} , and f^{soc} . The fourth alternative is the solution whose sum of their three objectives' values is the lowest. The remaining 6 are obtained by implementing the procedure based on analytical hierarchy process (AHP) proposed by Mejía-Moncayo *et al.* (2024). This uses the 6 different priority sequences that can be set for the three objectives of optimization model f^{eco} , f^{env} , and f^{soc} to select the best alternatives. The decision-maker may choose the most suitable option

from the previous ten alternatives. Finally, after numerical evaluation, the results were analyzed and discussed.

6.4 Multi-objective optimization model

This section provides a detailed explanation of the multi-objective optimization model formulated for the scheduling of RL and processing (recycling and remanufacturing) of EoL EV LIBs. The model is integrated into the smart architecture as a component of the data analysis and decision-making layer (see section 6.3.2.2). The model parameters are fed from the information management layer, which receives battery condition information from the data recovery and process control layer and stores RL information. The optimal model solution is transferred for execution to the operational layer by means of the layers of information management, and data recovery and process control. The proposed model is described and explained below.

Sets and Indices

$i, j \in \{1, \dots, n\}$: Indices for batteries, where n is the number of batteries by period.

$r \in \{1, \dots, R\}$: Index for each route, where R is the number of recovery routes.

$k \in \{1, \dots, K\}$: Index for trucks, where T is the number of trucks.

Parameters

d_{ij} : Travel distance from battery location i to battery location j or processing plant.

d_{rk}^{rt} : Travel distance of route r .

t_{ij} : Travel time from battery location i to battery location j or processing plant.

t_{rk}^{rt} : Travel time of route r .

t_i^{rm} : Remanufacturing processing time of battery i .

z_{last}^{rc} : End date of the last recycled battery.

z_{last}^{rm} : End date of the last remanufactured battery.

m_i : Mass of battery i .

m^{rec} : Mass of recycled batteries.

m^{rem} : Mass of remanufactured batteries.

l_i : Lifespan date of battery i .

c_k^t : Transport cost by distance traveled by truck k .

c_i^{wc} : Warehousing cost at the collection or consolidation center in the location of battery i .

c^{wp} : Warehousing cost at the processing plant by unit.

c^{rc} : Recycling cost by kilogram of battery recycled.

c_i^{rm} : Remanufacturing cost of battery i .

q_i^{dis} : Discharge capacity at EoL of battery i .

th^{qd} : Discharge capacity threshold

q_k^{truck} : Capacity in number of batteries by truck k .

q^{rec} : Capacity in mass of batteries for recycling by scheduling cycle.

q^{rem} : Capacity in time available to remanufacturing by scheduling cycle.

e_k^t : CO_2 emissions by distance traveled by truck k .

e_k^{rec} : CO_2 emissions by kilogram of battery recycled.

e_k^{rem} : CO_2 emissions by kilogram of battery remanufactured.

HRN_{ikr} : HRN of battery i transported by truck k following the route r .

th^{HRN} : HRN threshold.

Decision Variables

$X_{irk} \in \{0, 1\}$: Equals 1 if battery i is assigned to route r and truck k , and 0 otherwise.

$Y_{kr} \in \{0, 1\}$: Equals 1 if truck k is assigned to route r , and 0 otherwise.

$W_i \in \{0, 1\}$: Equals 1 if battery i is will be remanufactured and 0 recycled.

$S_{ijrk}^r \in \{0, 1\}$: Equals 1 if the truck k , following the route r , includes a trip from the battery location i to the battery location j , and 0 otherwise.

$S_{ij}^p \in \{0, 1\}$: Equals 1 if the battery i is processed before battery j , and 0 otherwise.

$Z_i^c \geq 0$: Collection date for battery i .

$Z_i^p \geq 0$: Processing date for battery i .

Objective Function

$$\text{Minimize } \{f^{eco} \wedge f^{env} \wedge f^{soc}\} \quad (6.3)$$

The objective function (equation 6.3) of this multi-objective optimization model considers three sustainable objectives : total cost as economic (f^{eco}), CO_2 emissions as environmental (f^{env}), and LIBs fire or explosion risk as social (f^{soc}). These are based on the three most common indicators in the sustainable remanufacturing literature (Mejía-Moncayo, Chaabane, Kenné & Hof, 2025c).

$$f^{eco} = \sum_{r=1}^R \sum_{k=1}^K c_k^t d_{rk}^{rt} Y_{kr} + \sum_{i=1}^n [c_i^{wc} |Z_i^c - l_i| + c_i^{wp} |Z_i^p - Z_i^c|] + \sum_{i=1}^n c_i^{rc} (1 - W_i) + \sum_{i=1}^n c_i^{rm} W_i \quad (6.4)$$

The equation 6.4 presents the first objective, or the total cost f^{eco} . It includes transport cost as the first term; the second term is the warehousing cost, while the fourth and fifth terms are, respectively, recycling and remanufacturing costs.

$$f^{env} = \sum_{r=1}^R \sum_{k=1}^K e_k^t d_{rk}^{rt} Y_{kr} + \sum_{i=1}^n e_i^{rc} (1 - W_i) + \sum_{i=1}^n e_i^{rm} W_i \quad (6.5)$$

The second objective, f^{env} or CO_2 emissions, is introduced by equation 6.5. f^{env} includes transport emissions as the first term, while the second and third terms are recycling and remanufacturing emissions.

$$f^{soc} = \sum_{r=1}^R \sum_{k=1}^K \sum_{i=1}^n \frac{m_i}{m_{rk}^{rt}} HRN_{ikr} X_{irk} \quad (6.6)$$

The equation 6.6 presents the third objective f^{soc} , LIBs fire or explosion risk. It is modeled using the procedure developed by Huang *et al.* (2022). HRN_{ikr} Values are provided a priori by smart architecture using the data recovered from the operational layer and the registries of previous scheduling cycles. This objective addresses existing social concerns regarding worker health and safety and enables the system to anticipate or avoid unexpected events. It helps minimize negative economic, environmental, and social impacts. As a result, it enables responsible decision-making processes, and the system becomes more resilient.

$$d_{rk}^{rt} = \sum_{\substack{i=1 \\ i \neq j}}^n \sum_{\substack{j=1 \\ j \neq i}}^n S_{ijrk}^r d_{ij} = 1 \quad \forall r, k \quad (6.7)$$

$$t_{rk}^{rt} = \sum_{\substack{i=1 \\ i \neq j}}^n \sum_{\substack{j=1 \\ j \neq i}}^n S_{ijrk}^r t_{ij} \quad \forall r, k \quad (6.8)$$

$$m_{rk}^{rt} = \sum_{i=1}^n m_i X_{irk} \quad \forall r, k \quad (6.9)$$

The equations 6.7, 6.8, and 6.8 describe how to calculate d_{rk}^{rt} , t_{rk}^{rt} and m_{rk}^{rt} .

Constraints

$$\sum_{r=1}^R \sum_{k=1}^K X_{irk} = 1 \quad \forall i \quad (6.10)$$

$$\sum_{r=1}^R \sum_{k=1}^K \sum_{\substack{j=1 \\ j \neq i}}^n S_{ijrk}^r = 1 \quad \forall i \quad (6.11)$$

$$X_{irk} X_{jrk} = S_{ijrk}^r \quad \forall i, r, k \quad (6.12)$$

$$X_{irk} - Y_{rk} = 0 \quad \forall i, r, k \quad (6.13)$$

Equation 6.10 ensures that each battery is assigned only to one truck, following one route. Similarly, equation 6.11 ensures that each battery location in the route is visited only once by a truck. While equations 6.12 and 6.13 provide consistency between X_{irk} and S_{ijrk}^r .

$$S_{ijrk}^r \left[X_{jrk} Z_j^c - X_{irk} Z_i^c - t_{ij} \right] \geq 0 \quad \forall i, j, r, k \quad (6.14)$$

$$X_{irk} \left[Z_i^p - Z_i^c - t_{rk}^{rt} \right] \geq 0 \quad \forall i, j, r, k \quad (6.15)$$

The purpose of Equation 6.14 is to ensure that the collection date for the following battery j in the sequence is later than that of the previous battery i , by more than the travel time between them. Equation 6.15 enforces that the processing date follows the completion of the battery recovery route.

$$\sum_{i=1}^n \sum_{r=1}^R X_{irk} \leq q_k^{truck} \quad \forall k \quad (6.16)$$

$$\sum_{i=1}^n m_i (1 - W_i) \leq q^{rec} \quad (6.17)$$

$$\sum_{i=1}^n t_i^{rm} W_i \leq q^{rem} \quad (6.18)$$

Truck capacity is enforced by equation 6.16, the recycling process capacity is ensured by equation 6.17, and equation 6.18 ensures the remanufacturing process capacity.

$$q_i^{dis} W_i \geq th^{qd} \quad \forall k \quad (6.19)$$

$$X_{irk} HRN_{irk} \leq th^{HRN} \quad \forall i, r, k \quad (6.20)$$

The equation 6.19 guarantees that only batteries with a discharge capacity higher than the threshold are chosen for remanufacturing. q_i^{dis} is provided the data recovered by smart architecture. In the same way, equation 6.20 ensures the choice of a safer truck for a path. This is because HRN_{irk} values that exceed the threshold can be dangerous (Huang *et al.*, 2022).

$$W_i Z_i^p \geq t_{last}^{rm} \quad \forall i \quad (6.21)$$

$$(1 - W_i) Z_i^p \geq t_{last}^{rc} \quad \forall i \quad (6.22)$$

$$W_i W_j S_{ij}^p \left[Z_j^p - Z_i^p - t_i^{rm} \right] \geq 0 \quad \forall i, j \quad (6.23)$$

The purpose of equation 6.21 is ensuring that the processing date for remanufacturing is after the date of the last battery remanufactured. Equation 6.22 has the same function for recycling batteries. The batteries' processing sequence for remanufacturing is defined through equation 6.23, in which t_i^{rm} is estimated a priori by analyzing battery lifecycle information.

