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POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

Conception d'un modèle d'évaluation de la maturité numérique des PME manufacturières dans le contexte de l'Industrie 4.0

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Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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Conception d'un modèle d'évaluation de la maturité numérique des PME manufacturières dans le contexte de l'Industrie 4.0

présenté par **Syrine NJAH**

en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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DÉDICACE

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RÉSUMÉ

Ce mémoire explore la transformation numérique des petites et moyennes entreprises manufacturières (PME) en s'intéressant au rôle de l'évaluation de la maturité numérique comme point de départ structurant la planification stratégique vers l'Industrie 4.0. Il propose un modèle d'évaluation de la maturité numérique adapté aux spécificités des PME manufacturières.

La contribution principale de cette recherche réside dans le développement d'un modèle d'évaluation doté d'une méthode de calcul fiable du score de maturité numérique, intégrant une pondération explicite des dimensions et des indicateurs. Contrairement aux approches existantes fondées sur des mesures agrégées ou simplifiées, le modèle fournit un diagnostic détaillé et multidimensionnel des capacités numériques de l'entreprise, incluant des scores par indicateur et par dimension. Ce diagnostic permettra aux PMEs d'identifier précisément les écarts entre l'état actuel mesuré et leur niveau cible, et constitue une base structurée pour prioriser les actions de transformation numérique et soutenir l'élaboration de feuilles de route technologiques.

Le modèle couvre des dimensions clés telles que la stratégie et la gouvernance, les compétences numériques, les technologies, les systèmes industriels ainsi que le portefeuille de produits et services. Il tient compte des contraintes organisationnelles et des ressources limitées propres aux PME. Son développement s'appuie sur l'expertise conjointe d'acteurs académiques, de consultants et de praticiens des PME, et repose sur une méthodologie combinant des mesures qualitatives et quantitatives, garantissant une évaluation à la fois fiable, comparable et contextualisée.

Les résultats de la recherche montrent que la transformation numérique des PME ne repose pas principalement sur l'adoption technologique, mais sur des facteurs stratégiques et humains, en particulier la gouvernance et le développement des compétences. Les facteurs humains et organisationnels agissent comme médiateurs dans la conversion des investissements numériques en résultats concrets, tandis que les contraintes externes et les ressources limitées fonctionnent comme modérateurs de la réussite de la transformation numérique. Par ailleurs, Les priorités stratégiques identifiées des PME concernent majoritairement la compétitivité, l'efficacité opérationnelle et l'expérience client, au détriment des enjeux de durabilité et d'innovation à long terme.

ABSTRACT

This work examines the digital transformation of small and medium-sized manufacturing enterprises (SMEs), focusing on the role of digital maturity assessment as the foundational element of strategic planning towards Industry 4.0. It introduces a digital maturity assessment model specifically tailored to the characteristics of SMEs within the context of Industry 4.0.

The main contribution of this research lies in the development of an assessment model with a reliable method to calculate the digital maturity score, incorporating explicit weighting of both dimensions and indicators. Unlike existing approaches based on aggregated or simplified measures, the model provides a detailed and multidimensional diagnosis of a company's digital capabilities, including scores at both the indicator and dimension levels. This diagnosis enables SMEs to precisely identify gaps between the measured current state and their target level, and it constitutes a structured basis for prioritizing transformation actions and supporting the development of technological roadmaps.

The developed model incorporates several key dimensions, including strategy and governance, digital skills, technology, industrial systems, portfolio, products and services, while explicitly considering the organizational constraints and limited resources characteristic of SMEs. Its development draws on the combined expertise of academic researchers, consultants, and SME practitioners, employing a methodology that integrates objective and subjective measures, ensuring reliable, comparable and context-sensitive evaluations.

Findings reveal that digital transformation in SMEs extends beyond technology adoption. It primarily depends on strategic and human dimensions, notably governance and skills development. The results highlight that human and organizational factors act as mediators in converting digital investments into tangible outcomes, while external constraints and limited resources moderate the effectiveness of transformation initiatives. Moreover, strategic priorities in SMEs focus on enhancing competitiveness, operational efficiency and customer experience, whereas sustainability and long-term innovation remain secondary.

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API – Average Perceived Importance

C1 – Contribution 1

C2 – Contribution 2

DMM – Digital Maturity Model

FCEI – Fédération Canadienne de l'Entreprise Indépendante

HR – Human Resources

IoT – Internet of Things

IT – Information Technology

KPI – Key Performance Indicator

MCDM – Multi-Criteria Decision-Making

NAICS – North American Industry Classification System

PIB – Produit Intérieur Brut

PME – Petite et Moyenne Entreprise

RH – Ressource Humaine

RQ – Research Question

SME – Small and Medium-sized Enterprise

SO – Sous-Objectif

TI – Technologie de l'Information

I4.0 – Industrie 4.0 / Industry 4.0

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CHAPITRE 1 INTRODUCTION

1.1 Contexte de l'étude

Au cœur de la quatrième révolution industrielle, le futur des petites et moyennes entreprises manufacturières (PME) se joue désormais dans leur capacité à orchestrer la rencontre entre technologie et stratégie. L'adoption des technologies numériques comme l'intelligence artificielle, la robotisation et l'internet des objets ne se limite plus à un choix d'investissement, elle devient une condition de pérennité et un levier essentiel de compétitivité (R. Kumar et al., 2020). Pourtant, la transformation numérique ne se résume pas à une accumulation de technologies, elle requiert une vision structurée, une compréhension claire du positionnement actuel de l'entreprise et un plan cohérent pour atteindre une cible stratégique (Verhoef et al., 2021; Vial, 2019). Par conséquent, la transformation numérique constitue d'abord une démarche stratégique avant d'être un projet technologique.

1.1.1 Le contexte canadien et québécois : un potentiel encore sous-exploité

Le défi de transformation numérique revêt une importance particulière au Canada, où les PME forment l'épine dorsale de l'économie nationale. En décembre 2021, le pays comptait 1,2 million d'entreprises avec employés, dont 99,8% étaient des PME. Ces dernières emploient plus de 10 millions de travailleurs, soit environ 85% de la main-d'œuvre totale des secteur privé et public (ISDE, 2024). Au Québec, la situation est similaire où les PME représentent plus de 99% des entreprises et génèrent environ la moitié du produit intérieur brut (PIB) provincial, contribuant ainsi de manière décisive à la vitalité économique et à la création d'emplois (ISDE, 2024).

Cependant, malgré ce rôle central, les PME canadiennes demeurent confrontées à des retards significatifs dans leur transformation numérique. Selon la Fédération Canadienne de l'Entreprise Indépendante (FCEI), 92 % des PME canadiennes utilisent les technologies numériques, mais à peine 10 % les intègrent à l'ensemble de leurs activités et moins d'un tiers maîtrisent la collecte structurée de données pour la prise de décision stratégique (FCEI, 2025b). Cette lenteur d'adoption se traduit notamment par une stagnation de la productivité : entre 2015 et 2025, la productivité du travail au Canada n'a progressé que de 3 %, contre 18 % aux États-Unis (FCEI, 2025a). Un écart qui illustre à quel point le virage numérique représente un enjeu de compétitivité.

1.1.2 Rôle stratégique de l'évaluation de la maturité numérique dans la transition vers l'Industrie 4.0

La transition vers l'Industrie 4.0 ne peut pas être abordée comme une simple adoption technologique ponctuelle. Elle s'inscrit dans une démarche stratégique structurée qui nécessite, en amont, une compréhension claire de la situation actuelle de l'entreprise. À ce titre, la Fédération Canadienne de l'Entreprise Indépendante (FCEI) identifie plusieurs étapes critiques du virage numérique des PME, parmi lesquelles figurent la définition d'une vision et d'objectifs clairs, l'identification des processus à améliorer et l'élaboration d'une feuille de route numérique cohérente (FCEI, 2025b). La FCEI souligne également que la maturité numérique constitue aujourd'hui un levier central de performance pour les PME.

Dans la littérature scientifique, la transition numérique est fréquemment décrite comme un processus d'amélioration continue plutôt que comme un projet linéaire (Colli et al., 2019; Schumacher et al., 2019; Norouzi et al., 2023). Elle s'inscrit dans un cycle structuré où l'évaluation initiale de la maturité numérique constitue le point de départ fondamental, en permettant de comprendre les capacités numériques existantes, identifier les écarts à combler et structurer les étapes futures de la transformation (Schumacher et al., 2019). Les résultats de cette évaluation alimentent ensuite la construction d'une feuille de route technologique, définie comme un plan reliant des objectifs stratégiques à court et long terme à des solutions technologiques spécifiques (Phaal et al., 2013; Mittal et al., 2018). Alors que l'évaluation de la maturité se concentre sur l'état actuel des capacités, la feuille de route relève d'un outil de planification stratégique orienté vers l'action, permettant de prioriser et de séquencer les initiatives de transformation, dans ce cas organisées selon des niveaux progressifs de maturité (Colli et al., 2019; Schumacher et al., 2019; Norouzi et al., 2023). Une fois la stratégie déployée, une nouvelle évaluation permet d'actualiser le diagnostic et de boucler ainsi le cycle d'amélioration continue.

Pour les PME manufacturières, cette démarche est particulièrement sensible. Confrontées à une pénurie de ressources humaines, techniques et financières (Masood & Sonntag, 2020), la phase initiale du cycle décrit précédemment, à savoir l'évaluation de la maturité numérique, devient déterminante. En effet, elle conditionne la capacité des PME à planifier de manière réaliste et stratégique le développement de leurs capacités numériques et à éviter des investissements mal ciblés ou prématurés (Mittal et al., 2018).

Dans ce cadre, les modèles de maturité numérique (Digital Maturity Models - DMM) représentent des outils d'évaluation essentiels. Ils permettent de mesurer le niveau de maturité numérique d'une entreprise à travers des dimensions telles que la stratégie, la technologie, les processus, la culture et les compétences (Gökalp & Martinez, 2022). Selon Williams et al. (2024) les DMM adaptés aux PME permettent de mieux comprendre les capacités numériques, de guider la transition vers des modèles d'affaires digitaux et de renforcer la confiance dans les décisions de transformation numérique. De même, Marcos et al. (2024) démontrent qu'un modèle de maturité bien conçu fournit à la fois un cadre de diagnostic et une base de référence pour définir une feuille de route d'amélioration continue adaptée aux PME industrielles.

Ainsi, les DMM constituent la source d'entrée essentielle pour la conception de feuilles de route technologiques. Fantoni et al. (2025) et Phaal et al. (2013) soulignent qu'une feuille de route efficace doit s'appuyer sur des données factuelles reflétant l'état réel des capacités technologiques et organisationnelles de l'entreprise afin de garantir l'alignement stratégique entre objectifs, compétences et ressources. Les DMM permettent dans ce contexte d'identifier les écarts entre la situation actuelle et la cible souhaitée, de prioriser les initiatives numériques et d'établir une trajectoire de transformation réaliste et cohérente (Schumacher et al., 2019).

1.2 Énoncé du problème

Au cours des dernières années, de nombreux modèles de maturité numérique ont été développés par des chercheurs, des industriels et des cabinets de conseil pour évaluer la maturité numérique des entreprises (Cognet et al., 2023). Ces modèles ont contribué à structurer la compréhension de la transformation numérique, mais leur utilité pour la prise de décision stratégique demeure limitée, en particulier dans le contexte des PME manufacturières (Mittal et al., 2018).

Plusieurs travaux soulignent que la valeur de la majorité des DMM réside dans la mesure du score de maturité numérique plutôt que dans leur capacité à expliciter les forces, faiblesses et écarts entre les dimensions, afin de soutenir l'interprétation stratégique des résultats (Gökalp et al., 2022; Mittal et al., 2018). Cette situation est problématique pour les PME manufacturières, pour lesquelles un diagnostic difficilement interprétable réduit fortement la valeur pratique de l'évaluation (Mittal et al., 2018).

Les revues de littérature mettent également en évidence plusieurs limites récurrentes des DMM existants. Premièrement, les dimensions de la maturité numérique sont souvent définies de manière hétérogène, ce qui complique la compréhension globale de ce que recouvre la notion de maturité numérique (Cognet et al., 2023; Teichert, 2019). Deuxièmement, de nombreux modèles reposent sur des méthodes d'évaluation simplifiées et subjectives, ignorant l'interdépendance des composantes de la maturité numérique (Gökalp et al., 2022). Troisièmement, l'implication des praticiens et la transparence méthodologique demeurent limitées, ce qui affecte la crédibilité, la reproductibilité et l'applicabilité des résultats (Gökalp et al., 2022).

Dans le cas des PME manufacturières, ces limites sont accentuées par le fait que la transformation numérique débute souvent à un niveau très bas de structuration organisationnelle et technologique, rendant les outils existants partiellement inadaptés à leur réalité (Mittal et al., 2018).

Ainsi, la problématique centrale qui émerge est la suivante : **Comment concevoir un modèle de maturité numérique adapté aux besoins des PME manufacturières permettant d'avoir une évaluation fiable, contextualisée et exploitable pour orienter leur planification stratégique vers l'Industrie 4.0 ?**

1.3 Objectifs de recherche

Ce mémoire a pour objectif principal de : **Développer un modèle d'évaluation de la maturité numérique adapté aux PME manufacturières, conçu pour fournir un diagnostic détaillé allant au-delà d'un simple niveau de maturité, afin de soutenir leur transformation numérique.**

Les sous-objectifs sont les suivants :

- **SO1 :** Développer un outil de mesure de la maturité numérique adapté aux spécificités des PME manufacturières en prenant en considération les lacunes des modèles existants dans la littérature.
- **SO2 :** Définir les pondérations des composantes de l'outil de mesure de la maturité numérique en s'appuyant sur une méthode de calcul de score fiable et reproductible.

1.4 Organisation du mémoire

Ce mémoire par articles est structuré en six chapitres. Après cette introduction, le **Chapitre 2** présente une revue de littérature couvrant les différents aspects de la maturité numérique et situant la continuité avec les recherches antérieures. Le **Chapitre 3** expose la méthodologie générale adoptée. Les deux chapitres suivants se présentent sous la forme d'articles scientifiques :

- **Chapitre 4**: Njah, S., Danjou, C., Armellini, F., Beaudry, C., & Mosconi, E. (2026). A digital maturity model for assessing SMEs in the manufacturing sector. Digital Engineering, 9, 100084. 10.1016/j.dte.2025.100084
- **Chapitre 5**: Njah, S., Armellini, F., Danjou, C. (2026) Designing a multi-criteria approach to measure the digital maturity score of manufacturing SMEs. Submitted to Journal of Manufacturing Technology Management.

Finalement, le **Chapitre 6** présente une conclusion générale, les limitations de l’étude et les perspectives des futures recherches.

CHAPITRE 2 REVUE DE LA LITTÉRATURE

2.1 Les spécificités des PME manufacturières dans la transition vers l'Industrie 4.0

Dans le contexte nord-américain et selon le « North American Industry Classification System (NAICS) », le secteur manufacturier couvre un spectre allant de l'agroalimentaire à la production d'équipements électroniques, automobiles ou métalliques (Government of Canada, 2022a). Ces industries sont au cœur des mutations de l'Industrie 4.0, caractérisée par l'intégration croissante de technologies numériques (Statistics Canada, 2024).

Les PME comptent moins de 500 employés ou réalisent un chiffre d'affaires inférieur à 20 millions de dollars et elles représentent la majorité du tissu manufacturier canadien (Innovation et al., 2025; ISDE, 2024). Leur rôle est essentiel, mais leur transition vers l'Industrie 4.0 demeure inégale (FCEI, 2025b).

Ces entreprises se distinguent des grandes organisations par une structure hiérarchique réduite, une prise de décision centralisée et peu formalisée, ainsi qu'une forte dépendance aux ressources internes limitées, qu'elles soient financières, humaines ou technologiques (Gamache et al., 2019; S. Kumar et al., 2023; Masood et al., 2020; Orzes et al., 2018). Sur le plan stratégique, les PME adoptent souvent une vision à court terme, centrée sur la survie et la satisfaction immédiate des clients, ce qui freine l'investissement dans des projets numériques d'envergure (Mittal et al., 2018).

Malgré leurs vulnérabilités structurelles et ressources limitées, les PME manufacturières possèdent un fort potentiel pour tirer parti des opportunités offertes par l'Industrie 4.0. Elles peuvent notamment bénéficier d'une amélioration significative de leur productivité grâce à l'automatisation, à l'optimisation des opérations et à l'utilisation accrue de données en temps réel (FCEI, 2025b; OECD, 2021). L'Industrie 4.0 leur permet d'augmenter leur flexibilité face aux demandes variables, de réduire les coûts d'exploitation et de mieux répondre à la personnalisation des produits. Cette flexibilité accrue offre un avantage compétitif notable, notamment dans des marchés de niche ou locaux.

Plusieurs études récentes mettent en évidence des médiateurs essentiels pour accélérer la transformation numérique des PME manufacturières. Parmi ces médiateurs figurent le développement des compétences numériques, une culture organisationnelle ouverte au changement, un support externe via des partenariats ou des agences spécialisées, ainsi que l'utilisation d'outils structurés comme les modèles de maturité numérique (Kampoowale et al., 2025; Merín-Rodrigáñez et al., 2024; Sutrisno, 2023).

À titre d'exemple, le renforcement des compétences numériques permet de réduire la barrière liée au manque de savoir-faire technique et une culture organisationnelle favorable au changement stimule l'adhésion des équipes (Kampoowale et al., 2025). Par ailleurs, la flexibilité et la proximité des dirigeants avec les opérations au sein des PME peut favoriser une adoption progressive et pragmatique des technologies numériques, mais cette dynamique nécessite un accompagnement structurant pour être pleinement efficace (Chonsawat et al., 2023). Ainsi, le support externe, qu'il soit fourni par des consultants, des réseaux sectoriels ou des programmes gouvernementaux, aide à pallier les limites internes en apportant expertise, ressources et bonnes pratiques. Dans le même contexte, les outils de maturité numérique jouent un rôle crucial en offrant un cadre objectif et opérationnel pour évaluer la situation actuelle de l'entreprise, identifier les priorités d'évolution et structurer une feuille de route technologique réaliste et adaptée aux capacités spécifiques de chaque PME (Mittal et al., 2018; Brodeur et al., 2021). Ces médiateurs peuvent transformer les défis intrinsèques des PME en leviers d'innovation et de compétitivité.

Ainsi, la transformation numérique des PME manufacturières ne dépend pas uniquement de la disponibilité technologique, mais aussi de la capacité à développer une stratégie de transition efficiente et une culture organisationnelle propice au changement et à l'apprentissage.

2.2 Les modèles d'évaluation de la maturité numérique

2.2.1 La maturité numérique

La « maturité » en général est définie comme étant un état « *complet, parfait ou prêt* » (Weiner & Simpson, 1989). Elle désigne la capacité, pour quelqu'un ou quelque chose, d'atteindre le meilleur niveau possible (Cognet et al., 2023).

Dans le contexte de l'Industrie 4.0, en 2017, le terme « maturité numérique » a été considéré comme étant le stade final de la transformation numérique que les entreprises veulent acquérir. Les entreprises qui ont atteint cette maturité numérique, ont eu d'importantes améliorations dans le fonctionnement de l'entreprise et ont augmenté la satisfaction de leurs clients (Aslanova & Kulichkina, 2020). Rossmann (2019) l'a définie comme étant « *la capacité à acquérir et à utiliser* *les technologies dites numériques pour améliorer l'ensemble de son activité* ». Fortier et al. (2025) l'ont présenté comme étant le niveau de préparation, de compétences et d'intégration des technologies numériques au sein d'une organisation.

Ce concept de maturité numérique est intrinsèquement multidimensionnel, car il englobe plusieurs axes essentiels pour une intégration complète et efficace des technologies numériques au sein d'une organisation. Selon Chanias & Hess (2016), cette intégration se manifeste à travers les processus, la culture, la stratégie et le modèle d'affaires. Cette approche multidimensionnelle est confirmée et approfondie dans la littérature scientifique. Par exemple, Kane et al. (2017) élargissent cette vision en considérant la maturité numérique comme un processus d'adaptation continue qui dépasse la simple adoption technologique, impliquant des changements culturels et organisationnels profonds alignés sur les besoins des clients, partenaires et employés. Teichert (2019) identifie quant à lui une quinzaine de dimensions récurrentes dans les modèles de maturité numérique, incluant notamment la gouvernance, la vision stratégique, l'innovation, les compétences numériques, la culture numérique et les opérations, démontrant la complexité et la richesse du concept. Gökalp et al. (2022) valident également que les modèles de maturité incluent des dimensions technologiques, organisationnelles, stratégiques et culturelles, insistant sur la nécessité d'une approche holistique. Par conséquent, la maturité numérique ne peut être réduite à un seul aspect technologique, mais doit être comprise comme un cadre intégrateur de multiples dimensions interdépendantes qui façonnent la transformation digitale d'une organisation.

En s'appuyant sur ces perspectives, la maturité numérique peut être synthétisée comme : « la capacité d'une organisation à adopter et à exploiter les technologies émergentes tout en alignant les dimensions technologiques, organisationnelles, managériales et humaines pour atteindre ses objectifs stratégiques ». Cette vision intégrative positionne la maturité numérique non pas comme un point final statique, mais comme un processus dynamique d'adaptation et d'innovation en réponse aux impératifs de l'Industrie 4.0.

2.2.2 Les modèles de maturité numérique

Les modèles de maturité numérique (DMM) constituent des cadres analytiques permettant d'évaluer la progression d'une organisation sur la voie de la transformation numérique. Schumacher et al. (2016) définissent un DMM comme étant un : *« Outil pour conceptualiser et* *mesurer le niveau de maturité d'une organisation ou d'un processus, il donne les bases pour guider la transformation de l'état actuel vers l'objectif ciblé et ainsi accroître le niveau de maturité. »*

La littérature distingue les outils de mesure de la maturité numérique et ceux de la « readiness » numérique, bien que ces deux approches soient souvent mobilisées de manière complémentaire. Les modèles de maturité numérique visent à évaluer le niveau actuel de maturité d'une organisation et à situer sa progression dans un processus d'amélioration continue structuré par étapes successives (Wendler, 2012; Mittal et al., 2018). Les outils de readiness numérique se concentrent sur l'évaluation du degré de préparation d'une organisation à engager une transformation, en examinant les conditions, ressources, attitudes et capacités nécessaires à la mise en œuvre d'une vision cible, dans le contexte de l'Industrie 4.0 (Cognet et al., 2023; Mittal et al., 2018).

Dans ce mémoire, l'outil proposé adopte une approche combinée, intégrant à la fois une logique de maturité et une logique de readiness. Il vise à fournir un diagnostic descriptif détaillé de l'état actuel des capacités numériques des PME manufacturières, au-delà d'un simple score de maturité, afin d'éclairer l'analyse de leur transition vers l'Industrie 4.0. L'outil ne se positionne pas comme un dispositif prescriptif produisant des recommandations opérationnelles, mais plutôt comme une base analytique exploitable pour alimenter, en aval, le processus de planification stratégique. Par souci de clarté et de cohérence terminologique, le terme « modèle de mesure de la maturité numérique » sera utilisé ci-après pour désigner ce type d'évaluation.

Compte tenu du caractère multidimensionnel de la maturité numérique évoqué précédemment, un DMM s'appuie généralement sur un ensemble de dimensions interdépendantes (technologie, stratégie, organisation, culture, ressources humaines, etc.), déclinées en sous-dimensions et en indicateurs mesurables. Ces indicateurs parfois désignés comme des items, des variables ou des KPIs, visent à fournir une représentation structurée et quantifiable du niveau de maturité d'une organisation (Cognet et al., 2023). La littérature distingue principalement trois grandes approches de conception des DMM: descriptive, lorsqu'elle se limite à dresser un portrait du niveau actuel de maturité; prescriptive, lorsqu'elle associe les résultats à des recommandations opérationnelles; et comparative, lorsqu'elle permette un benchmarking sectoriel (de Bruin et al., 2005).

Cependant, malgré leur large diffusion, plusieurs limites structurelles persistent dans les modèles existants. D'une part, la majorité des modèles ont été conçus pour des grandes entreprises, sans adaptation contextuelle aux PME, ni proposition d'orientations post-évaluation (Mittal et al., 2018). D’autre part, les dimensions culturelles, managériales et humaines sont souvent sous-représentées, réduisant la portée opérationnelle du diagnostic (Gökalp et al., 2022; Teichert, 2019). Par ailleurs, de nombreux modèles présentent des faiblesses méthodologiques, tant dans la définition des indicateurs que dans la pondération des dimensions et la validation empirique des résultats (Cognet et al., 2023; Gökalp et al., 2022). Ces constats appellent à une refonte des DMM pour les rendre plus adaptatifs, contextuels et opérationnels pour les PME manufacturières.

2.2.3 Travaux de Cognet et al. (2023) et continuité de la recherche

Les travaux de Cognet et al. (2023), auxquels ce mémoire s’inscrit comme une continuation, représentent une contribution majeure à la formalisation des modèles de maturité appliqués à l’Industrie 4.0. À partir d’une revue de 18 modèles existants, les auteurs ont identifié 12 dimensions et 74 indicateurs de performance, couvrant à la fois les aspects technologiques, organisationnels, managériales et humains. Leur modèle visait à proposer une vision systémique de la maturité numérique, intégrant l’ensemble des leviers de transformation.

Une particularité méthodologique importante de leur étude réside dans l’analyse de la redondance et de la saturation des dimensions. Les auteurs ont utilisés une approche de rétro-ingénierie des indicateurs clés de performance à partir des différents modèles de maturité numérique existants. Cette étape manuelle, réalisée par un groupe d'experts, consiste à extraire et à formaliser les KPI sous-jacents aux questions et réponses des modèles, assurant ainsi une représentation standardisée et comparable des évaluations malgré l'hétérogénéité des modèles. Par la suite, chaque KPI est caractérisé par un ensemble de mots-clés spécifiques, eux-mêmes regroupés en dimensions et sous-dimensions, permettant de créer un espace commun de comparaison. Sur cette base, Cognet et al. (2023) ont appliqué des techniques semi-automatiques de corrélation interdimensionnelle afin d'analyser la redondance et la saturation des dimensions évaluées. Ils ont démontré qu'au-delà d'un certain nombre de dimensions, les apports d’informations supplémentaires deviennent marginaux. Autrement dit, l’ajout de nouvelles dimensions n’enrichit plus significativement la compréhension de la maturité numérique, ce qui suggère l’existence d’un seuil de saturation conceptuelle (Figure 2.1).

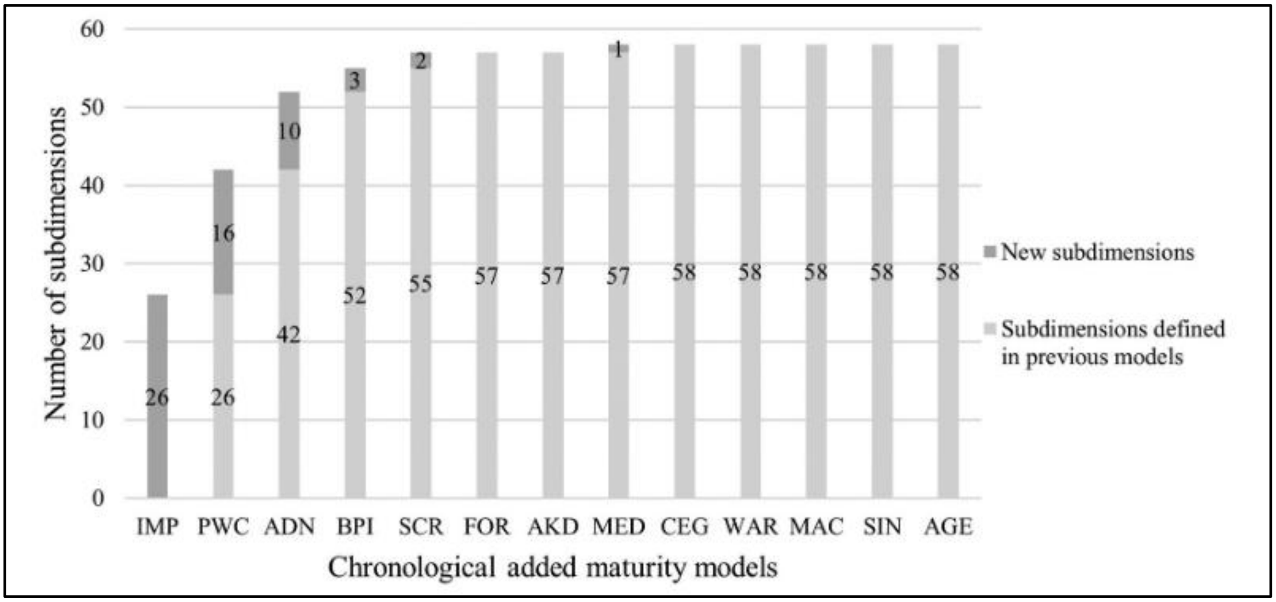

Figure 2.1 Évolution chronologique du nombre de sous-dimensions de la maturité numérique extrait des travaux de Cognet et al. (2023)

Cette approche innovante, combinant une rétro-ingénierie rigoureuse des KPI et une analyse quantitative systématique des recouvrements, fournit un cadre méthodologique à la fois robuste et exhaustif. Elle permet de démontrer que les dimensions et indicateurs retenus couvrent l'ensemble des facettes de la maturité numérique. Cependant, le modèle de Cognet et al. (2023) reste essentiellement descriptif : il ne propose ni pondération des dimensions ni méthode d'évaluation intégrée. Il ne fournit pas non plus de recommandations post-évaluation, ce qui limite son utilisation opérationnelle dans des contextes réels.