6.5 Results and discussion

The numerical evaluation of the illustrative case study of an R5.0 system is presented below, following the process carried out. The performance of the battery lifespan forecasting is analyzed

in section 6.5.1, and the results of the optimization model are examined in section 6.5.2. Then sensitivity analysis is presented in section 6.5.3, and finally, results are discussed in section 6.5.4.

6.5.1 Performance of the battery lifespan forecasting

For illustrating the performance of lifespan forecasting, figures 6.14 and 6.15 present a comparison of neural network training runs at first and after 1352 weeks (26 years). Figure 6.14 illustrates how predicted lifespan (output) fits lifespan (Target). Figures 6.14 *a* and *b*, both present a good correlation coefficient R between the output and the target, almost 1. A comparison of errors between the same training runs is presented in Figure 6.15; it evidences a reduction in the error dispersion.

Figure 6.16 presents the R^2 coefficient and mean squared error of training of the neural network for lifespan forecasting. Along training cycles, R^2 coefficient keeps near to 1 evidencing a good correlation between predicted and actual values, while the mean squared error decreases in the first training cycles, and then it stabilizes around 300.

6.5.2 Multi-objective optimization model for scheduling a R5.0 system

Figure 6.17 presents in a 3D graph an example of the solutions obtained by the customized version of NSGA2. These solutions correspond to the simulated scheduling cycle at week 1352, at the end of the year 2037. The bar graphs in figures 6.18, 6.19, and 6.20, illustrate about how the values of the best alternatives are distributed for each objective, f^{eco} , f^{env} , and f^{soc} .

The points, in black in figure 6.17, represent all the non-dominated solutions, while the red ones were identified after implementing the process of selection of the best alternatives, explained in section 6.3.4. These four points correspond to ten different alternatives. Some of them are overlapped because, when applying the ten criteria established for this process, a solution can be selected by more than one criterion. This is evidenced by the fact that several solutions share the same values of f^{eco} , f^{env} , and f^{soc} in figures 6.18 to 6.20. AHP procedure implemented in this case can not identify alternatives with enough diversity among them.

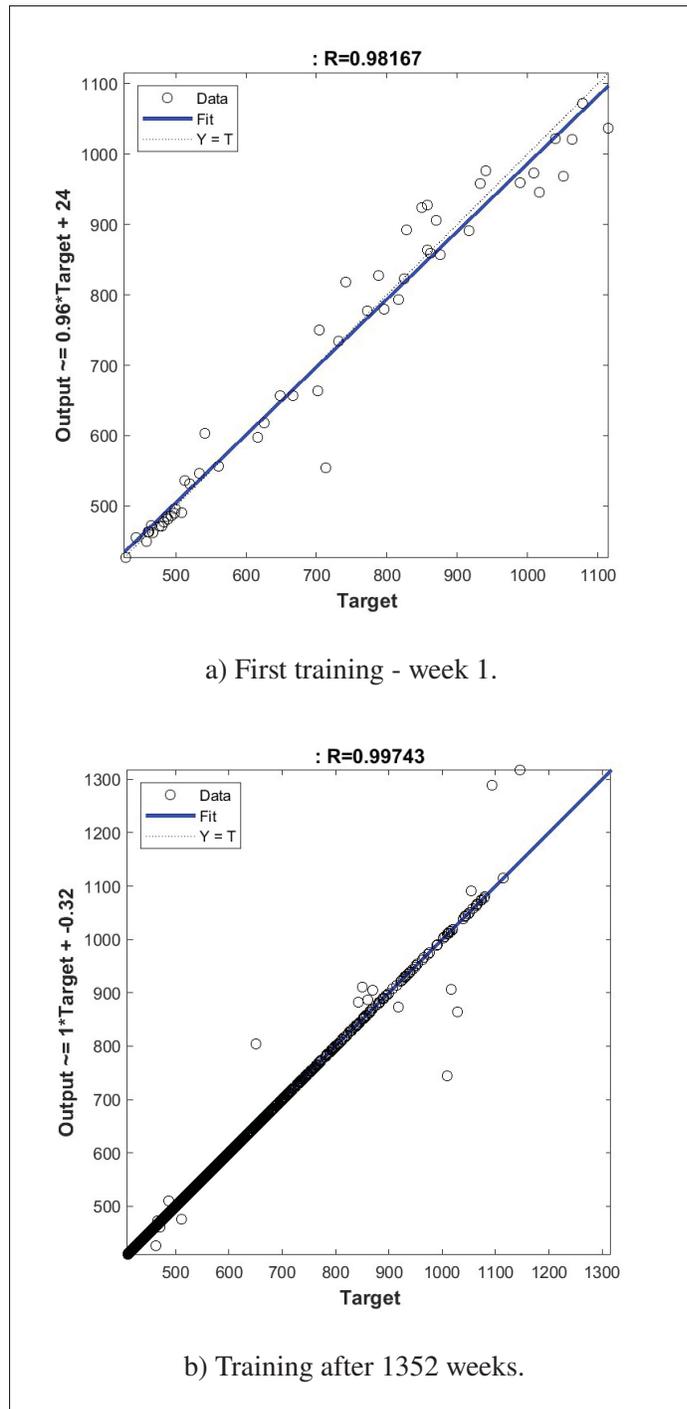


Figure 6.14 Regressions of training process at first and after 1352 weeks, of lifespan forecasting neural network

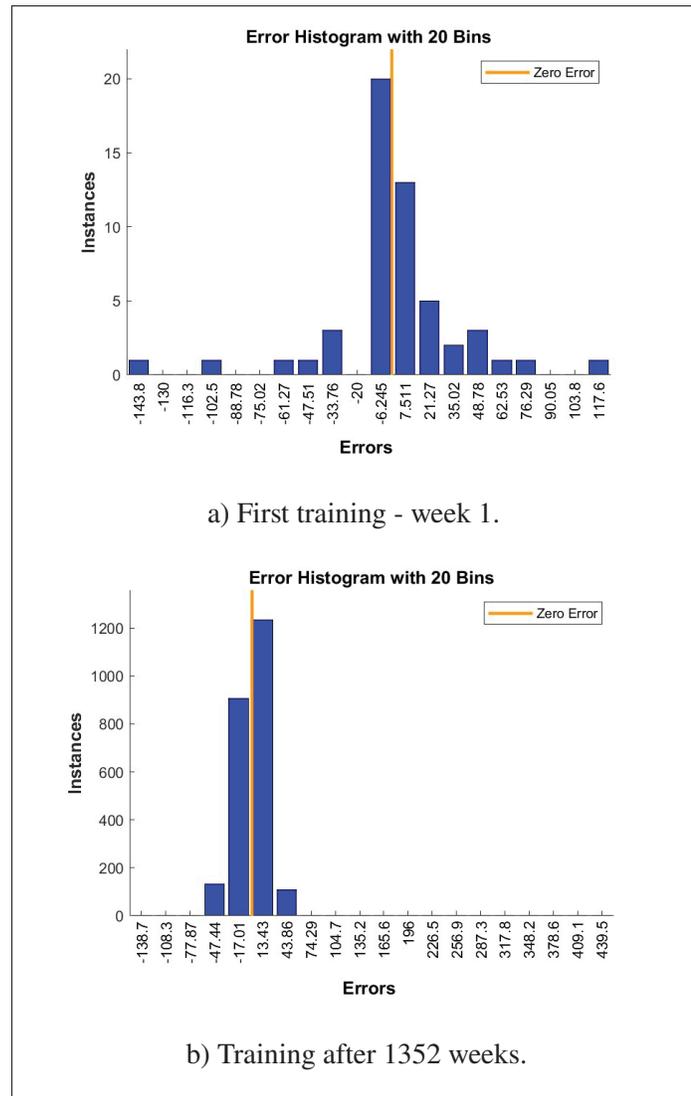


Figure 6.15 Comparison of error histograms from training of the neural network for lifespan forecasting

Figures 6.18 to 6.20 have a line that represents a goal or limit for f^{eco} , f^{env} , or a threshold for f^{soc} . After analyzing these figures, the third alternative is out of limits for f^{eco} , f^{env} , the first alternative is less expensive but generates more CO_2 emissions. Alternatives four and six are good candidates; they are less expensive than the other ones and generate the same amount of CO_2 emissions, and they are also under the threshold for f^{soc} . Hence, the fourth alternative is selected as the "best solution" to be implemented.