Ainsi, cette présente recherche s'inscrit dans la continuité directe des conclusions de Cognet et al. (2023) où leurs dimensions et indicateurs serviront de base solide et fiable pour le développement du nouvel outil de maturité numérique.

2.3 Feuilles de route technologiques

La feuille de route technologique est un outil de planification stratégique. Selon Phaal et al. (2001), elle vise à relier sur une ligne temporelle, les objectifs technologiques, les ressources, les produits et les marchés.

Dans le cadre défini par Phaal et al. (2013), la démarche de construction d'une feuille de route technologique débute par la détermination du point de départ, c'est-à-dire la situation actuelle de l'entreprise en termes de capacités technologiques, de ressources organisationnelles et de positionnement concurrentiel. Cette étape « Où sommes-nous aujourd'hui ? » est essentielle pour évaluer la distance à parcourir vers l'état cible et orienter les choix d'investissement et de développement.

Pour être pertinente, la feuille de route doit intégrer plusieurs perspectives interdépendantes permettant de structurer la vision de l'évolution de l'entreprise (Phaal et al., 2013) (Figure 2.2):

- La perspective commerciale et stratégique, qui relie la trajectoire technologique aux besoins du marché et aux objectifs d'affaires ;
- La perspective conception, développement et production, qui traduit les priorités technologiques en projets d'innovation et d'amélioration des processus ;
- La perspective technologique et de recherche, qui identifie les connaissances, compétences et technologies critiques à développer ou à acquérir.

Dans le contexte de l'Industrie 4.0, la feuille de route technologique devient une méthodologie intégrée au management de l'innovation, permettant de lier la planification des investissements technologiques aux niveaux actuels de maturité et aux capacités internes de l'entreprise (Fantoni et al., 2025). Elle permet ainsi aux entreprises d'identifier les étapes de progression vers un état cible et piloter la transformation numérique.

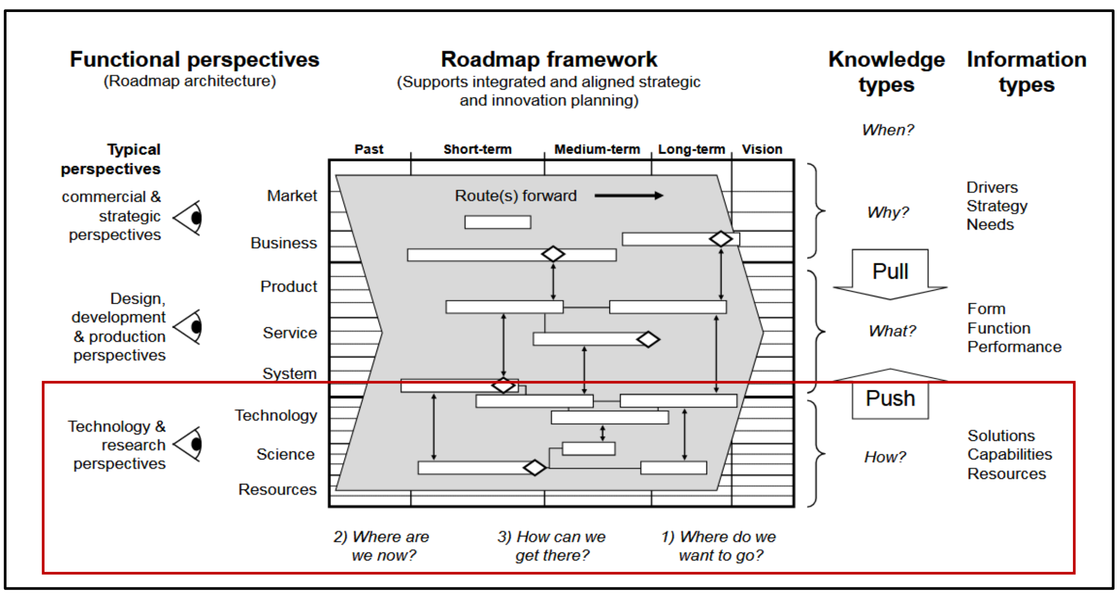

Figure 2.2 Structure généralisée de la feuille de route technologique adaptée de Phaal et al. (2013)

Le présent travail cherche à créer un outil de mesure de la maturité numérique fournissant un diagnostic détaillé qui alimentera ensuite le développement d’une feuille de route technologique contextualisée, permettant aux PME de traduire leur niveau de maturité en plan d’action évolutif et mesurable.

2.4 Organisation de la revue de littérature des articles

Le tableau ci-dessous illustre l’organisation des principaux aspects traités dans la revue de littérature des deux articles inclus dans ce mémoire, en complémentarité avec les éléments développés dans le présent chapitre.

Le premier article analyse les spécificités des PME manufacturières dans le contexte de l’adoption de l’Industrie 4.0. Il aborde également la notion de maturité numérique, les outils d’évaluation, ainsi que leur structure et leur utilité pour ces entreprises.

Les limites des modèles de maturité numérique sont discutées de manière progressive dans les deux articles, afin de souligner la continuité et la complémentarité de la recherche.

Le deuxième article se concentre sur l’utilisation des modèles de maturité numérique comme leviers pour le développement de feuilles de route technologiques. Il propose une revue systématique des travaux existants et examine les méthodes d’évaluation utilisées dans les DMM pour le calcul des scores de maturité numérique.

Tableau 2.1 Organisation de la revue de littérature des articles

Article	Section	Aspect étudié
Article 1	4.2.1	Spécificités des PME manufacturières lors de l’adoption de l'industrie 4.0
	4.2.2.1	Maturité numérique
	4.2.2.2	Modèles de maturité numérique : Structure et objectif
	4.2.2.3	Limites de outils de maturité numériques existant dans la littérature
Article 2	5.2.1	
	5.2.2	Modèles de maturité numérique pour guider les feuilles de route technologiques
	5.2.3	Méthodes de calcul du score de la maturité numérique

CHAPITRE 3 ORGANISATION GÉNÉRALE DE LA RECHERCHE

L'organisation générale de la recherche repose sur deux études complémentaires, chacune donnant lieu à un article scientifique intégré dans le mémoire.

3.1 Logique de la recherche

L'objectif principal de ce travail est de concevoir un modèle de mesure de la maturité numérique adapté aux besoins des PME manufacturières afin de fournir une évaluation fiable, contextualisée et exploitable pour orienter leur transformation numérique.

Pour atteindre cet objectif, cette recherche positionne l'évaluation de la maturité numérique comme le point de départ fondamental d'un cycle continue de transformation numérique, inspiré des modèles de Schumacher et al. (2019), Colli et al. (2019) et Norouzi et al. (2023), présentés respectivement aux figures 3.1, 3.2 et 3.3. Cette approche circulaire permet de structurer la stratégie de transformation de manière progressive, contextualisée et alignée sur les capacités réelles des PME manufacturières.

Schumacher et al. (2019) illustrent ce processus de « réalisation de l'Industrie 4.0 » (figure 3.1) en dix étapes qui commencent par l'évaluation de la maturité numérique sur huit dimensions clés et aboutit à la définition de chemins de réalisation regroupés en champs d'action spécifiques, permettant ensuite de construire une feuille de route technologique adaptée à l'entreprise.

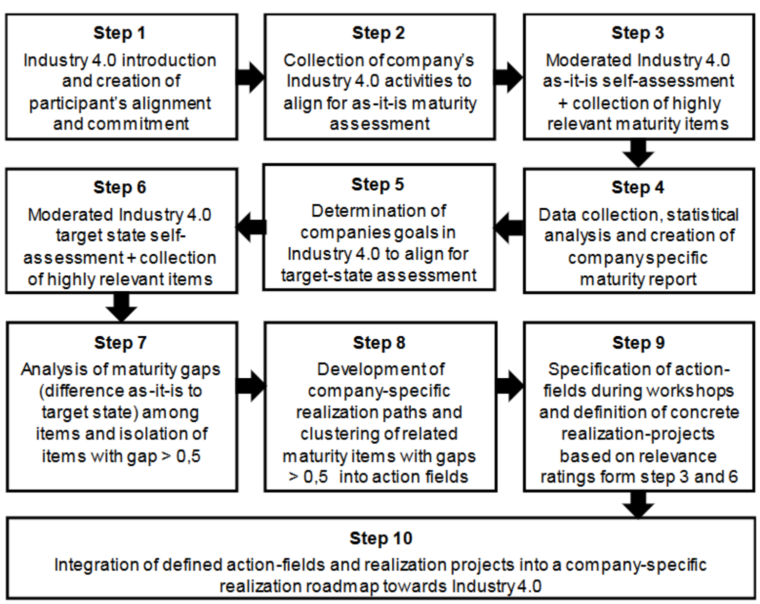

Figure 3.1 Processus de « réalisation de l'Industrie 4.0 »
extrait de l'étude de Schumacher et al. (2019)

Dans la même approche, Colli et al. (2019), proposent une démarche d'évaluation de la maturité numérique structurée en cinq étapes (figure 3.2), centrée sur l'apprentissage par problème (PBL). Leur méthode combine l'évaluation du niveau actuel de maturité sur des dimensions stratégiques, technologiques et organisationnelles avec l'identification des importants écarts spécifiques à chaque entreprise. Les écarts observés servent ensuite de base pour formuler des recommandations et orienter la planification stratégique, tout en permettant une itération continue à chaque cycle d'amélioration.

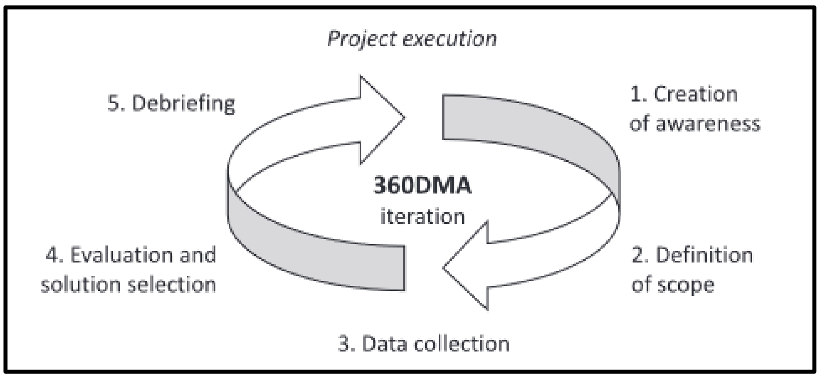

Figure 3.2 Approche d'évaluation de la maturité numérique à 360°
extraite de l'étude de Colli et al. (2019)

Norouzi et al. (2023) confirment l'importance de l'évaluation initiale pour orienter la stratégie. Leur approche en cinq étapes (figure 3.3) commence par l'évaluation de la maturité numérique actuelle, identifie les écarts par rapport à un niveau cible et priorise les actions selon leur impact potentiel. Cette procédure itérative assure que la stratégie de transformation soit toujours alignée sur le niveau réel de maturité et sur les capacités disponibles, en adaptant les actions à chaque cycle d'amélioration.

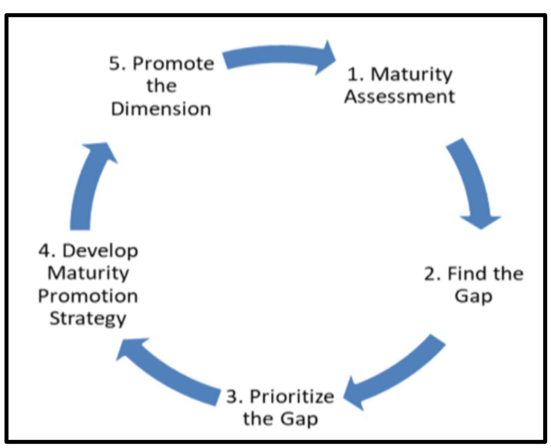

Figure 3.3 Stratégie d'implémentation de l'amélioration de la
maturité numérique extraite de l'étude de Norouzi et al. (2023)

Ces travaux convergent vers une même logique : le diagnostic issu de l'évaluation de la maturité numérique permet de caractériser les capacités de l'entreprise et d'identifier les écarts entre le niveau actuel et le niveau cible, fournissant ainsi les informations nécessaires à la construction d'une feuille de route technologique et à la définition d'une stratégie de transition vers l'I4.0.

Dans ce cadre, cette étude développe un outil de mesure de la maturité numérique reposant sur une méthode de calcul de score fiable, destinée à quantifier ces écarts. Le diagnostic détaillé obtenu, constitue un support analytique pour alimenter la planification stratégique et la construction de feuilles de route technologiques. L'outil développé s'inscrit ainsi comme le point de départ d'un cycle d'amélioration continue de la transformation numérique (figure 3.4), inspiré des approches présentées précédemment. Ce cycle débute par l'évaluation de la maturité numérique, suivie de l'identification de l'écart entre le niveau actuel et le niveau cible. Les résultats issus de ces deux étapes alimentent ensuite l'élaboration d'une feuille de route technologique ainsi que la priorisation des actions à mettre en œuvre. Enfin, la stratégie définie est implémentée, permettant au cycle d'être réitéré dans une logique d'amélioration continue.

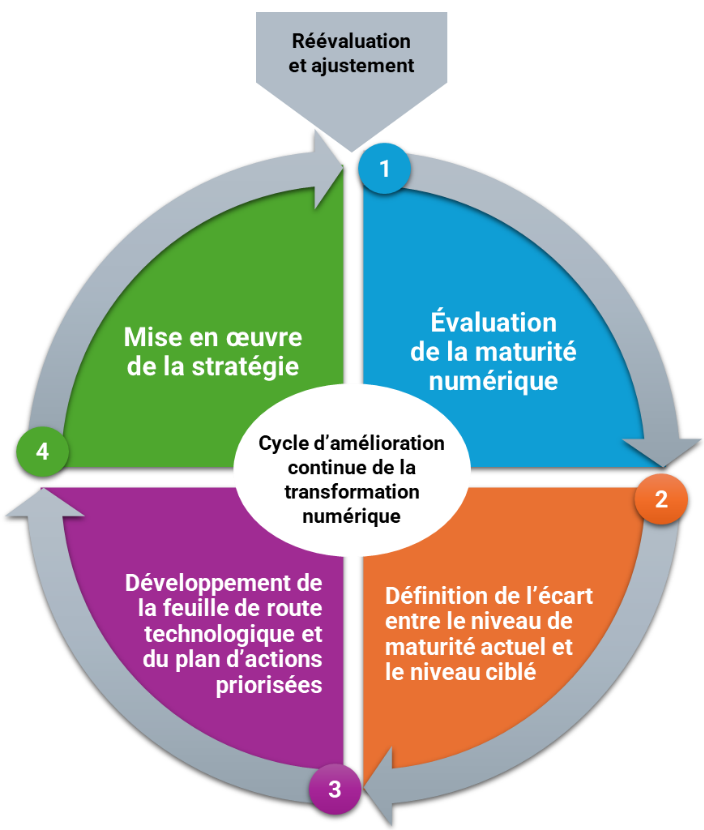

Figure 3.4 Cycle d'amélioration continue de la transformation numérique

La figure 3.5 constitue un zoom analytique sur les trois premières étapes du cycle d'amélioration continue de la transformation numérique (figure 3.4), en mettant en évidence la logique de passage entre l'évaluation, l'analyse de l'écart et la planification. Elle illustre de manière séquentielle, le positionnement initial de la PME à partir de l'évaluation de la maturité numérique, la définition de l'écart entre le niveau actuel et le niveau de maturité ciblé, puis la construction de la feuille de route technologique. Cette représentation permet de rendre explicite la transition entre un diagnostic de maturité et sa traduction en trajectoire d'évolution, en répondant de façon structurée aux trois questions fondamentales pour le développement d'une feuille de route « où se situe l'entreprise », « où souhaite-t-elle aller » et « comment peut-elle y parvenir » (Phaal et al., 2013).

Néanmoins, afin de construire une feuille de route pertinente, il est nécessaire d'intégrer les différentes perspectives présentées précédemment (figure 2.2), à savoir les perspectives commerciale et stratégique, conception, développement et production, ainsi que technologique et de recherche. Dans le cadre de cette étude, l'évaluation de la maturité numérique met plus spécifiquement l'accent sur la perspective technologique et de recherche. Cette dernière permet de relier les capacités numériques internes de l'entreprise à ses priorités d'investissement technologique et d'innovation, tout en tenant compte des contraintes propres aux PME manufacturières.

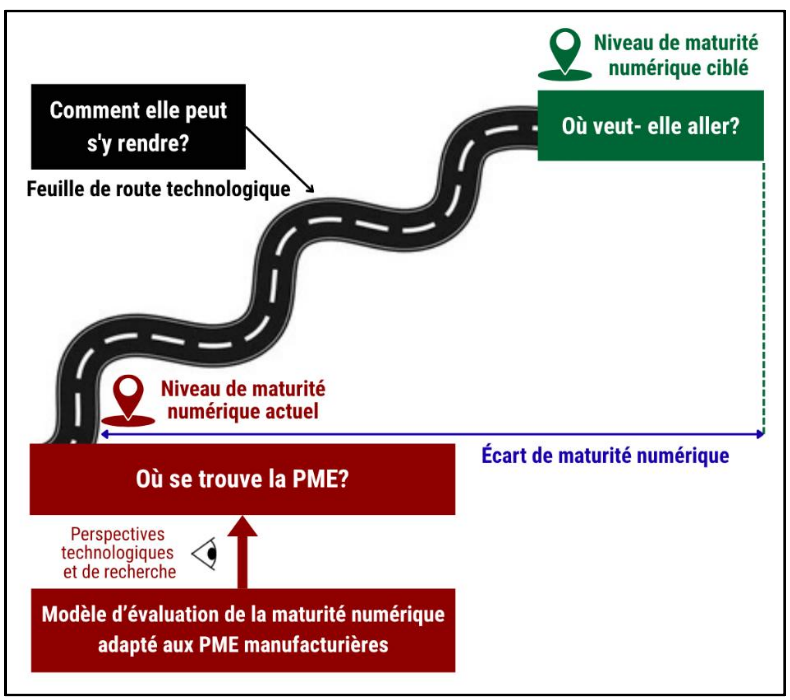

Figure 3.5 Parcours de développement de la feuille de route technologique

3.2 Articulation des articles et questions de recherche

La méthodologie générale de cette étude peut être décomposer en deux étapes principales correspondant aux deux articles scientifiques du mémoire (Tableau 3.1).

Le premier article, *« A Digital Maturity Model for assessing SMEs in the manufacturing sector »*, vise à identifier et à structurer les dimensions clés de la maturité numérique des PME manufacturières. En s'appuyant sur le cadre de développement des modèles de maturité proposé par de Bruin et al. (2005), cet article aboutit à la conception d'un modèle d'évaluation intégrant les spécificités structurelles, organisationnelles et technologiques de ce type d'entreprises. L'approche méthodologique est renforcée par une étude de cas qualitatives (Creswell & Creswell, 2017 ; Yin, 2018) permettant d'assurer la validité contextuelle du modèle. Cet article, après une revue de la littérature qui a permis d'identifier les lacunes des outils d'évaluation existants, répond à la question de recherche suivante **(RQ1)** : **« Quelles sont les caractéristiques clés d'un modèle de maturité numérique conçu pour évaluer de manière fiable les PME du secteur manufacturier? »** et permet d'atteindre le premier sous-objectif **(SO1)**, à savoir la conception d'un outil de mesure adapté aux spécificités des PME manufacturières.

Toutefois, dans la perspective de transformation numérique structurée comme un cycle continu, l'identification des dimensions de la maturité numérique ne suffit pas à elle seule. Pour permettre l'opérationnalisation de cette logique circulaire, il est nécessaire de disposer d'une méthode de calcul rigoureuse permettant de quantifier le niveau de maturité, afin de définir les écarts entre l'état actuel et un niveau cible, et de suivre leur évolution dans le temps. Cette exigence méthodologique conduit au développement du second article et fonde la seconde question de recherche **(RQ2)** : **« Quelle approche méthodologique peut être utilisée pour établir des mesures quantitatives standardisées de la maturité numérique ? »**

Ainsi, le deuxième article, *« Designing a multi-criteria approach to measure the digital maturity score of manufacturing SMEs »*, vient compléter et opérationnaliser le modèle conceptuel du premier article. Il utilise une approche multicritère permettant de pondérer les différentes dimensions du DMM et d'obtenir un score global de maturité numérique. La méthodologie adoptée est inspirée d'une approche MCDM (Brown & Gibson, 1972), intégrant une étude Delphi modifiée (Schneider et al., 2016; Shang, 2023) et la méthode d'entropie de Rényi (Görçün et al., 2024). Elle assure ainsi une mesure quantitative, fiable et reproductible du niveau de maturité (SO2).

Tableau 3.1 Étapes de développement du modèle de mesure de la maturité numérique

Étape		Article	Méthodologie	Section
1	Développer les composantes de l'outil de mesure de la maturité numérique adaptées aux spécificités des PME manufacturières.	Article 1	Cadre de développement de modèles de maturité proposé par (de Bruin et al., 2005) et étude de cas qualitative (Creswell & Creswell, 2017; Yin et al., 2018)	4.3
2	Opérationnaliser le modèle à travers une méthode de calcul du score de la maturité numérique.	Article 2	Approche de prise de décision multicritère inspirée du modèle de (Brown et al., 1972), intégrant une étude Delphi modifiée (Schneider et al., 2016; Shang, 2023) et la méthode d'entropie de Rényi (Görçün et al., 2024)	5.3

3.3 Méthodologies adoptées

3.3.1 Article 1

La méthodologie de l'article 1 combine un cadre de développement de modèle de maturité et une étude qualitative inspirée des références classiques en méthodes de recherche. Le développement du DMM suit le cadre en six phases de Bruin et al. (2005) (Scope, Design, Populate, Test, Deploy, Maintain), qui offre une structure itérative et systématique pour concevoir, peupler et tester un modèle de maturité. Le contenu initial du modèle s'appuie sur l'étude de Cognet et al. (2023) qui synthétise les modèles de maturité existants et aboutit à 12 dimensions, 58 sous-dimensions et 74 indicateurs (KPI) couvrant l'Industrie 4.0. Sur cette base, l'équipe de recherche mène une revue critique pour réduire ces 74 KPI à 37 indicateurs, en éliminant les redondances, en vérifiant leur pertinence pour le contexte manufacturier et leur mesurabilité, puis en les reformulant en questions fermées avec des options de réponse détaillées sur une échelle ordinale non métrique allant de « 1 » (niveau d'entrée très faible) à « 5 » (niveau avancé) avec un niveau « 0 » si l'aspect évalué est non pertinent pour l'entreprise. Des exemples des indicateurs révisés sont mentionnés dans le tableau 3.2.

L'étude de cas qualitative multiple est conçue et conduite selon le design de Yin et al. (2018) pour les études de cas (planification, conception, préparation, collecte, analyse, rapport), et s'inscrit dans les normes de la recherche qualitative telle que décrite par Creswell & Creswell (2017). Trois PME manufacturières sont sélectionnées par échantillonnage opportuniste, conformément aux recommandations de Palinkas et al. (2015) pour les recherches qualitatives lorsque l'accès aux organisations est contraint. Six entrevues semi-structurées d'environ une heure sont réalisées avec des vice-présidents, managers TI et responsables de production, à l'aide d'un guide élaboré de manière déductive à partir de la littérature, puis ouvert à l'émergence de thèmes inductifs. L'analyse des données repose sur une analyse thématique hybride (inductive-déductive) avec QDA Miner, en suivant les orientations de Creswell & Creswell (2017), Saldaña (2021) et Krippendorff (2018) pour le codage, la triangulation des sources (entrevues, sites web, données statistiques, observations) et la construction de validité par convergence des données. La fiabilité inter-codeurs est assurée par un processus de consensus interprétatif entre deux codeurs, selon l'approche préconisée par O'Connor & Joffe (2020).

Les entrevues réalisées n'avaient pas pour objectif de valider le modèle de maturité, mais de vérifier si les spécificités des PME identifiées dans la littérature correspondaient aux pratiques observées sur le terrain. Une fois la saturation des données atteinte, c'est-à-dire lorsque les entrevues n'apportaient pas d'informations nouvelles par rapport à la littérature, les résultats des études de cas ont été utilisés pour confronter le socle théorique du modèle à la réalité des PME manufacturières et ajuster le modèle lorsque certaines dimensions ne reflétaient pas adéquatement cette réalité. Les principaux ajustements ont concerné les obstacles à la transformation numérique, les usages concrets des technologies, les compétences et la culture numériques, ainsi que la gestion du changement. L'analyse qualitative a permis d'identifier 107 codes de premier ordre, regroupés en 34 codes de second ordre. Sur cette base, des indicateurs supplémentaires ont été intégrés au modèle afin de mieux refléter les spécificités des PME étudiées. Le DMM final comprend ainsi 5 dimensions, 34 sous-dimensions et 49 indicateurs, administrés via 38 questions, auxquelles s'ajoutent 4 questions de caractérisation de l'entreprise.

La phase de test, toujours conformément au cycle de de Bruin et al. (2005), a permis de restructurer certains formats de questions, d'affiner les options de réponse et d'ajouter des définitions et des exemples pour faciliter l'autoévaluation par les PME. La phase de déploiement prévoit ensuite l'utilisation du questionnaire dans une étude quantitative de validation qui a été déjà diffusée, mais cette validation empirique est explicitement annoncée comme relevant de travaux futurs et ne fait pas partie du périmètre de l'article.

Tableau 3.2 Exemples des indicateurs révisés

Argument	Exemple(s)
Certains indicateurs sont corrélés de façon à pouvoir les fusionner et créer un seul indicateur évaluant le même aspect.	1* « Disponibilité et mise à jour des indicateurs clés de performance (KPI) pour surveiller l'efficacité opérationnelle de l'organisation » sous dimension « Modèle d'affaire et stratégie ». 2* « Disponibilité et mise à jour des indicateurs clés de performance (KPI) pour surveiller la progression de l'organisation dans la mise en œuvre de sa transformation numérique » sous-dimension « Stratégie numérique ». 3* « Disponibilité des indicateurs permettant d'évaluer la création de valeur et les avantages économiques liés aux investissements de l'organisation dans sa transformation numérique » sous-dimension « Gestion de la performance ». ⇨ Ces trois indicateurs font partie de la dimension « Stratégie et gouvernance ». Les experts ont choisi de créer un nouvel indicateur qui les regroupe : « Disponibilité d'indicateurs clés de performance pour évaluer la transformation numérique de l'entreprise » qui a été associé à une sous-dimension intitulée « Modèle d'affaire et stratégie numérique ». Il est à mentionner que le type des KPIs sera pris en compte dans les choix de réponses.
Certains indicateurs sont complexes à mesurer, leur évaluation ne peut pas se baser sur des critères objectifs et les résultats de mesure ne seront pas fiables.	Indicateur de la sous-dimension « Technologies TI » inclus dans la dimension « TI et outils informatiques » : « Capacité de l'organisation à intégrer et à utiliser les TI dans les activités de l'organisation pour soutenir sa transformation numérique » ⇨ Cet indicateur est difficile à mesurer car il reflète à la fois l'intégration, l'usage et l'impact des TI dans l'ensemble de l'organisation. Les experts ont convenu que sa valeur correspond à la définition même de la maturité numérique et que sa réponse se déduit de l'ensemble du questionnaire. L'intégration et l'usage des technologies numériques sont abordés dans d'autres indicateurs.
	Indicateur de la sous-dimension « Connaissances » incluse dans la dimension « Innovation et gestion des connaissances » : « Capacité de l'organisation à gérer la capitalisation des connaissances. » ⇨ Les experts ont jugé que la capacité d'une entreprise à transformer ses connaissances en actifs exploitables est une pratique complexe à mesurer.
Certains indicateurs n'évaluent pas l'intégration de l'industrie 4.0.	Indicateur de la sous-dimension « Modes de gestion » incluse dans la dimension « Ressources Humaines » : « Capacité de l'organisation à contrôler l'efficacité et la charge de travail des employés. »

3.3.2 Article 2

Cette recherche met en œuvre une méthodologie multi-critères visant à produire un score fiable de la maturité numérique pour les PME manufacturières. Elle articule trois composantes principales : adaptation du modèle de Brown-Gibson, processus Delphi modifié et pondération objective par entropie de Rényi, afin de combiner de manière cohérente jugements d'experts et mesures quantitatives, ce que les méthodes existantes ne réalisent que partiellement.