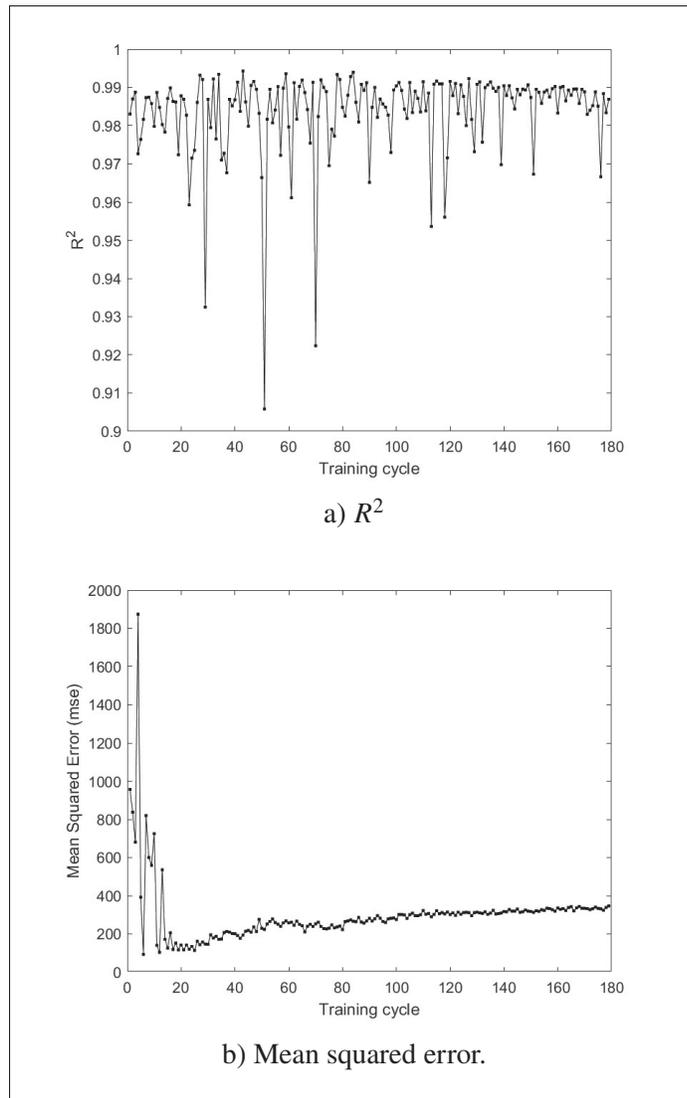


Figure 6.16 R^2 and mean squared error from training of the neural network for lifespan forecasting

Tableau 6.3 Truck types and number of batteries by route for the scheduling cycle

Route	1	2	3	4	5	6	7	8	9	10	11
Truck type	8	8	8	8	8	8	7	8	9	8	9
Batteries	13	10	1	8	6	18	1	2	4	4	1

Table 6.3 presents the truck type and the number of batteries by route for the scheduling cycle. The preferred truck type in this cycle is number 8; the descriptions of the capacity,

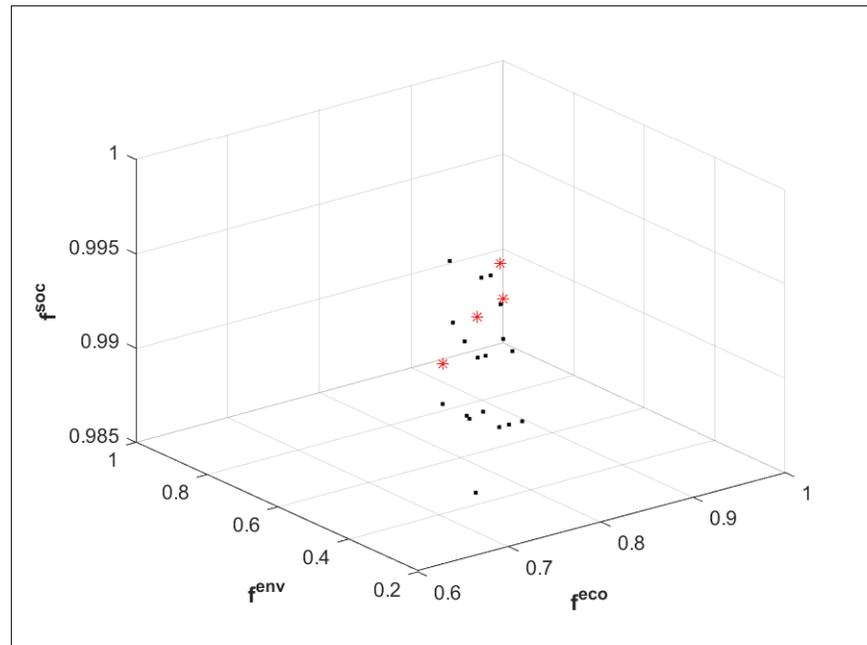


Figure 6.17 Example of the solutions obtained by the customized NSGA2 for a scheduling cycle

Tableau 6.4 Recovery sequence and EoL process for batteries in the trip along Route 1, illustrated in figure 6.21-a

Route	Region	Location	Battery number	EoL Process
1	Montérégie (16)	Longueuil (58)	14544	Recycling
1	Montérégie (16)	Longueuil (58)	3958	Recycling
1	Montérégie (16)	Roussillon (67)	4340	Recycling
1	Montérégie (16)	Vaudreuil-Soulanges (71)	7503	Recycling
1	Montérégie (16)	Les Jardins-de-Napierville (68)	7597	Remanufacturing
1	Montérégie (16)	Les Jardins-de-Napierville (68)	5499	Recycling
1	Montérégie (16)	La Vallée-du-Richelieu (57)	1090	Recycling
1	Montérégie (16)	La Vallée-du-Richelieu (57)	8854	Recycling
1	Montérégie (16)	Acton (48)	6572	Remanufacturing
1	Montérégie (16)	Acton (48)	3667	Remanufacturing

costs, and emissions of the different trucks are presented in the supplementary material. Figure 6.21 illustrates four trips in different routes, which follow the recovery sequences established previously. Table 6.4 and figure 6.22 present the recovery sequence and EoL processes for the batteries recovered in the trip described by figure 6.21-a. The route number in Table 6.4 depends on the administrative region; route 1 is for Montérégie (16). The location refers to the city or

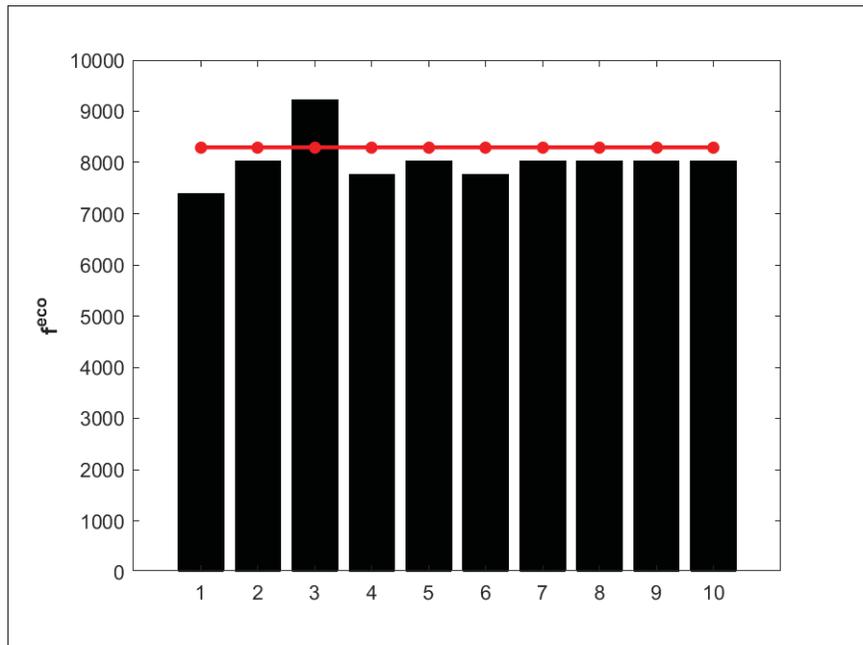


Figure 6.18 Economic performance f^{eco} of the solutions in red of the example presented in figure 6.17

town where the car was registered. The battery number indicates its position in the list of 15,168 electric vehicles in the case study. For example, battery 1,090 has a longer lifetime than battery 14,544. The EoL process determines which batteries are recycled or remanufactured. Seven of the ten batteries on this route will be recycled; only three will be remanufactured.