Les travaux antérieurs sur la mesure de la transformation numérique s'appuient majoritairement sur des approches de décision multicritère (MCDM) à forte composante subjective, en particulier l'AHP (Kaya et al., 2023; Görçün et al., 2024), souvent combinée à d'autres techniques telles que DEMATEL (Zhu et al., 2024), Q-Sort (Samaranayake et al., 2017), TOPSIS (Martins et al., 2023), VIKOR (Büyüközkan et al., 2021)... (Le tableau présentant les méthodes fréquemment utilisées est présenté dans le chapitre 5 - section 5.2.3). Ces cadres structurent généralement des critères qui correspondent aux dimensions ou indicateurs des modèles de maturité numérique, puis en extraient des poids à partir de comparaisons par paires ou de jugements experts, ce qui conduit à des pondérations largement fondées sur les préférences des répondants, avec une intégration limitée de mesures objectives et, dans plusieurs cas, une analyse de sensibilité absente. Les travaux les plus récents couplent des poids subjectifs à des méthodes objectives afin de renforcer la robustesse des scores, mais sans proposer de schéma explicitement paramétrable d'intégration subjectif–objectif comparable à la structure mathématique de Brown-Gibson (Brown et al., 1972; Yimen et al., 2022).

La méthodologie proposée s'en distingue en (i) définissant des critères directement corrélés aux résultats de la maturité numérique (compétitivité, innovation, durabilité, efficience, etc.) pour comparer les composantes du modèle, (ii) calculant systématiquement des poids subjectifs (via un Delphi modifié) et objectifs (via l'entropie de Rényi) pour les dimensions et les KPIs, puis (iii) les combinant au moyen des équations de Brown-Gibson, dans lesquelles un paramètre de sensibilité contrôle l'équilibre entre contributions subjectives et objectives.

Les pondérations subjectives des dimensions et des KPIs de la maturité numérique sont obtenues via un processus Delphi modifié impliquant 16 experts en Industrie 4.0 et maturité numérique issus du monde académique, du conseil et de l'industrie. La procédure est structurée en trois étapes : (1) comparaison par paires des critères, (2) évaluation des dimensions par paires sous critères prioritaires et des KPIs sur échelle Likert 5 points, (3) rétroaction anonymisée et révision pour convergence. Contrairement au Delphi classique, qui repose sur plusieurs cycles complets de collecte et de retour, cette version condensée (deux tours de collecte de données et un tour de consensus) a été adoptée pour structurer un consensus efficace et accéléré (Nasa et al., 2021). Cette modification répond également à des considérations pratiques, telles que le maintien de l'engagement des experts et la gestion efficace de la complexité des critères et KPIs évalués. Cette approche s'aligne sur la littérature récente soulignant la flexibilité des applications Delphi, qui peuvent s'écarter de la méthode classique pour mieux s'adapter aux contextes de recherche spécifiques (Schneider et al., 2016 ; Shang, 2023). Ces études confirment qu'une itération consolidée de rétroaction, après plusieurs tours indépendants de questionnaires, permet d'atteindre efficacement le consensus tout en préservant la rigueur méthodologique et en réduisant l'attrition des participants.

Les évaluations subjectives sont ensuite transformées en poids objectifs par l'entropie de Rényi, méthode MCDM qui exploite la dispersion des jugements pour quantifier le pouvoir discriminant de chaque dimension et chaque indicateur. Pour chaque critère, la matrice des évaluations des experts est normalisée en distributions de probabilité par dimension, puis l'entropie de Rényi est calculée afin de mesurer le degré d'accord ou de variabilité des experts. Une faible entropie traduit une forte convergence des jugements et, par conséquent, une plus grande capacité discriminante. Les dimensions correspondantes reçoivent des poids objectifs plus élevés après normalisation, tandis que les dimensions pour lesquelles les avis sont plus dispersés obtiennent un poids réduit. Ce mécanisme limite le risque de biais liés à des opinions individuelles extrêmes ou à des effets de groupe et fournit un contrepoids quantitatif aux préférences exprimées dans le Delphi.

Enfin, les poids subjectifs et objectifs sont intégrés dans le cadre Brown-Gibson pour obtenir une pondération finale des composantes de la maturité numérique. Ce poids final est soumis à une analyse de sensibilité afin de vérifier la stabilité des pondérations et du classement des dimensions (et, des KPIs) sur un intervalle de valeurs réalistes. À travers ces poids finaux, une mesure de maturité numérique fiable et transparente peut être calculée pour les PME manufacturières.

3.4 Contributions de l'étude

Cette recherche apporte deux contributions majeures à la transformation numérique des PME manufacturières. La première contribution (**C1**) enrichit la littérature sur la maturité numérique en concevant un modèle d'évaluation spécifiquement adapté à la réalité stratégique, organisationnelle, humaine et technologique des PME manufacturières. Ce modèle se distingue par sa transparence méthodologique et par son élaboration collaborative, mobilisant à la fois des experts académiques, des consultants en Industrie 4.0 et des praticiens issus des PME. Il fournit une analyse détaillée permettant de diagnostiquer finement le niveau de maturité numérique, y compris pour les entreprises se situant aux niveaux les plus bas de développement technologique.

La deuxième contribution (**C2**) consiste à opérationnaliser ce modèle à travers le calcul du score de maturité numérique, fondée sur une approche de prise de décision multicritère (MCDM) combinant mesures subjectives et objectives et validée par une analyse de sensibilité. Cette démarche garantit la fiabilité et la comparabilité des évaluations entre PMEs. Elle facilite l'identification des forces, des faiblesses et des écarts entre le niveau actuel et le niveau cible de maturité, constituant ainsi le point de départ d'un cycle d'amélioration continue de la transformation numérique. **C2** consolide ainsi **C1** en surmontant l'une des principales limites des modèles existants, à savoir l'absence de rigueur dans le calcul du score de maturité.

L'organisation générale de la recherche et la visualisation des contributions sont présentées dans la figure ci-dessous:

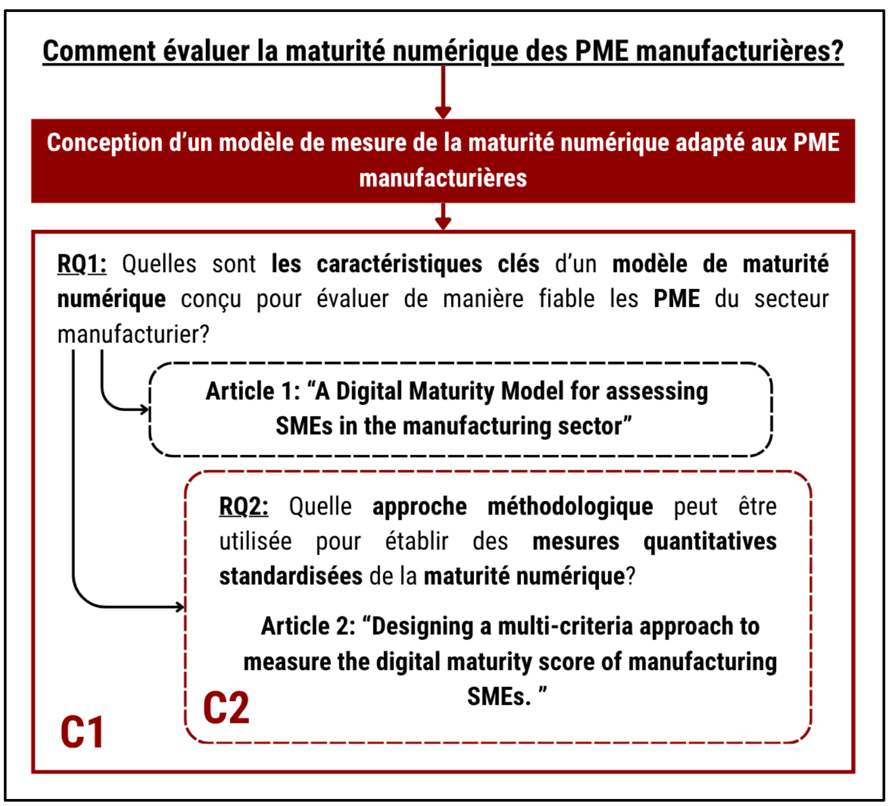

Figure 3.6 Organisation générale de la recherche

CHAPITRE 4 ARTICLE 1: A DIGITAL MATURITY MODEL FOR ASSESSING SMES IN THE MANUFACTURING SECTOR

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Authors' contributions: *Syrine Njah* led the conceptualization of the paper, the original draft writing, review and editing, the literature review, the methodology design, the data collection and analysis, and the project administration. *Christophe Danjou* and *Fabiano Armellini* supervised the project and the paper, guided the development and the implementation of the methodology, validated the results and contributed to the writing, review, and editing of the manuscript. *Catherine Beaudry* and *Elaine Mosconi* contributed to the design of the methodology, provided supervision and validation.

Abstract: This paper presents the development of a Digital Maturity Model (DMM) designed to support small and medium-sized manufacturing enterprises (SMEs) in their transition towards Industry 4.0. SMEs face distinct challenges compared to large enterprises, mainly due to financial constraints, limited digital skills and reliance on short-term operational priorities, which necessitate flexible and modular solutions adapted to their context. Existing DMMs show critical limitations, including weak practitioner involvement, lack of multidimensional integration, insufficient consideration of lower maturity levels and absence of actionable strategic outputs. To address these gaps, a six-phase methodology was followed, including qualitative case studies with three Canadian manufacturing SMEs. The final DMM includes five dimensions, 34 subdimensions and 49 indicators covering technological, managerial and organizational aspects. Case studies revealed an overview of digital maturity in SMEs with a strong strategic awareness of digital transformation and early-stage integration of emerging technologies. They also highlighted persistent barriers such as limited digital capabilities, resistance to change and regulatory challenges. The DMM provides practical value as a descriptive tool for assessing maturity and guides both ecosystem positioning and the development of digital transformation roadmaps. It also contributes to the academic field as a replicable and adaptable approach for evaluating digital maturity in SMEs and fostering innovation in manufacturing ecosystems. Future research should focus on developing a scoring methodology and conducting quantitative validation to enhance reliability.

Keywords: Digital Maturity Model (DMM); Industry 4.0; Manufacturing; SME; Qualitative case study.

4.1 Introduction

The manufacturing sector is facing a large transformation driven by the emergence of Industry 4.0 technologies, such as the Internet of Things (IoT), big data analytics, artificial intelligence and advanced robotics (Xu et al., 2021). This technological revolution, often referred to the Fourth Industrial Revolution, is reshaping the way manufacturing companies operate, compete and create value (Schwab, 2017). However, despite the rapid evolution of digital technologies, many industrial companies, especially small and medium-sized enterprises (SMEs), struggle to remain competitive at the international level (Bamidele Micheal Omowole et al., 2024). SMEs encounter significant challenges due to their limited resources when striving to implement a successful digitalization strategy (Bamidele Micheal Omowole et al., 2024; Hein-Pensel et al., 2023). For example, according to a survey conducted by the Business Development Bank of Canada (BDC), only 40% of Canadian manufacturing SMEs have executed Industry 4.0-related projects (Pierre-Olivier Bédard-Maltais, 2017).

The literature highlights that SMEs often start from a lower baseline of digital transformation compared to larger organizations, with limited access to specialized knowledge, structured digital strategies and essential resources such as skills and funding (Masood et al., 2020; Mittal et al., 2018). These constraints make it difficult for SMEs to adopt advanced Industry 4.0 technologies at the same pace as larger firms. Consequently, there is a critical need for tools and frameworks that support SMEs in assessing their current digital capabilities and identifying actionable steps for transformation.

Digital maturity models (DMMs) have emerged as essential instruments for guiding organizations through digital transformation by evaluating their ability and readiness to adopt, integrate and use digital technologies to enhance operations, foster innovation and achieve strategic goals. However, existing models often present significant gaps (Gökalp et al., 2022). Many fail to comprehensively assess Industry 4.0 dimensions, lack rigorous methodological framework or rely on subjective evaluations (Barry et al., 2022; Colli et al., 2019; Gökalp et al., 2022). Furthermore, literature review reveals a predominance of models developed for assessing large manufacturing firms or the industrial sector in general. Thereby, they often overlook the specific needs and constraints of SMEs, failing to provide tailored recommendations for these companies (Mittal et al., 2018).

This research aims to address the existing maturity models' gaps by developing a holistic DMM tailored to the special requirements of manufacturing SMEs, considering managerial, organizational, human and technological dimensions. The main objective of the developed tool is to provide a reliable assessment of SMEs' digital maturity. Building on this foundation, future research can generate potential improvement recommendations to support the development of a technological roadmap that guides and prioritizes digital transformation efforts.

To demonstrate the applicability of the proposed tool, this paper includes case studies conducted in a Canadian city manufacturing sector. These case studies serve to test the model and illustrate its practical utility for industrial organizations.

To introduce the proposed DMM, this paper is structured as follows. S**ection 4.2** presents the specific requirements of SMEs in adopting Industry 4.0 and reviews existing digital maturity models, focusing on their structure, applicability and limitations. **Section 4.3** details the methodology used to design the proposed model and describes the qualitative study approach. **Section 4.4** presents the case studies results conducted across three manufacturing firms, illustrating how the model was refined and tested. Finally, **section 4.4** presents the discussion and the conclusion, highlighting the findings' implications for both academia and industry, the study's limitations and the directions for future research.

4.2 Theoretical background

4.2.1 Manufacturing SMEs requirements in adopting Industry 4.0

In the North American context, manufacturing refers to the transformation of raw materials or components into finished goods through physical, chemical or mechanical processes, typically conducted in factories or plants. It is classified under sectors 31 to 33 of the North American Industry Classification System (NAICS) (Government of Canada, 2022a, 2022b), which include a broad spectrum of activities from food production to electronics and automotive components.

To identify the specific requirements of SMEs in comparison to large enterprises within the manufacturing sector, it is first necessary to define what constitutes an SME. Innovation, Science and Economic Development Canada (ISED) and Statistics Canada primarily classify SMEs based on employee count (Innovation et al., 2025). While the European Commission classifies SMEs as enterprises with fewer than 250 employees (European Commission, 2003), the North American classification includes larger enterprises. According to NAICS, and more specifically within the Canadian context, SMEs are enterprises that employ fewer than 499 individuals or that generate annual revenues less than $20,000,000. For this study, the NAICS definition of SMEs will be adopted.

SMEs and large enterprises present distinct requirements when adopting Industry 4.0, primarily due to differences in scale, resources, knowledge and strategic focus (Bamidele Micheal Omowole et al., 2024; Mittal et al., 2018). Studies consistently underline that while large companies benefit from abundant resources and structured innovative strategies, SMEs often face unique barriers that limit their ability to pursue digital transformation at the same pace (Bamidele Micheal Omowole et al., 2024; Masood et al., 2020). Table 4.1 presents specific SME aspects compared to the large firms, emphasizing the differences between the two categories.

Table 4.1 Comparison of SMEs and large companies in Industry 4.0 adoption

Aspect	SMEs	Large companies
Financial Resources	• Limited capital reserves • Difficulty with large-scale investments • Dependence on external funding	• Strong financial capacity • Investment in equipment and platforms • Support for workforce development
Knowledge Resources	• Low awareness of Industry 4.0 opportunities • Shortage of digital skills • Employees multitasking with less structured training	• High internal expertise • Specialized teams • Continuous training and technological benchmarking
Technology Adoption	• Solutions tailored to immediate needs • Frequent reliance on external consultants • Difficulty sustaining long-term transformation	• Dedicated staff for digital implementation • Long-term, enterprise-wide strategies
Decision-Making & Structure	• Decisions concentrated in owner or small group of managers • Reliance on practical experience over formal plans • Vertical structures with limited advisory roles	• Decisions distributed across specialized departments • Reliance on formalized strategies and data analysis • Horizontal structures with advisory bodies
Strategic Focus	• Short-term priorities • Digital solutions adapted to niche and customized production	• Balance between short- and long-term investments • Enterprise-wide strategic initiatives
Market and Networks	• Dependence on local or niche markets • High vulnerability to supply chain disruptions and shifting demand	• Operations in global markets • Greater resilience through diversified supply chains

Literature consistently identifies three key obstacles for SMEs: financial, knowledge and technological limitations. According to Mittal et al, SMEs generally lack the capital reserves of larger firms, which restricts their ability to invest in new equipment, digital platforms, or workforce development (Mittal et al., 2018; S. Mittal et al., 2018). This financial constraint makes large-scale investment difficult without external support (S. Kumar et al., 2023; Masood et al., 2020; Mittal et al., 2018; Orzes et al., 2018).

Knowledge resources also diverge sharply between SMEs and large enterprises. Masood et al., (2020) highlighted a persistent disconnection between SMEs and Industry 4.0 knowledge, noting their limited awareness of opportunities and their shortage of digital skills. Employees in SMEs often work across several domains, which restricts specialization and reduces access to structured training in advanced technologies (Pissareva et al., 2025). In opposite, large companies typically have specialized teams, higher internal expertise and rely on continuous technological watch and benchmarking to remain competitive (Masood et al., 2020).

Technological limitations further reinforce this gap. Masood et al., (2020) argued that SMEs often turn to external consultants to support their digital transition, but these services require funding that is not always available. As a result, SMEs usually implement technologies to address immediate operational needs rather than long-term strategies.

Strategic orientation also differs. While SMEs tend to prioritize short-term outcomes, especially given their resource constraints, large companies can balance short and long-term investments. Mittal al., (2018) also observed that SMEs often operate in highly specialized or niche markets, which require flexible solutions rather than standardized systems. This reliance on local networks also increases their vulnerability to supply chain disruptions and shifting customer demands, whereas large enterprises are more resilient due to their global scope (Kanyepe et al., 2025).

Decision-making processes and organizational structures also differ significantly. In SMEs, decision-making is often concentrated in the owner or a small group of managers, rather than distributed across specialized departments. SMEs tend to rely more on practical experience than on formalized strategic plans or data-driven analysis (Leso et al., 2023). Their organizational structure is usually vertical, with fewer advisory bodies or consultants involved in shaping strategic direction (Petrou et al., 2020). In contrast, decisions in large companies are informed by specialized departments, advisory committees and systematic data analysis.

Given these distinct characteristics and in order to provide a reliable assessment of SMEs' digital maturity and generate efficient context-sensitive recommendations, a DMM must be tailored to their specific requirements. Most existing models tend to overlook the structural, financial and strategic constraints that define SMEs, thereby limiting their practical relevance and impact (Mittal et al., 2018). The following section introduces the concept of DMMs, outlines their structure and presents a review of existing models, highlighting their limitations and assessing the extent to which they address the specific needs of SMEs.

4.2.2 Digital Maturity Models (DMMs) to support Industry 4.0 implementation

4.2.2.1 Digital Maturity: A Multidimensional Construct

Chanias et al., (2016) define digital maturity as the state reflecting a company's digital transformation efforts. They focus on assessing the company's overall achievements in digital transformation including changes in products, services, processes, skills, culture and abilities. Aslanova et al., (2020) conceptualize digital maturity as a company's reaction to changes in the digital era through the integration of digital advancements into business processes and the development of employees' digital competences.

Further refining this construct, Rossmann, (2019) defines digital maturity as the degree of adoption and application of digital technologies within corporate business models. Rossmann extends the digital maturity framework proposed by Westerman et al., (2014), which distinguishes between *digital capabilities* such as strategy, technological expertise, business models and customer experience; and *leadership capabilities* including governance, change management and organizational culture. The synergistic integration of these capabilities drives measurable improvements in corporate performance, including revenue growth, profitability and operational efficiency. According to Rossmann, (2019), developing both of these capabilities enables digital mastery.

Building on these perspectives, digital maturity can be synthesized as an organization's ability to strategically adopt and leverage emerging technologies while aligning technological, managerial, human and organizational dimensions to achieve long-term objectives. This integrative view positions digital maturity not as a static endpoint but as a dynamic process of adaptation and innovation in response to Industry 4.0 imperatives.

4.2.2.2 Digital Maturity Models: Structure and Purpose

DMMs serve as structured frameworks to conceptualize, assess and guide organizational progress in digital transformation. Schumacher et al., (2016) defines these models as a tool to conceptualize and measure the maturity level of an organization or a process. It provides the basis for guiding the transformation from the current state to a targeted objective and thus increasing the maturity level.

At their core, DMMs evaluate an organization's capacity to respond to digital transformation using predefined milestones within dimensions and sub-dimensions (Berghaus & Back, 2016). A dimension represents a critical and measurable component of digital maturity, such as technology integration or organizational culture. For example, within technology integration, a key subdimension is digital data processing (Teichert, 2019). This subdimension can be quantified by KPIs such as the data quality checks and the accuracy of data analysis (Cognet et al., 2023). According to Cognet et al., (2023), although models may vary in terminology, they are all structured around the same core concepts and their primary goal remains to characterize a company's processes, technologies and organizational structure. These models often use different terms like "items", "factors", "variables" or "Key Performance Indicators (KPIs)" to refer to the components of each dimension or sub-dimension, and they evaluate these components using a series of targeted questions and predefined answer sets (Cognet et al., 2023).

While DMMs share a common organizational structure (Figure 4.1), de Bruin et al., (2005) argue that the intended purpose of applying a model can vary significantly. It depends whether the resulting maturity assessment is descriptive, prescriptive or comparative (Table 4.2).

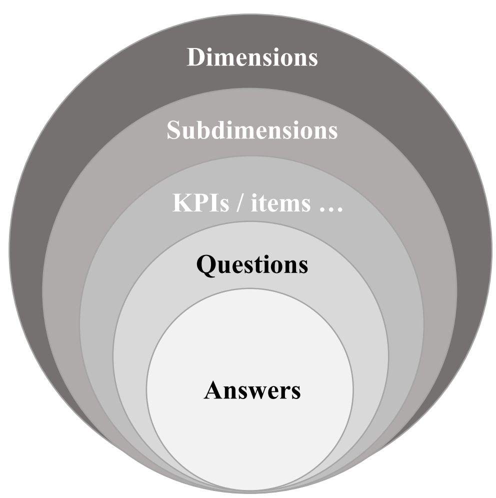


Figure 4.1 DMM's common organizational structure

Table 4.2 Types of DMMs

Type	Description
Descriptive Model	A purely descriptive model provides an overview of the company's current situation without offering recommendations for improving maturity or linking to performance outcomes.
Prescriptive Model	A prescriptive model emphasizes the relationship between digital maturity and business performance, offering guidance on how to enhance maturity to positively impact business value and enable the creation of a technological roadmap.
Comparative Model	A comparative model facilitates benchmarking across industries, ecosystems or regions, allowing organizations to compare practices and maturity levels.

Although these model types may seem distinct, they can represent evolutionary phases within a model's lifecycle (de Bruin et al., 2005). Initially, a model is descriptive to gain a comprehensive understanding of the company's current maturity level. It then evolves into a prescriptive model to drive improvements aimed at achieving optimal maturity levels. Finally, the model can be applied comparatively across a range of organizations to gather sufficient data for valid comparisons. Existing digital maturity models in the literature are designed for specific purposes, either focusing on a single phase or combining two or more phases to provide organizations with flexibility in aligning their maturity assessment goals with specific business objectives.

4.2.2.3 Critical review of existing digital maturity models

Over the past few years, a plethora of DMMs has emerged, developed by academics, industry practitioners or consulting firms. These tools are generally organized in the same structure as defined above, but few of them are in accordance with all the elements to be evaluated. Several literature reviews have compared the available models, identifying essential gaps in the existing models and highlighting their limited applicability for SMEs due to their specific typological, sectoral and geographical aspects (Mittal et al., 2018; Quenum et al., 2025).

Cognet et al., (2023) performed a comprehensive study of 18 frameworks and identified 12 core dimensions and 74 KPIs covering Industry 4.0 aspects. Their analysis revealed that most models fail to adopt a holistic perspective, with a focus on specific aspects of digital transformation, such as technology integration or organizational factors, while neglecting the interconnection of different dimensions. For SMEs, which require both integrated and resource-efficient solutions, this fragmented approach reduces the operational value of maturity assessments models (Quenum et al., 2025).

This narrow focus is also evident when examining dimension coverage in other studies. For example, Teichert, (2019) found that while digital strategy and governance appear frequently across 22 analyzed models, organizational culture remains inconsistently integrated despite its proven impact on transformation outcomes (Scremin et al., 2018). This represents a crucial gap in assessing SMEs, where the ability to overcome resource limitations is fundamentally linked to strong cultural values and committed managerial leadership (Bamidele Micheal Omowole et al., 2024).

The challenges extend beyond dimension selection to fundamental design flaws. Many models tend to be either overly generic or narrowly sector-specific, failing to accommodate the nuanced needs of diverse type of companies and industries (Gökalp et al., 2022).

Even when models are properly targeted, their utility is often limited by methodological weaknesses. Gökalp et al., (2022) confirmed that many tools lack robust documented and comprehensive standards, compromising their validation and credibility. Additionally, Mittal et al. (2018) demonstrated that fewer than 30% of models provide actionable post-assessment guidance such as technological roadmaps or transformation plans, limiting their operational value for SMEs. Given that these firms cannot always rely on external consultants, accessible and easy-to-use maturity models that integrate readiness assessment with strategic roadmapping are essential to effectively support their digital transition (Mittal et al., 2018). Furthermore, the evaluation methods frequently rely on oversimplified calculations that fail to capture the multidimensional and interconnected nature of digital maturity, leading to assessments that lack objectivity and theoretical rigor (Cognet et al., 2023; Gökalp et al., 2022).

Unlike large enterprises, SMEs typically start from a lower baseline of digital maturity, with limited financial resources, scarce R&D capabilities and insufficient digital skills. Yet, Mittal et al., (2018) demonstrated after a critical analysis of 15 models that most of them assume that firms already possess advanced, interconnected systems and the capacity to immediately adopt new technologies. This oversight creates a misalignment between the realities of SMEs and the assumptions of maturity models (Masood et al., 2020). To address this, scholars propose the introduction of a "level 0", defined as the stage where organizations lack awareness and have not yet started the

Industry 4.0 journey (Mittal et al., 2018). Transitioning from this stage to the conventional "level 1" requires not only technological investments but also a significant cultural and managerial shift within SMEs.

These limitations question the reliability of current assessment tools. Efforts to address these issues remain uneven. The analysis of more than 30 existing DMMs revealed the following unresolved challenges:

- *Comprehensive methodology:* The lack of holistic frameworks that simultaneously address technological, organizational and cultural dimensions while maintaining theoretical rigor. This limitation is particularly problematic for SMEs, where cultural and managerial factors are often decisive for overcoming resource constraints.
- *Practitioners' involvement:* Insufficient involvement of SME practitioners in the design of existing models, resulting in academic frameworks disconnected from operational realities of smaller firms.
- *Empirical validation:* Weak validation processes reduce confidence in the models' capacity to reliably measure maturity across diverse SME contexts, where resource availability, market positioning and sectoral dynamics vary significantly.
- *Interdependent objective assessment:* Existing evaluation methods are often oversimplified and primarily subjective, failing to consider the interdependent and multidimensional nature of digital maturity components. For SMEs, this produces biased assessments that don't reflect the challenges they face in adopting Industry 4.0.
- *Maturity levels:* Most existing models assume that firms already possess advanced systems and capabilities, overlooking the fact that many SMEs begin their digital journey from a much lower level.
- *Actionable roadmaps:* Few models provide tailored, practical guidance following the assessment. Since SMEs cannot always rely on external consultants, the absence of clear post-assessment recommendations leaves them without the strategic direction necessary to plan and execute their digital transition.

These gaps hinder the models' applicability in manufacturing SMEs, where the complexity of Industry 4.0 adoption demands a multidimensional assessment tool adapted to their specific needs to effectively measure their digital capabilities and develop tailored strategies.

Building on these limitations, this paper addresses the following research question: "***What are the key features of a Digital Maturity Model designed to reliably evaluate SMEs' digital maturity in the manufacturing sector?***" To answer this question, the study proposes a collaborative and holistic DMM that incorporates lower entry maturity levels and the specific requirements of SMEs. The results can be used to generate context-specific recommendations that support achieving an optimal level of digital maturity. The methodology used to develop this tool is detailed in the following section.

4.3 Methodology

4.3.1 DMM development process

The methodology employed in this study to develop the DMM follows the foundational framework established by de Bruin et al., (2005), which specifies six key phases for developing maturity assessment models: Scope, Design, Populate, Test, Deploy and Maintain (see Figure 4.2). This approach was selected not only for its clear structure but also for its flexibility to adapt the process to diverse digital transformation contexts and unique organizational needs, such as those of SMEs.