6.5.3 Sensitivity analysis

Uncertainty regarding the quality, quantity, and condition of used products is one of the most significant inherent challenges of remanufacturing. In the analyzed case study, the lifespan is predicted in cycles, based on the discharging capacity. However, the lifespan in terms of time requires considering the battery's charge duration, which in practice is related to vehicle usage or mileage. Taking the above into account, the influence of mileage on the expected battery lifespan was verified. Mileage values were randomly generated using a normal distribution. The mean range was $\mu = \{10,000, 12,000, 14,000, 16,000, 18,000, 20,000\}$ km/year, and the standard deviations include $\sigma = \{500, 1,500, 2,500, 3,500, 4,500, 5,500\}$ km/year.

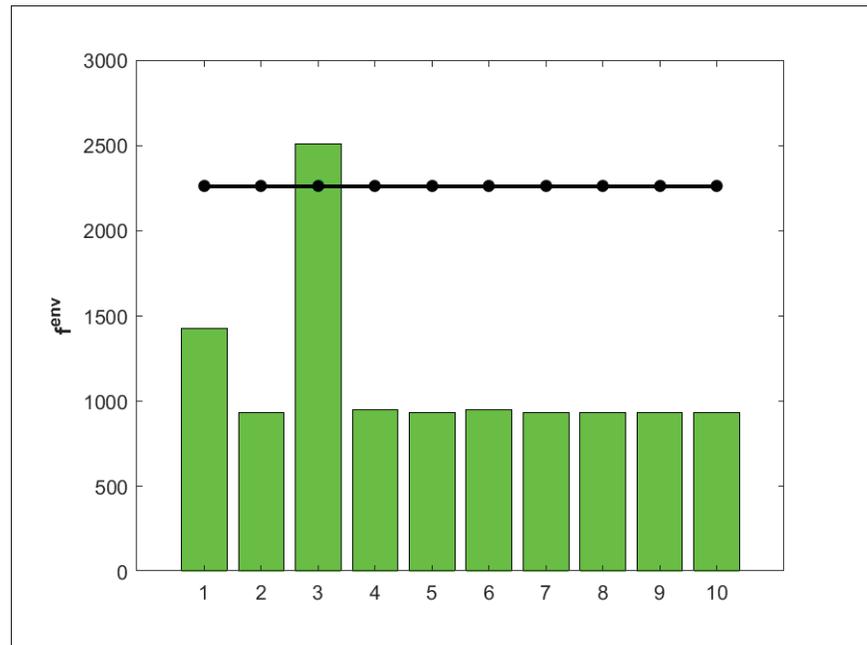


Figure 6.19 Environmental performance f^{env} of the solutions in red of the example presented in figure 6.17

The resulting curves are shown in figure 6.23. Figure 6.23-a illustrates that an increase in the standard deviation σ of the mileage can increase the average lifespan date. When $\sigma \leq 2000$, the average lifespan date is stable for the different mileage curves. This helps to improve system accuracy.

In figure 6.23-b, the average lifespan date decreases when the mileage mean μ increases; this happens for all σ values. A reduction in lifespan date will increase the number of batteries to be collected and processed, affecting system capacity.

In the practice, it is necessary to establish mileage from users or identify which curve describes the situation better. This highlights the importance of PLCI for the system's accuracy and robustness. In high dispersion of the expected lifespan, it is recommended to segment the data by brand, model, location, or other criteria to reduce dispersion and increase forecasting accuracy.

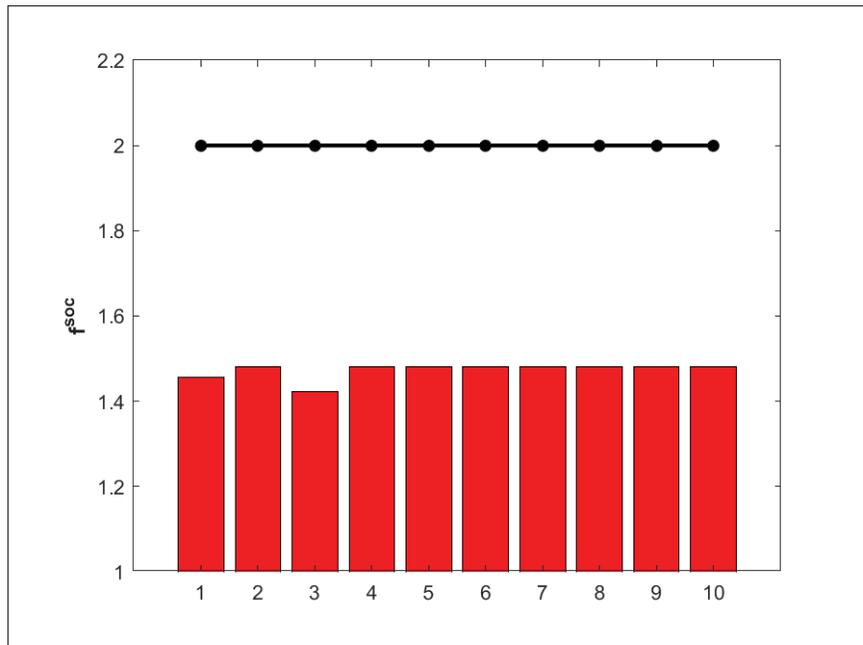


Figure 6.20 Social performance f^{soc} of the solutions in red of the example presented in figure 6.17

6.5.4 Discussion

This study has provided fundamental elements for understanding R5.0, highlighting the role of PLCI in the system's operation. R5.0 requires access to a large amount of PLCI. In this study, the simulation process allowed the generation of data to feed the lifespan forecast and the optimization model. However, the access to product deterioration data represents a challenge for R5.0. In practice, such access is restricted to third parties. It would only be possible if OEMs sold the information or by collecting it gradually oneself. This last option would initially imply high uncertainty, but over time, the databases would be completed and the uncertainty would decrease. In this case, a company already part of the value chain, such as a dismantling or recycling company, would be an ideal candidate. Its prior experience with the product can be used to gradually overcome the lack of PLCI.

The ML-based lifespan forecast directly addresses the uncertainty in the condition and return time of the used product. The predictions closely match the expected values, reducing and

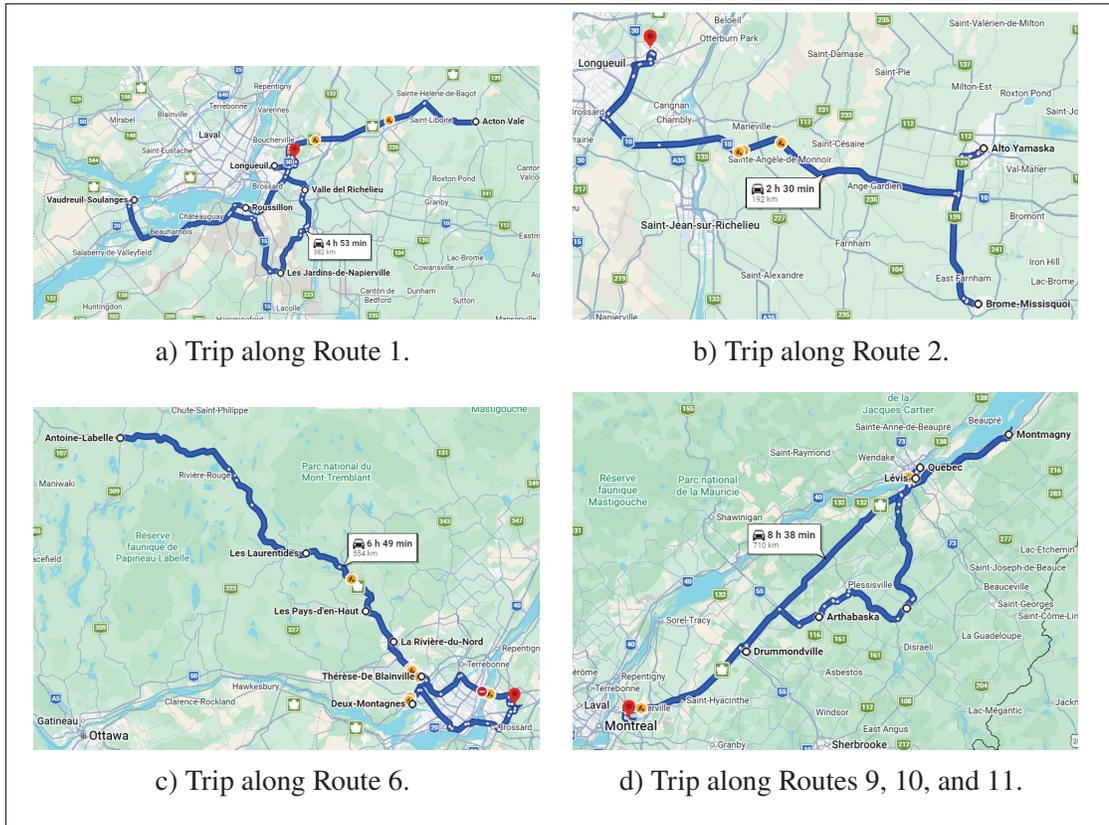


Figure 6.21 Recovery trip examples established by the best solution obtained by NSGA2