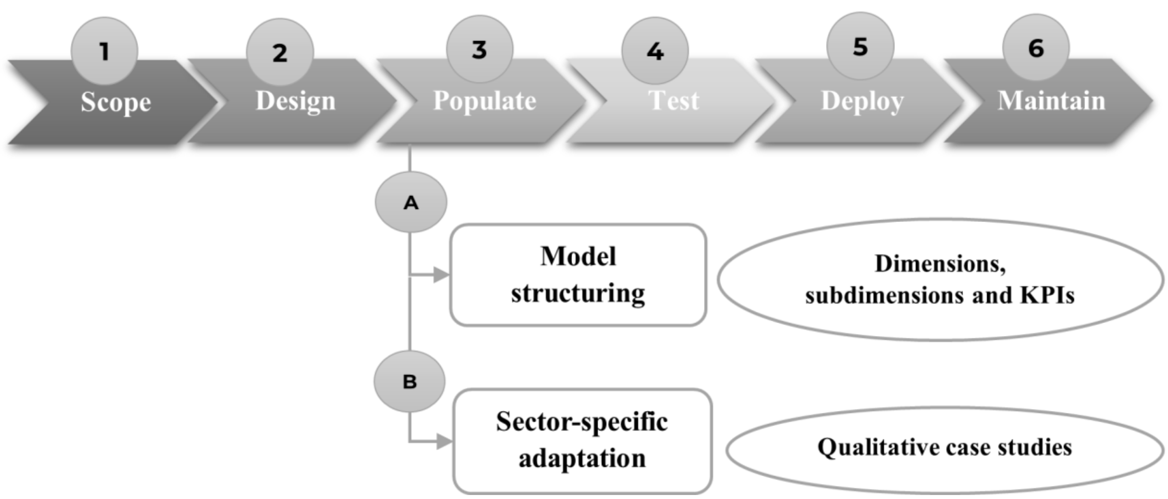


Figure 4.2 DMM's development key phases

Many existing studies proposing new digital maturity models often rely on systematic literature reviews, expert consultations or qualitative case studies but do not always formalize a structured development process. Among methodologies that do, de Bruin et al., (2005) and Becker et al., (2009) are prominent for their phased and iterative approaches. Becker et al. start with benchmarking and comparative analysis, while de Bruin et al. offer greater flexibility in model iteration and contextual adaptation. In this study, rather than repeating extensive benchmarking and comparison of existing digital maturity models, which has already been comprehensively conducted by studies such as Cognet et al., (2023), we based the selection of dimensions on their systematic synthesis. Their approach halted the aggregation of additional models once redundancy in dimensions was reached, providing a sound empirical foundation for subsequent development steps. They identified 12 key dimensions, 58 sub-dimensions and 74 KPIs. This provided a comprehensive foundation for our model content, enabling focus on developing a relevant and operational model for SMEs in Industry 4.0 contexts.

To ensure both academic rigor and practical relevance, an interdisciplinary team was assembled combining expertise from academia (including a professor specialized in digital transformation, a postdoctoral researcher and a research master's student) and from industry (including an Industry 4.0 consultant and manufacturing SMEs' practitioners).

Figure 4.2 outlines the six key phases of the DMM development process. The "Populate" and "Test" phases are particularly critical where practitioners from SMEs in the manufacturing sector of a medium-sized city located in Quebec, Canada, were strategically engaged to test the model within the operational realities.

The "Populate" phase involved a comprehensive review of existing models through the literature analysis, followed by qualitative multiple case studies. The collected data was analyzed using computer-assisted qualitative analysis (QDA Miner) and validated through an iterative process and different data sources.

This integrated methodology ensures the resulting DMM is both theoretically robust and practically applicable for assessing Industry 4.0 maturity in manufacturing SMEs.

4.3.1.1 Scope and design the DMM

The development process starts with the scope and design phases, guided by the methodology of de Bruin et al., (2005). These stages require several strategic decisions to shape the DMM, including defining the model's focus and boundaries, identifying the stakeholders' involvement and the respondent profiles and clarifying the primary drivers for model application.

These decisions (summarized in Table 4.3) provided the structural basis for the subsequent phases.

Table 4.3 Key decisions in scoping and designing the DMM

Criteria	Characteristics		
Focus of the model	Specific domain: Manufacturing sector - SME focused approach		
Development stakeholders	Academics	Industry 4.0 Consultant	Practitioners from manufacturing SMEs
Respondents	Senior executives, operations managers or digital technology managers		
Driver of application	- Provide a reliable digital maturity assessment for manufacturing SMEs. - Identify potential improvement recommendations to help SMEs become smart factories.		

4.3.1.2 Populate the DMM

Following the scope and design phases, the populate phase focuses on defining the key measurable elements to be evaluated and their assessment methods (de Bruin et al., 2005).

This stage was guided by Cognet et al.'s study, (2023), which identified 12 key dimensions, 58 sub-dimensions and 74 KPIs covering Industry 4.0 aspects. However, a set of 74 KPIs can reveal some practical constraints. Completing a questionnaire based on this full set would take around 37 minutes, which exceeds the typical 15 to 25-minute range for effective online assessments. This length increases the risk of respondent fatigue and inaccurate responses, which can affect data quality.

To ensure the model is both rigorous and user-friendly, the following simplification process was initiated to structure the new DMM's components:

- Dimensions consolidation :

The 12 initial dimensions were grouped into five dimensions described in Table 4.4. This revision was guided by the conceptual recurrence of these dimensions across existing maturity models, with particular attention to the characteristics of SMEs. Mittal et al. (2018) provide a critical review of digital maturity models, highlighting the need to adapt them to SMEs, which often operate under resource constraints and therefore require dimensions that integrate strategy, management, technology and workforce capabilities. Recent studies also reveal substantial convergence around core thematic areas covering managerial, organizational and technological dimensions (Hlel et al., 2025; Barry et al., 2023; Gökalp et al., 2022). In particular, Tonder et al., (2024) identifies strategy, leadership, people/employees, technology, processes, products and customers as key dimensions for assessing the digital maturity of SMEs, reinforcing the proposed model.

Table 4.4 Dimensions of the new developed DMM

Dimensions of Cognet et al. 2023	New dimensions	Description
Business, strategy & governance Innovation & knowledge management Finance	**(1) Strategy and governance**	The dimension covers critical elements of organizational management. It centers on the company's strategic decision-making processes related to the company's business model, digital strategy, leadership, and performance management and the efficient allocation of financial resources.
Human resources	**(2) Human resources and digital skills**	The dimension focuses on the workforce's digital competencies, training, and organizational culture.
IT & software tools Digital Data Digital security & compliance	**(3) Information technology (IT), data and security**	The dimension evaluates the company's IT infrastructure, the adoption of advanced technologies, data management, and cybersecurity practices.
Smart manufacturing Internal value chain digitalization External value chain digitalization Sales (dimension Sales and marketing)	**(4) Industrial systems and value chain**	The dimension assesses the product lifecycle, from design to sales. It covers intelligent manufacturing and the digitization of the company's internal and external value chains.
Smart portfolio & customer service Marketing (dimension Sales and marketing)	**(5) Portfolio, products and services**	The dimension focuses on the optimization of the company's products and services, based on the use of data to create an intelligent portfolio and maximize customer satisfaction.

Given that SMEs' are characterized by limited resources, the consolidation of multiple related dimensions into broader thematic categories improves the model's usability and relevance (S. Mittal et al., 2018; Re et al., 2023). For example, merging business strategy, innovation and finance into a single "Strategy and governance" dimension reflects SMEs' need for integrated decision-making frameworks that align strategic priorities with digital investments under resource constraints. Similarly, the grouping of Information Technology, data and security recognizes the technical and security challenges SMEs face when adapting digital tools and protecting assets. The focus on human resources combined with digital skills addresses the critical role SMEs play in developing workforce competencies and fostering a digital culture with limited training budgets and staff (Gökalp et al., 2022). Grouping internal and external value chain digitalization alongside smart manufacturing within "Industrial systems and value chain" supports SMEs' efforts to digitize production and supply processes holistically for competitive advantage (Kanyepe et al., 2025). The inclusion of "Portfolio, products and services" captures SMEs' imperative focus on products, services and customer satisfaction (S. Mittal et al., 2018).

- KPIs review and selection **:**

Each KPI was critically examined through a structured review process to reduce the number of indicators and thus the sub-dimensions. The research team started the refinement with individual analysis followed by collaborative sessions to discuss the relevance, overlap and measurability of each indicator. Indicators were retained, merged or deleted based on:

- Redundancy: elimination or merging indicators assessing similar aspects.
- Contextual relevance: exclusion of indicators not aligned with manufacturing practices.
- Objectivity and feasibility: exclusion of indicators that were difficult to quantify or lacked clear evaluation criteria.

This review process resulted in a refined list of 37 KPIs, reducing the total by 50%. Each was reformulated into a question with clearly defined answer choices, structured on a non-metric ordinal scale. This scale, illustrated in Figure 4.3, reflects the level of digital integration and ensures an objective assessment. Notably, each question presents different options of answers designed to provide detailed insights for assessing the SME's maturity level (see Figure 4.4). This approach ensures objectivity by avoiding generic or subjective inputs, resulting in more reliable maturity profiles.

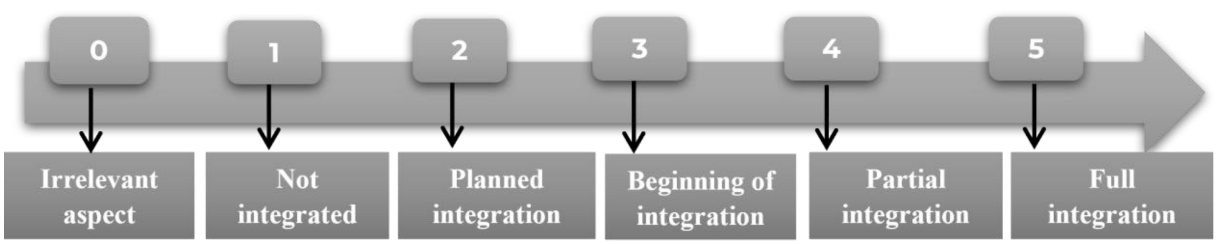
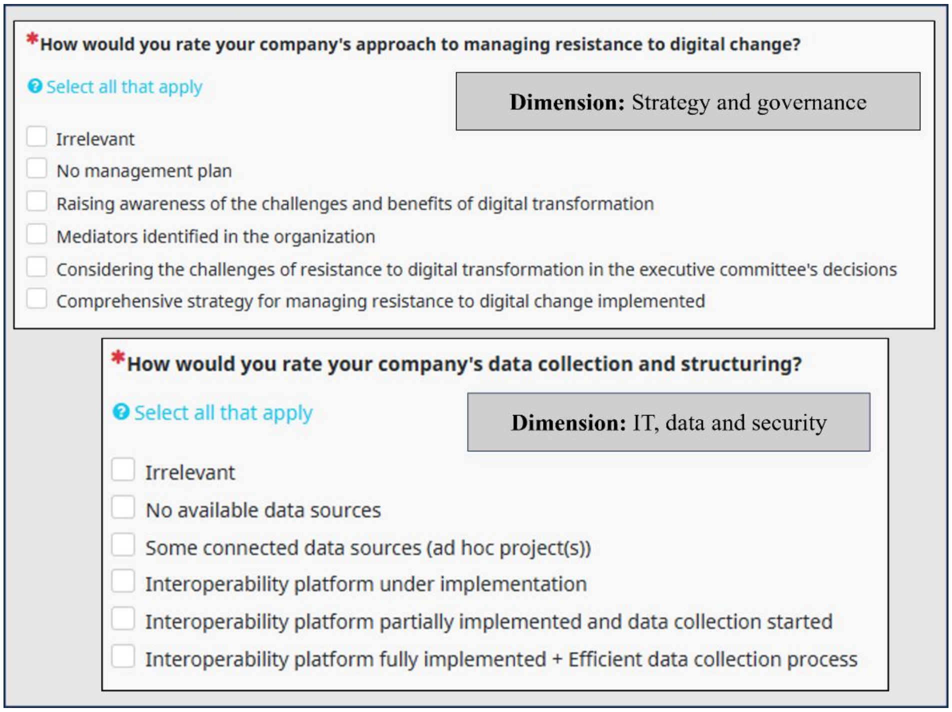


Figure 4.3 DMM's ordinal scale



*How would you rate your company's approach to managing resistance to digital change?

Select all that apply

Dimension: Strategy and governance

- Irrelevant
- No management plan
- Raising awareness of the challenges and benefits of digital transformation
- Mediators identified in the organization
- Considering the challenges of resistance to digital transformation in the executive committee's decisions
- Comprehensive strategy for managing resistance to digital change implemented

*How would you rate your company's data collection and structuring?

Select all that apply

Dimension: IT, data and security

- Irrelevant
- No available data sources
- Some connected data sources (ad hoc project(s))
- Interoperability platform under implementation
- Interoperability platform partially implemented and data collection started
- Interoperability platform fully implemented + Efficient data collection process

Figure 4.4 Examples of DMM Assessment Questions

Furthermore, all answers were designed to include a lower entry level that corresponds to the realities of SMEs, where digital maturity often begins at a very limited stage. This ensures that the developed DMM accommodates organizations starting with minimal awareness, resources or digital capabilities, thereby capturing their progression from this initial stage toward higher levels of maturity.

During this same phase, qualitative case studies were conducted in three manufacturing SMEs in Quebec, Canada. These studies ensured that the requirements identified through the literature review and addressed in the design of the DMM's dimensions, subdimensions and KPIs accurately reflected the practical challenges and realities of these companies.

4.3.1.3 Test the DMM

Following refinements from the qualitative study, the research team engaged the same three manufacturing companies in the DMM testing phase. The purpose was not to validate the model but rather to examine its comprehensibility and usability in real-world SME contexts. A researcher supervised each session to observe participants' interactions with the tool, to provide contextual explanations when needed and to record feedback on question clarity and response options.

This phase significantly improved the tool's reliability by capturing real-time usability challenges that might otherwise remain unnoticed in unsupervised scenarios. As a result, three key improvements were made: question-specific guidance was improved, answer formats were restructured for greater precision and time estimates for completing the questionnaire were optimized.

4.3.1.4 Deploy and maintain the DMM

With the DMM successfully tested, the subsequent deploy and maintain phases are planned for a future quantitative study, which falls outside the scope of this paper. These phases involve the implementation of the DMM to generate benchmark data for sector-wide digital maturity analysis and to inform the development of tailored technological roadmaps. The maintenance phase will incorporate periodic reviews to ensure the DMM remains aligned with the evolving standards of the industrial revolution, SMEs requirements and emerging digital transformation practices.

4.3.2 Qualitative study approach

To tailor the DMM to the manufacturing SMEs, its structure was refined following qualitative case studies in three companies from a medium-sized city in Quebec, Canada. The adjustments were based on the practical insights of the qualitative data, ensuring the model better reflected the operational realities of SMEs.

4.3.2.1 Methodology and case selection

The selection of the three manufacturing firms followed an opportunistic sampling, which is frequently used in qualitative research when access to companies is limited and relies on existing professional networks and the willingness of organizations to collaborate (Palinkas et al., 2015). These firms were open to participate in the study as they are actively involved, to varying degrees, in digital adoption initiatives. They were medium-sized manufacturing enterprises (100-249 employees) with over 20 years of operational experience, characteristics that align with the study's focus on SME practices. Their profiles are presented in Table 4.5.

Table 4.5 Overview of the involved SMEs in the qualitative study

Company	Sector	Activity	Size	Focus/Activity
A	Furniture	40-60 years	100-249 employees	• Manufacturer of laboratory furniture. • Structured digital transition plan initiated. • Awareness of Industry 4.0 benefits. • Active technological watch and benchmarking.
B	Plastic	40-60 years	100-249 employees	• Producer of advanced plastic components for industrial applications. • Resistance to digital transformation. • Reliance on strong market niche and unique product development. • Adoption of new technologies only with immediate ROI.
C	Aeronautics	20-40 years	100-249 employees	• Supplier of aerostructures and aerospace components. • SME operating in a large-firm-dominated sector. • Motivation to remain technologically competitive. • Commitment to Industry 4.0 adoption to secure supply chain position.