	Current recovering trip																							
Recovery	3667	6572	1090	8854	5499	7597	7503	4340	3958	14544														
Recycling	170	387	636	2344	2523	2608	2656	2945	3285	3361	3401	3582	1090	8854	5499	7503	4340	3958	14544					
Remanufacturing		4121		4332		4490		4513			3667	6572		7597										

Batteries for recycling
 Batteries for remanufacturing
 Batteries in processing

Figure 6.22 Recovery and EoL processing sequences for batteries in the trip along Route 1, illustrated in figure 6.21-a

stabilizing errors over time. However, it can be susceptible to various sources of uncertainty.

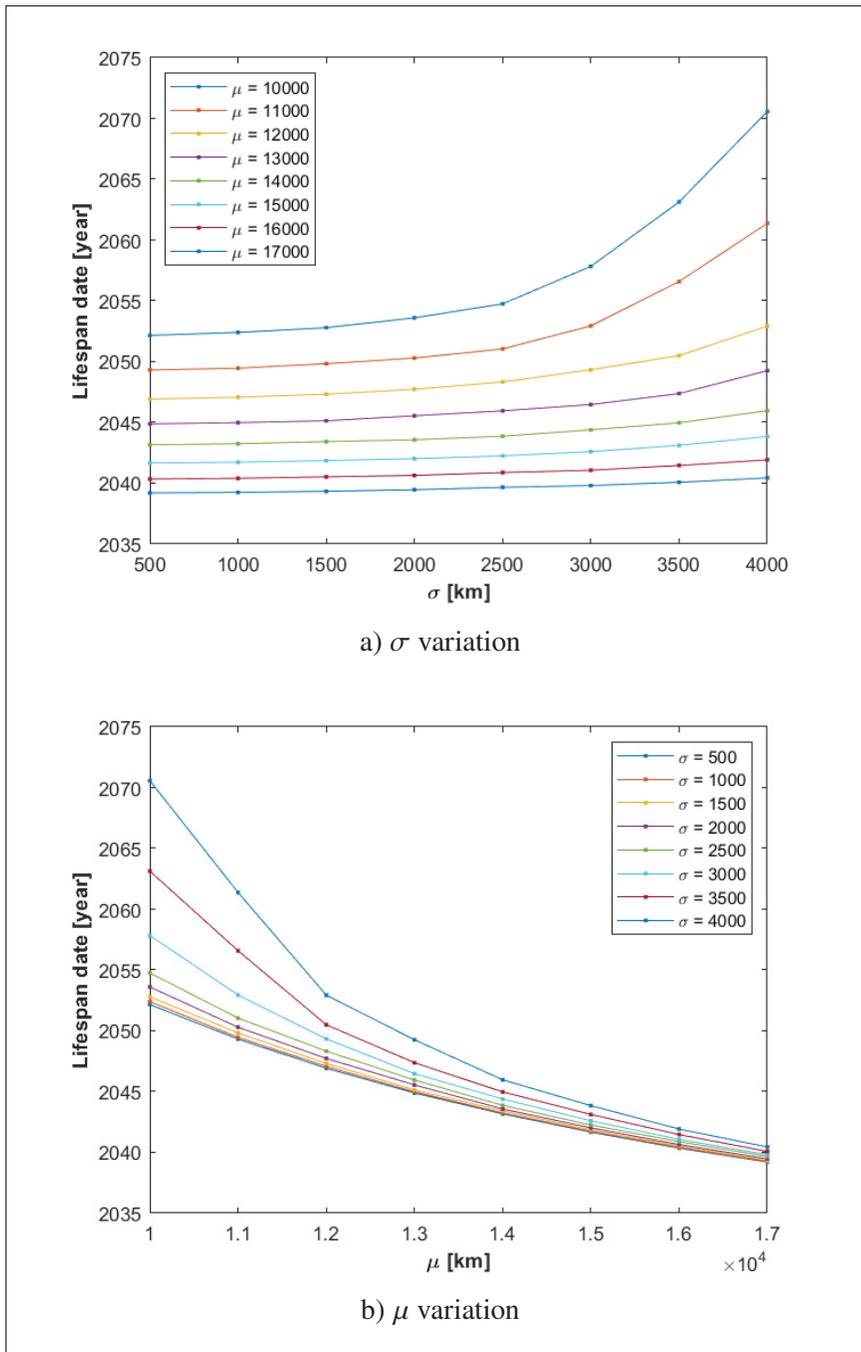


Figure 6.23 Influence of mileage on the expected battery lifespan date

An example of this is the mileage for the EV LIBs case, which was addressed in the sensitivity analysis.

The optimization model demonstrated the integration and balance of sustainability objectives into system management. It also helps to illustrate their interaction and role in the smart architecture. The results obtained allow for the sustainable management and control of system operation. This approach should be updated regularly, adjusting objectives, limits, thresholds, and targets to reflect the system's evolution.

The NSGA2 algorithm helped manage the imbalance in the scale of the objectives. However, it generates suboptimal solutions. Therefore, in a real-world implementation, it is recommended to implement a mathematical programming algorithm. The results presented, which exemplify a future scheduling cycle, make it essential to focus on the R5.0 system lifecycle and its capabilities.

The case study helps to identify three key aspects for implementing R5.0 : access to the PLCI, a remanufacturable product structure, and access to a value chain. The last one is an important enabler for R5.0. It provides access to essential markets for product sales and spare parts. In addition to the necessary human and material resources required for success.

Currently, the technology and smart architectures for implementing R5.0 are present in many smart products. Certain companies offer applications that improve product performance, enhance battery life, or offer additional features for users' benefit. However, the same technology applies to implementing programmed obsolescence, which goes in the opposite direction of R5.0 principles. This highlights the need to evaluate the role of technology in sustainability, because this represents a rebound effect (solution enabler - problem source).

6.6 Conclusions

This study discusses "Remanufacturing 5.0" or "smart sustainable remanufacturing systems," an implementation of I5.0 principles in remanufacturing. The process performed was guided by four research questions (RQ1-RQ4), which are answered through sections 6.2 to 6.5. This was achieved through a case study that simulates an R5.0 system for recycling and remanufacturing EoL EV LIBs in Quebec. The case study contributes to explaining R5.0's main components and

operation, while address remanufacturing uncertainty, stakeholders requirements and integrate and balance sustainable objectives.

R5.0 components, including the operational layer and smart architecture, are addressed in this study, providing theoretical and methodological knowledge about them. The operational layer includes the RL network -from users to processing plants- and key processes such as inspection, disassembly, recycling, remanufacturing, and disposal. While smart architecture integrates I5.0 for PLCI recovery, processing, and analysis for the decision-making processes. This also highlights the need to address remanufacturing regarding its interactions in RL.

The simulation of batteries' life cycles through discharging capacity helps to exemplify their deterioration. However, the numerical results of this simulation process have practical limitations. This is because the process performed cannot accurately represent all the different battery compositions and users' mileage. Furthermore, this influences the lifespan prediction of ML-based approach implemented, which relies on the accuracy of PLCI. It highlights the importance of accessing, storing, and PLCI in R5.0.

The proposed multi-objective optimization model contributes to the harmonization of sustainability objectives. It demonstrates the stakeholders' focus declared in the smart architecture regarding investors, community or users, and workers. The model evidences a human-centered focus by introducing social concerns - workers' health and safety - into operational decision-making. It also enhances system resilience through risk assessment for avoiding unexpected events.

Research opportunities emerge in sustainable product disassembly and repairing of non-remanufacturable products as current EV LIBs. The development of new optimization-based models to address human-centered sustainable production or remanufacturing. Smart architectures for small and medium enterprises for enabling R5.0, the development of faster alternatives to address the lack of PLCI, and the identification of value chains able to implement R5.0.

Data availability - The case study data are available in : https://github.com/cmm14art/Case_study_article-Towards-Remanufacturing-5.0.

Declaration of generative AI and AI-assisted technologies in the writing process - During the preparation of this work the authors used ProWritingAid in order to improve document readability. After using these services, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

CRedit authorship contribution statement - **Camilo Mejía-Moncayo** : Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Software, Data curation, Conceptualization. **Jean-Pierre Kenné** : Writing – review & editing, Validation, Supervision. **Lucas Hof** : Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization, Methodology.

Declaration of competing interest - The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CHAPITRE 7

DISCUSSION

Cette thèse visait à mettre en œuvre les principes de l'Industrie 5.0 dans les systèmes de refabrication. Cet objectif a été atteint grâce à une méthodologie en trois étapes. La première étape, ou refabrication durable, s'attache à identifier les liens entre le système de refabrication, le développement durable et les parties prenantes. Ce processus a été mené à travers une revue systématique de la littérature portant sur les indicateurs de performance de la refabrication durable. L'analyse des documents et des indicateurs identifiés a permis d'établir comment différents auteurs ont abordé le développement durable dans la refabrication, comment il a été quantifié et quelles parties prenantes sont prises en compte. Elle a même permis de formuler une définition de la refabrication durable, présentée au chapitre 3.

Le processus entrepris démontre que la refabrication durable requiert une approche multi-dimensionnelle qui considère ses processus et sa chaîne d'approvisionnement, ainsi que les différentes parties prenantes impliquées. Cette approche s'inscrit dans le cadre de l'Industrie 5.0, car elle intègre le développement durable et place l'humain au cœur du processus. De même, le cadre méthodologique proposé au chapitre 3 illustre l'intégration des trois dimensions du développement durable et des exigences des parties prenantes pour la prise de décision relative au démantèlement, au recyclage et à la refabrication durables. Le développement durable et l'approche centrée sur l'humain sont également abordés au chapitre 4. Ce chapitre décrit le rôle de l'architecture intelligente, du modèle économique et de la couche opérationnelle dans le soutien et la garantie de la durabilité du système, tout en contribuant à surmonter les défis inhérents au refabrication. Il présente en outre la manière dont les parties prenantes interagissent avec l'architecture intelligente et le rôle de la technologie dans la mise en œuvre de ces principes.

La deuxième étape, ou structure, du système de refabrication présente une architecture intelligente et une architecture de production. À ce stade, tous les principes de l'Industrie 5.0 sont intégrés au système. Premièrement, une architecture intelligente est formulée, intégrant le modèle économique, les parties prenantes, la couche opérationnelle du système (ses processus et sa

chaîne d'approvisionnement), ainsi que les couches de cette architecture avec des systèmes intelligents basés sur les Industrie 4.0 et 5.0, comme décrit au chapitre 4. Cette architecture intelligente constitue le cœur et la structure du système, et tous les principes et technologies de l'Industrie 5.0 y sont mis en œuvre.

Le chapitre 4 souligne comment la durabilité du système repose sur le modèle économique, qui définit non seulement comment générer des bénéfices économiques, mais aussi comment l'organisation interagit avec les différentes parties prenantes sur les plans environnemental et social. Ceci met en évidence la nécessité d'établir une durabilité globale et responsable pour l'ensemble du système de refabrication.

La résilience du système est également intégrée à l'architecture intelligente. La collecte, la gestion, le traitement et l'analyse des informations relatives au cycle de vie des produits tout au long de la chaîne d'approvisionnement en boucle fermée permettent au système de surmonter l'incertitude inhérente à la refabrication et d'en renforcer la résilience. Ceci lui permet de s'adapter aux variations de produits et même d'aller plus loin en autorisant des actions préventives basées sur des prévisions de scénarios futurs potentiels, contribuant ainsi à atténuer les risques et à relever d'autres défis liés à la refabrication identifiés au chapitre 4.

L'architecture de production présentée au chapitre 5 suit également cette approche. Elle postule la nécessité d'établir une stratégie d'entreprise pour gérer l'incertitude, dans laquelle le modèle économique, l'architecture intelligente et l'architecture de production ou couche opérationnelle contribuent tous à réduire et à maîtriser cette incertitude. Cette approche met en lumière le rôle et la contribution de chaque composant à la réalisation des objectifs du système. L'architecture productive contribue à la résilience en réduisant la complexité de l'usine de traitement grâce à l'utilisation de cellules de refabrication, tout en offrant adaptabilité et flexibilité grâce à l'utilisation de systèmes cyberphysiques reconfigurables.

La troisième étape, ou Remanufacturing 5.0, synthétise les étapes précédentes en présentant méthodiquement le fonctionnement d'un système de refabrication intégrant les principes de l'Industrie 5.0, comme décrit au chapitre 6. À cette fin, une étude de cas simule un système de

Remanufacturing 5.0 pour la récupération des batteries de véhicules électriques en fin de vie au Québec, au Canada. Le système proposé comprend une architecture intelligente intégrant le réseau de logistique inverse et les installations de traitement (recyclage et refabrication), les parties prenantes et leurs objectifs respectifs, le modèle économique et les différentes couches de l'architecture intelligente.

La durabilité du système est présentée à travers trois objectifs qui répondent aux besoins des parties prenantes et à chacune des dimensions de la durabilité. Ces objectifs sont intégrés dans un modèle d'optimisation multiobjectif résolu par l'algorithme NSGA2, qui, grâce à son principe de dominance de Pareto, permet une pondération égale de tous les objectifs. Ces objectifs comprennent le coût total pour la dimension économique, les émissions de CO_2 pour la dimension environnementale et le risque d'incendie ou d'explosion pour la dimension sociale. Ce dernier point contribue à l'intégration d'un objectif social lié aux variables du processus par le biais d'une analyse des risques. Ceci favorise la prise de décisions opérationnelles tenant compte des trois dimensions de la durabilité et du bien-être humain, tandis que l'approche fondée sur les risques assure la résilience du système.

La simulation du cycle de vie des batteries décrit leur détérioration cycle par cycle. Ces informations servent à prévoir la fin de leur durée de vie utile, ce qui réduit l'incertitude quant à leur retour et leur état de détérioration. Ces processus alimentent le modèle d'optimisation multiobjectif qui permet d'établir des itinéraires et des séquences pour la récupération et le traitement des batteries, aboutissant à une planification système plus efficace, durable et résiliente. Ceci clôt le cycle de processus du système Remanufacturing 5.0.

Le système Remanufacturing 5.0 nous invite à réfléchir aux scénarios possibles où une refabrication intelligente, durable, résiliente et centrée sur l'humain est envisageable. De plus, il représente une opportunité, car l'étude de cas de la refabrication des batteries de véhicules électriques illustre une opportunité pour un avenir proche qui peut être développée par étapes dans les petites et moyennes entreprises, grâce à la chaîne de valeur déjà existante au Québec.

CONCLUSION ET RECOMMANDATIONS

Cette recherche propose l'intégration des principes de l'Industrie 5.0 dans les systèmes de refabrication, en répondant rigoureusement aux questions posées et en atteignant les objectifs définis, comme démontré dans les chapitres correspondants. L'approche adoptée contribue de façon significative à la compréhension de la refabrication durable et intelligente, en comblant les lacunes identifiées dans la littérature et en offrant une perspective méthodologique qui facilite son application dans le secteur industriel.

La première contribution de ce travail est l'identification des liens entre la durabilité, les parties prenantes et le système de refabrication. De plus, les indicateurs clés de performance (KPIs) les plus cités ont été identifiés (32 économiques, 16 environnementaux et 3 sociaux), répartis dans six domaines d'application : évaluation de la durabilité, conception de produits pour la refabrication, évaluation du démontage, évaluation de la refabricabilité, évaluation de la circularité et chaînes d'approvisionnement fermées. Aussi, que la formulation d'une définition de la refabrication durable, qui intègre les différents points de vue présents dans la littérature. Un cadre méthodologique applicable à tout produit est présenté, axé sur l'évaluation du démontage, du recyclage et de la refabrication dans une perspective durable, en regardant les parties prenantes.

En deuxième lieu, une architecture intelligente intégrant les principes de l'I5.0 a été développée pour surmonter les défis de la refabrication et s'intégrer à la stratégie d'entreprise. Cette architecture facilite la gestion efficace et durable des produits usagés à valeur ajoutée, répond aux besoins des parties prenantes et soutient la prise de décision pour assurer une performance économique, environnementale et sociale optimale. Ses caractéristiques peuvent être appliquées à d'autres stratégies d'économie circulaire.

La troisième contribution consiste en une architecture productive qui intègre la fabrication cellulaire et reconfigurable, conçue pour atténuer les effets négatifs de l'incertitude, tant en amont

qu'en aval, dans la refabrication. Le modèle d'optimisation proposé permet de configurer le système en cellules de refabrication, en utilisant la modularisation pour réduire la complexité et la reconfigurabilité pour augmenter l'adaptabilité. Différentes méthodes de solution et stratégies de sélection sont explorées.

Enfin, le concept de Remanufacturing 5.0 est introduit à travers une étude de cas illustrant la revalorisation des batteries de véhicules électriques en fin de vie au Québec, Canada. Cette étude aide à expliquer les composantes et le fonctionnement de R5.0, en abordant l'incertitude, les exigences des parties prenantes et en équilibrant les objectifs de durabilité. Le processus illustre la prise de décision opérationnelle durable et intègre l'évaluation des risques sociaux, ce qui améliore la résilience du système. L'étude met en lumière trois facteurs facilitant l'adoption de R5.0 : une structure de produit adaptée à la refabrication, l'accès à la PLCI et une chaîne de valeur appropriée. Elle souligne aussi l'importance de traiter de façon critique l'obsolescence programmée et les systèmes intelligents, car la technologie peut autant favoriser la durabilité que contribuer à la détérioration intentionnelle des produits.

À partir des résultats obtenus, plusieurs recommandations sont proposées pour enrichir et orienter le travail réalisé :

- Le cadre méthodologique présenté peut être élargi par le développement d'un outil informatique personnalisable, relié aux systèmes de gestion d'entreprise pour le suivi de la performance et la sélection de produits et fournisseurs.
- Pour valider l'applicabilité et la robustesse des modèles d'optimisation, il est recommandé de les évaluer dans une gamme plus large de cas industriels, ce qui permettrait d'adapter le système à différents contextes.
- Il serait aussi pertinent d'explorer de nouvelles méthodes de solution et stratégies de sélection, ainsi que de développer des jumeaux numériques pour les différents types de batteries simulées, afin d'améliorer la précision du système.

- Comme l'Industrie 5.0 est un concept en évolution, où la durabilité, l'approche humaine et la résilience ne sont pas encore clairement définies, il est conseillé d'évaluer les implications éthiques de chaque mise en œuvre et de revoir les cadres réglementaires existants.

Des opportunités de recherche sont identifiées dans la mise en œuvre de la norme internationale ISO 59000 pour la refabrication durable, l'intégration de pratiques d'économie circulaire dans les systèmes de gestion d'entreprise et leur lien avec les architectures intelligentes.

Il est aussi essentiel d'aborder l'obsolescence programmée, la réparabilité, l'améliorabilité et la durée de vie des produits dans une perspective durable, en établissant des limites claires entre les parties prenantes.

Les architectures intelligentes pour les systèmes de refabrication 5.0 constituent un domaine émergent, avec de nombreuses possibilités pour le développement de technologies circulaires et durables adaptées.

De nouvelles pistes de recherche s'ouvrent aussi dans le démontage durable et la réparation de produits non refabricables, comme les batteries actuelles de véhicules électriques, ainsi que dans le développement de nouveaux modèles d'optimisation pour une production durable centrée sur l'humain.

ANNEXE I

NSGA2 FOR A RECONFIGURABLE CELLULAR REMANUFACTURING ARCHITECTURE (NSGA2-RCRA)

The Nondominated Sorting Genetic Algorithm II (NSGA2) (Deb *et al.*, 2002), is a well known multi-objective evolutionary algorithm widely used in diverse engineering fields by its efficient performance. This study used Matlab 2021a to implement a customized version of NSGA2, based on the framework proposed by Deb *et al.* (2002). In a first step, the developed algorithm randomly generated the initial population and a set of non-dominated solutions was obtained. These solutions fed the next iteration step as part of the initial population, which was then completed randomly. Following this incremental solution process, the final iteration provided the best last non-dominated solutions. Here, the NSGA2-RCRSA was run with the following parameters : number of individuals = 250, generations = 1000, iterations = 10, crossover probability = 0.9, and the mutation probability = 0.1 for a total of 2.500.000 of objective function calls.

0.1 Coding solutions

The customization of NSGA2 starts by defining a hybrid data structure for the solutions codification. Similarly, the generation of the initial population, crossover, and mutation processes were customized.

The decision variables X_{ik} , Y_{jk} , Z_{ij} , and $W_{jj'p}$ described in the mathematical model, were coded in Var as a set of four vectors :

$$Var = (Var^X, Var^Y, Var^Z, Var^W) \quad (A I-1)$$

The first vector, Var^X , is defined by a binary structure that contains the rows of the X_{ik} matrix.

$$Var^X = [0, 1, 1, 0, 1, 1, 0, 1, 0, 1, 1, 1, 0, 1] \quad (A I-2)$$

The second vector, Var^Y , contains the number of the product family or cell k to which each product j was assigned, according to the solution codification based on the cell number exposed by Gen *et al.* (2009). This data structure allows to manage directly equation (5.13), which ensures that each product j is only assigned to a single family or cell k .

$$Var^Y = [1, 2, 2, 1, 2, 1] \quad (\text{A I-3})$$

The third vector, Var^Z , contains the number of type i workplaces required to manufacture product i .

$$Var^Z = [3, 4, 7, 1, 2, 1, 3, 5, 4, 2, 3, 7, 3, 4, 1, 2, 3, 4, 1, 2, \dots, 2, 5, 1, 2, 3, 1, 1, 7] \quad (\text{A I-4})$$

The fourth vector, Var^W , contains numbers between 0 and 1, which represent the relative position among the products to determine the production sequences $W_{jj'p}$, as is described next.

$$Var^W = [0.34, 0.25, 0.16, 0.07, 0.14, 0.95, 0.86, 0.77, 0.17, 0.27, 0.49, 0.63] \quad (\text{A I-5})$$

The decodification of the variable $W_{jj'p}$ requires more steps than the previously described ones. This process starts with the vector Var^W that store the rows of the matrix d_{pj}^W , where each row presents a period p and each column presents a product j . In a next step, for each period of d_{pj}^W , the values which belong to each product family were identified using variable Y_{jk} , hence defining d^{temp} . Then, in a following step, the obtained values were classified in ascending order to identify the production sequence for each product family in each period. Finally, using this information, the full $W_{jj'p}$ matrix was defined.

The model constrains were managed using data structure, and penalization and solution correction operators as described in the following. The constrains described as the model equations (5.12), (5.13) and (5.14) were managed using a penalization strategy. Here, each model constraint is verified in a prior step to calculate the objective function for each solution. If a solution is not in agreement with a constraint, a penalization factor is increased. Finally, the objective f_1 , f_2 , f_3 or f_4 related to this constraint is then multiplied by the penalization factor.

In addition, two solution correction operators were implemented to fulfill the constraints described in equations (5.12) to (5.14). After the solution decoding process, if a solution did not fulfill the constraints equations (5.13) and (5.13), workplace i was assigned to the cell or family belonging to product j .

0.2 Initial population

The initial population brings the seeds from it starts optimization process to NSGA2-RCRSA, based on solutions coded as $Var = (Var^X, Var^Y, Var^Z, Var^W)$, which was implemented according to two strategies. The first strategy defined the population randomly, and the second one followed a heuristic process. For each Var^X vector position, a random number a was generated, if $a \leq 0.5$ $Var^X = 1$, otherwise $Var^X = 0$. For each position of Var^Y and Var^Z a random integer ranging from 1 to mc was generated. Finally, Var^W was generated as a random vector. This strategy allowed to explore the search space; however, it could not be optimized. Hence, for half of the population, the second strategy was implemented. First, a base Var^Y was defined, where a product j that is processed in a workplace i was assigned to the same cell or product family. Second, to balance the workload and to reduce the lateness in scheduling, Var^Z adopts the values of the balanced workplaces $= \lceil \frac{t_{ijl}^{op}}{t_j^c} \rceil$, which approximates the ideal number of workplaces i to balance t_{ijl}^{op} . Finally, the normalized values of dd_{pj} are assigned to Var^W trying to be near to the ideal production sequences.

0.3 Reproduction

The algorithms use sexual reproduction as a mechanism to exchange information among individuals for improving the population. In this way, this process allows the population's evolution, providing the features of the best adapted individuals of the current generation to the next one. This process starts with parents' selection, which in this study was realized through a binary tournament.

A crossover process was conducted after parent selection. During this process, the information of the parents was exchanged. For Var^X , Var^Y , and Var^Z a crossover with a single cross point

was implemented, as shown in the following example :

$$Parent^1 = [1, 2, 3, 4, 5] \quad Parent^2 = [6, 7, 8, 9, 10] \quad (A I-6)$$

For this example, the cross point is the third position, hence as a result two children are obtained :

$$Child^1 = [1, 2, 3, 9, 10] \quad Child^2 = [6, 7, 8, 4, 5] \quad (A I-7)$$

Given that Var^W is a real vector, its crossover is implemented as a random weighted average of the two parents to generate a child :

$$Child = \alpha * Parent^1 + (1 - \alpha) * Parent^2 \quad (A I-8)$$

where α is a random weighted factor.

The last reproduction process is mutation. It allows exploring the search space to generate tiny random changes to some individuals. This mutation is an essential feature of evolutionary algorithms which helps to avoid local optimal solutions. The mutation process was applied to randomly selected individuals (GA-mo) or dominated by others (NSGA2). For each element of an individual vector, a random number was generated, and if less than the mutation probability the element was mutated. In the case of Var^X , if the element is "1", its value is changed to "0" and vice-versa. Var^Y and Var^Z were mutated increasing or decreasing the selected element by one unit. If the element value was "1", it can only be increased. Finally, Var^W is mutated multiplying the element by a random factor that can increase or decrease its value.

ANNEXE II

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4. Bourses

RRECQ

Cartographie matricielle de l'AMF.

CIRODD

Identification des mesures d'impacts économiques, environnementaux et sociaux ou des indicateurs de performance clés pour des systèmes de refabrication justes et équitables.

Mitacs - Capsolar

Development Of A Novel Approach Towards Smart Sustainable Circular Manufacturing (SSCM) For Custom Solar Modules - Subproject 1.

5. Présentations par affiche



Second International Innovation 5.0 Forum and Exhibition



VERS UNE SOCIÉTÉ SMART-DIGITAL-GREEN

A smart architecture for a sustainable manufacturing-remanufacturing system



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Introduction

- Remanufacturing adoption requires coordination among a business model (BM), smart architecture, and closed loop supply chain (CLSC) operations [1].
- Remanufacturing barriers and challenges are mainly related to the lack of product life cycle information [2].
- A smart architecture based on industry 4.0 principles has a strong potential to overcome much of these issues [3].

Objective

Develop a smart architecture enabling to control, optimize and execute remanufacturing and closed loop supply chain operations, to communicate with supply chain actors, and to support the sustainable BM.

Methodology

- Literature review.
- Identification of interactions among industry 4.0 technology, remanufacturing barriers and challenges, sustainability and the BMs.
- Design process

Design process

Step 1 Defining requirements.



Fig 1. Sustainability criteria.
Fig 2. Stakeholders

Step 2 Addressing remanufacturing barriers and challenges.

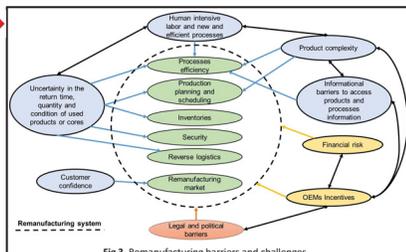


Fig 3. Remanufacturing barriers and challenges.

Step 3 Establishing components and structure.

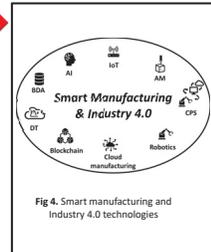


Fig 4. Smart manufacturing and Industry 4.0 technologies

Smart Architecture concept

- Modular customizable structure by layers.
- Cloud based architecture.
- Circular business model integration.
- Sustainable and stakeholders' focus.

Developed Smart Architecture Concept

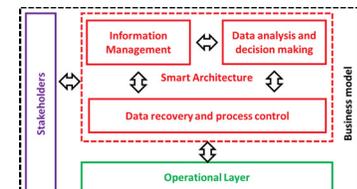


Fig 5. Smart architecture structure.

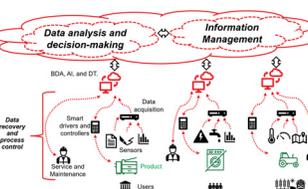


Fig 6. Smart architecture layers.

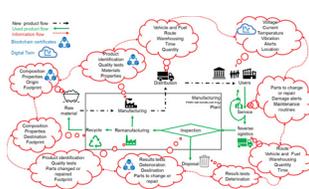


Fig 7. CLSC information flow.

The smart architecture Fig. 5, captures, shares, analyses, and processes product life cycle information as shows Fig. 6. Fig. 7 presents information flow along closed loop supply chain operations.

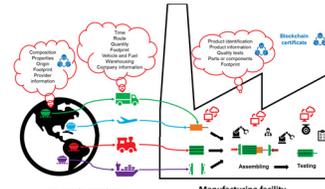


Fig 8. Suppliers and manufacturing schema.

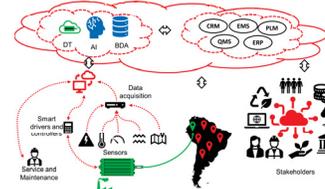


Fig 9. Stakeholders interactions.

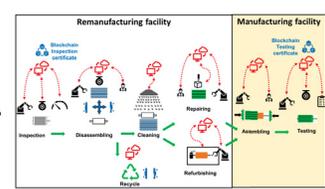


Fig 10. Manufacturing remanufacturing plant schema

Fig. 8, shows a schema of the smart architecture at suppliers and manufacturing. Fig. 9 presents the stakeholders' interactions with the smart architecture. While Fig. 10 exposes a schema of the manufacturing – remanufacturing plant.

Conclusions

- The developed smart architecture functionalities help to develop efficient and sustainable CLSC operations.
- The smart architecture addresses remanufacturing system barriers and challenges.
- The smart architecture supports CBM for capturing and trading value-added used products.
- The smart architecture includes a stakeholders' focus.
- The developed smart architecture opens up many research opportunities towards the development of customized circular and sustainable technologies and business models.

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Towards sustainable indicators for remanufacturing operations: a literature review



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Abstract

This study identifies sustainable key performance indicators (KPI) for remanufacturing operations. A systematic literature review (SLR) using Scopus database is performed. Sustainable and remanufacturing KPIs are identified.

Remanufacturing system

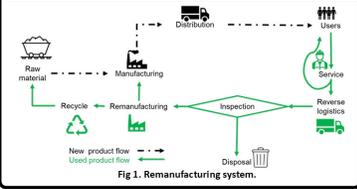


Fig. 1. Remanufacturing system.

Methodology

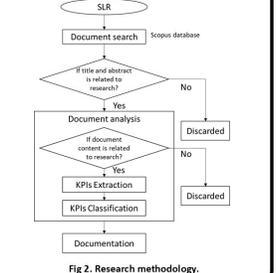


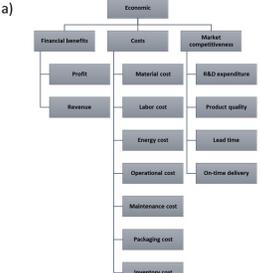
Fig. 2. Research methodology.

Research objective

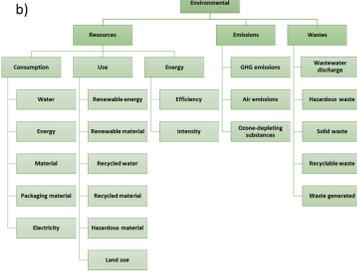
Identify how to **measure** and **control** the sustainable performance at the operational level of remanufacturing systems.

Sustainable indicators

a) Economic



b) Environmental



c) Social



Fig 3. Most used sustainable indicators a) economic, b) environmental and c) social dimensions.

Figure 3 summarizes the most used indicators to **measure** sustainable performance regarding economic, environmental, and social dimensions [1].

Remanufacturing indicators

Remanufacturing performance indicators can be classified into four dimensions (figure 4) [2] :

- Planning provides a first approach to economic remanufacturing feasibility.
- Procurement evaluates used products recovery and conditions.
- Scheduling and manufacturing evaluate the operational and technical requirements of remanufacturing.
- Order management and distribution are focused on closed loop supply chain performance.

Current applications of sustainable indicators on closed loop supply chains include suppliers' selection and sustainable scheduling.

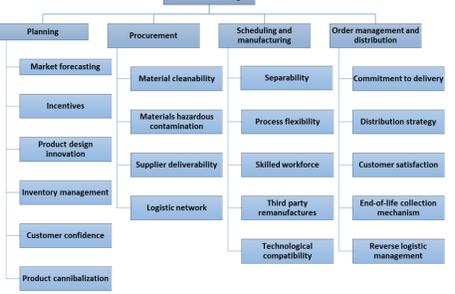


Fig 4. Remanufacturing performance indicators.

Conclusions

- Sustainable indicators allows to measure sustainability of products, processes, and operations along a closed loop supply chain.
- Remanufacturing indicators allow to control system performance.
- Future research opportunities include:
 - Reparability and remanufacturability indicators.
 - Smart evaluation of remanufacturable products based on industry 5.0.

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