The three cases represent different levels of engagement with Industry 4.0, making them particularly suitable for discussing the challenges faced by SMEs and for testing the proposed model under diverse conditions. One company has already initiated a structured digital transition plan, another demonstrates resistance to change due to a strong product niche and a focus on immediate returns on investment, while the third operates in a highly competitive sector where staying technologically up to date is essential. This diversity provides a relevant ground to assess whether the tool is comprehensible and usable across different adoption profiles.

The case study approach was selected to gain an in-depth understanding of the challenges and opportunities of digital transformation within manufacturing SMEs. Conducting multiple case studies allowed the research team to draw a preliminary overview of the digital maturity of the participating firms and to identify missing indicators relevant to the developed DMM. The methodology follows the case study research design presented by (Yin et al., 2018), which includes six key steps, as shown in the figure below (Figure 4.5):

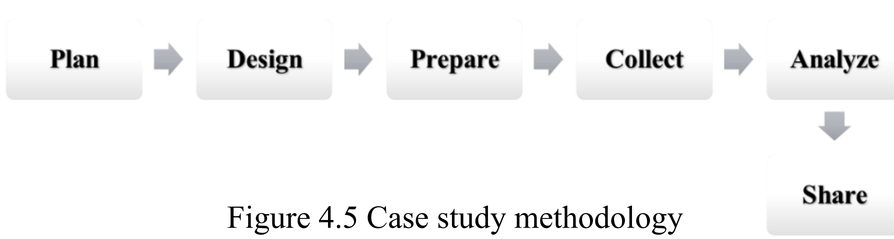


Figure 4.5 Case study methodology

During the planning phase, interviews were scheduled with six managers holding both strategic and technological roles, offering a multidimensional view of digital maturity. These interviewees were selected as they are directly responsible for decision-making or implementation related to digital transformation. Their positions allowed them to offer complementary insights: senior executives contributed strategic viewpoints on adoption priorities and long-term planning, while IT managers and coordinators provided operational perspectives on technological challenges and integration processes. This combination ensured that strategic, managerial and technological dimensions of digital maturity were represented. Table 4.6 presents the interviewees' profiles, highlighting their roles, departments, years of experience and the type of perspective they contributed.

Table 4.6 Overview of the industrial practitioners

Participant ID	Company	Role	Department	Years of experience	Interview type
P1	A	Vice president	IT	4 years	Strategy + Technologies
P2	A	Manager	IT	4 years	Strategy + Technologies
P3	B	Senior Management Controller	Production	9 years	Strategy + Technologies
P4	B	Manager	IT	4 years	
P5	C	Vice president	Technology and Innovation	13 years	Strategy aspects
P6	C	Project coordinator	IT	10 years	Technologies aspects

The purpose of conducting qualitative interviews in this study was not to ensure sector-wide representativeness, but rather to achieve data saturation with respect to SME requirements in order to refine the developed DMM. The sample of six participants was sufficient to reach thematic saturation (Guest et al., 2020). Across all interviews, participants consistently addressed similar strategic priorities, adoption barriers and mitigation strategies. This consistency was confirmed through systematic analysis of the primary interview data and triangulation with multiple secondary data sources, including company documents, national industry benchmarks and official websites (Creswell et al., 2017; Yin et al., 2018). The same key codes and patterns recurred throughout each category. This convergence reflected the typical range of SME digital transformation experiences and indicated that additional interviews were unlikely to produce substantially new findings, which aligns with established qualitative research standards (Creswell et al., 2017; Guest et al., 2020).

In the design phase, the research team selected a holistic multiple case study methodology to guide the qualitative interviews (Yin et al., 2018).

During the preparation phase, an interview guide was developed following the recommendations of Yin et al. for case study research. Consistent with his approach, the guide transparently presents the interview protocol by detailing the project description, the research question, the type of participation, the data privacy policy and the set of open-ended questions. To develop the interview questions, two researchers independently reviewed the literature on digital transformation in SMEs, synthesized their findings and consolidated them through joint discussions. These sessions aligned the insights with the dimensions and subdimensions defined in the earlier "populate" phase, ensuring theoretical consistency. The final guide was organized into five thematic categories: (1) objectives of adopting advanced technologies, (2) strategic planning tools, (3) use of advanced technologies, (4) obstacles to adoption, and (5) measures to overcome them. While these categories provided structure, the interview process remained flexible, allowing space for emerging themes and participant-driven insights. This hybrid methodology combined a literature-driven deductive foundation with an inductive, exploratory approach during data collection, enhancing the relevance of the qualitative study. The interview guide is provided in the supplementary material (Appendix C).

4.3.2.2 Data analysis

Interviews were conducted via video conferencing platforms or in person, depending on participant preference and logistical feasibility, allowing for observational insights when possible. Prior informed consent was obtained from all participants and audio recordings were made with their permission to ensure accurate data capture. Additionally, the interview protocol was reviewed and approved under the university's standard ethical procedures, ensuring compliance with institutional guidelines for human-subject data collection.

To strengthen the reliability of findings, a triangulation approach was implemented following the qualitative research recommendations (Creswell et al., 2017; Flick, 2022; Yin et al., 2018). Table

4.7 presents the different data sources used to ensure consistency. Besides interviews, data was collected from company websites, LinkedIn profiles of the six interviewees and direct on-site observations conducted by two members of the research team. Online sources provided information such as publicly available reports on company strategies and developments, descriptions of primary activities, mission and vision statements, number of employees and documented success stories in digital transformation implementation. This multi-source approach enabled to cross-validate individual perspectives with official company communications and researchers' observations of organizational practices. To further ensure validity, the findings were compared with external benchmarks from Statistics Canada's benchmarking data on advanced Information and Communication Technologies (ICT) adoption in the Canadian manufacturing sector, adding a valuable macro-level perspective to the case-specific insights and confirming that data saturation had been achieved through the six participants.

Table 4.7 Data sources and use

Type of data	Source	Use in the analysis
Semi-structured interviews	• Six industrial practitioners (strategic and IT roles) across three manufacturing SMEs.	Primary insights on strategic objectives and methods, technology adoption, obstacles and mitigation measures.
Secondary data	• Official company websites and publicly available materials • LinkedIn profiles of the interviewees • Statistics Canada ICT adoption benchmarks (dataset)	• Validation of firm positioning, technological initiatives and strategic communications. • Cross-checking roles, responsibilities and career trajectories to confirm positions and perspectives. • Macro-level validation and contextualization of firm-level practices within industry-wide trends. • Confirmation of data saturation, as no additional aspects emerged beyond the primary data.
Observations	• On-site visits by two researchers	Validation of digital practices, organizational routines, and resource allocation observed in practice.

All recorded interviews were transcribed and served as the primary dataset for analysis. The coding process was carried out using QDA Miner, a qualitative data analysis software designed to systematically organize, annotate and retrieve textual data. To ensure analytical rigor, two researchers did the coding process independently.

The analytical approach employed a hybrid (inductive and deductive) thematic analysis (Swain, 2018). The deductive components are the five broad categories pre-identified in the interview guide. Within these categories, first and second order codes were developed inductively through iterative examination of the transcribed interviews, company documents, professional profiles and real observations, adhering to established qualitative research coding (Saldana & Omasta, 2016).

After the independent coding sessions, the two researchers engaged in iterative consensus meetings to compare their coding outputs, discuss and resolve discrepancies, refine code definitions, and merge codes into the five predefined categories. This structured consensus-building process, which leverages investigator triangulation, is recognized as an appropriate strategy for ensuring intercoder agreement in qualitative content analysis, particularly when multiple coders apply common category systems and prioritize rich, negotiated interpretations (O'Connor & Joffe, 2020; Saldana, 2021).

First, the process resulted in 107 distinct first-order codes that captured granular features of digital transformation, practitioner challenges and strategies across the sample firms. Subsequently, through collaborative and iterative sessions, the first-order codes were grouped into 34 second-order codes that represented broader themes and recurring patterns across the dataset. Throughout the coding process, the researchers used constant comparison and triangulated with secondary data available online (presented in Table 4.7) which helped identify patterns, variations and relationships within the data. This iterative approach was crucial for refining the analytical structure and confirming theme consistency, aligning with recommendations for intercoder reliability in qualitative content analysis (Creswell et al., 2017; Krippendorff, 2018). The final data structure, including first-order codes, second-order codes and final categories, is presented in Appendix A.

The adoption of the hybrid coding strategy enabled both confirmation of anticipated themes and analytic flexibility, balancing theoretical structure with emergent understandings and reinforcing the reliability and validity of findings (Swain, 2018).

The final phase included synthesizing and sharing the results that led to two main outcomes. First, an overview of digital maturity levels across the manufacturing SMEs sample and second, evidence-based refinement to the DMM based on the data analysis findings.

The following section presents the key findings from the qualitative study, revealing critical insights into digital maturity challenges and opportunities within the Canadian SMEs manufacturing context.

4.4 Qualitative study results

The multiple case studies analysis revealed five key thematic categories regarding digital transformation in manufacturing SMEs:

1. *Objectives of adopting advanced technologies*
2. *Strategic planning tools*
3. *Use of advanced technologies*
4. *Obstacles to the adoption of advanced technologies*
5. *Measures taken to reduce digital transformation obstacles*

4.4.1 Objectives of adopting advanced technologies

The participating SMEs demonstrated a strong awareness of the strategic value of digital transformation. Figure 4.6 presents the results of the objectives discussed during the five interviews. The primary motivations included process improvement and operational flexibility, strengthening competitive positioning and enhancing productivity.

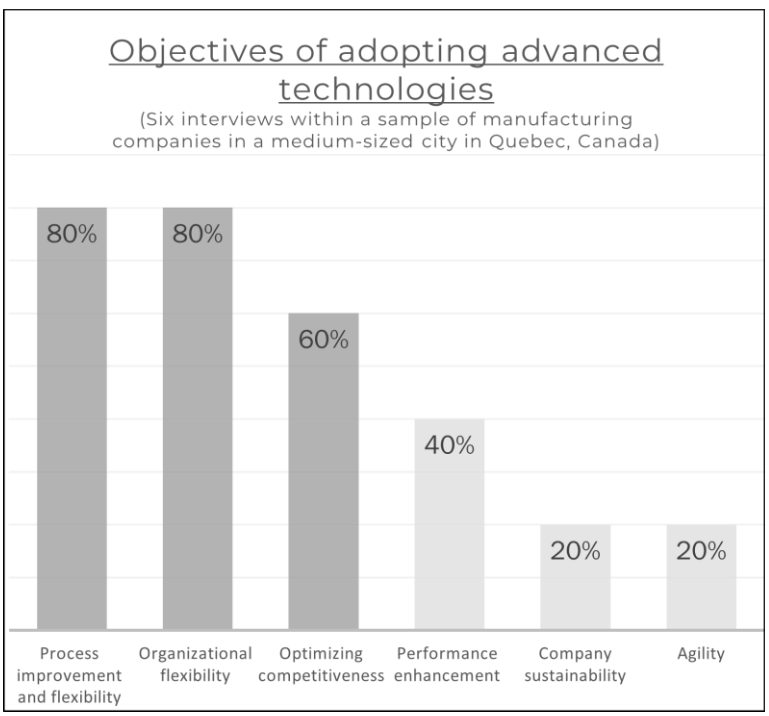


Figure 4.6 Objectives of adopting advanced technologies in manufacturing SMEs

Their objectives were closely aligned with the national manufacturing trends (Statistics Canada, 2023b). However, according to Statistics Canada, one of the primary objectives driving the adoption of emerging technologies among SMEs is compliance with regulatory standards, including those related to sustainability. This objective records the highest percentage among reported achieved goals within the national dataset. Although specific data for SMEs in Quebec is not available, the percentages observed across all types of enterprises in the province are consistent with national trends (Statistics Canada, 2023b). However, this objective was mentioned in the interviews as a significant challenge during the technology adoption process, rather than a goal.

Overall, the analysis highlights that the manufacturing companies recognize digital transformation as a competitive necessity rather than a simple technological upgrade.

4.4.2 Strategic planning tools

Figure 4.7 shows that the participating manufacturing SMEs are aware of the importance of evaluating their ecosystem (including partners and competitors) before developing strategic plans, particularly to stay up to date with technological advancements. In addition, they usually assess internal resources to identify needs related to management systems and digital skills. However, decision-making continues to be largely traditional. It’s typically driven by executive committees with limited use of technological roadmaps, no implementation of digital audit practices and reliance on ad hoc and experience-based planning.

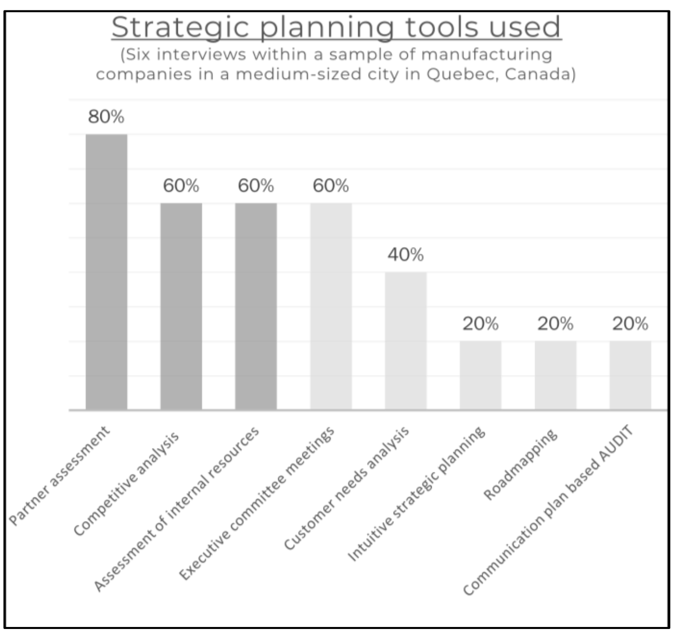


Figure 4.7 Strategic planning tools used in manufacturing SMEs

This reveals a critical gap between strategic awareness and methodological execution in digital transformation planning. Decisions are often made without structured processes, increasing the risk of inefficiencies and missed opportunities.

4.4.3 Use of advanced technologies

The case studies reveal that participating SMEs have started the adoption of Industry 4.0 technologies, though the level of implementation varies significantly depending on the type of technology. As shown in Figure 4.8, the most widely adopted technologies include cloud computing, artificial intelligence, cybersecurity and big data analytics.

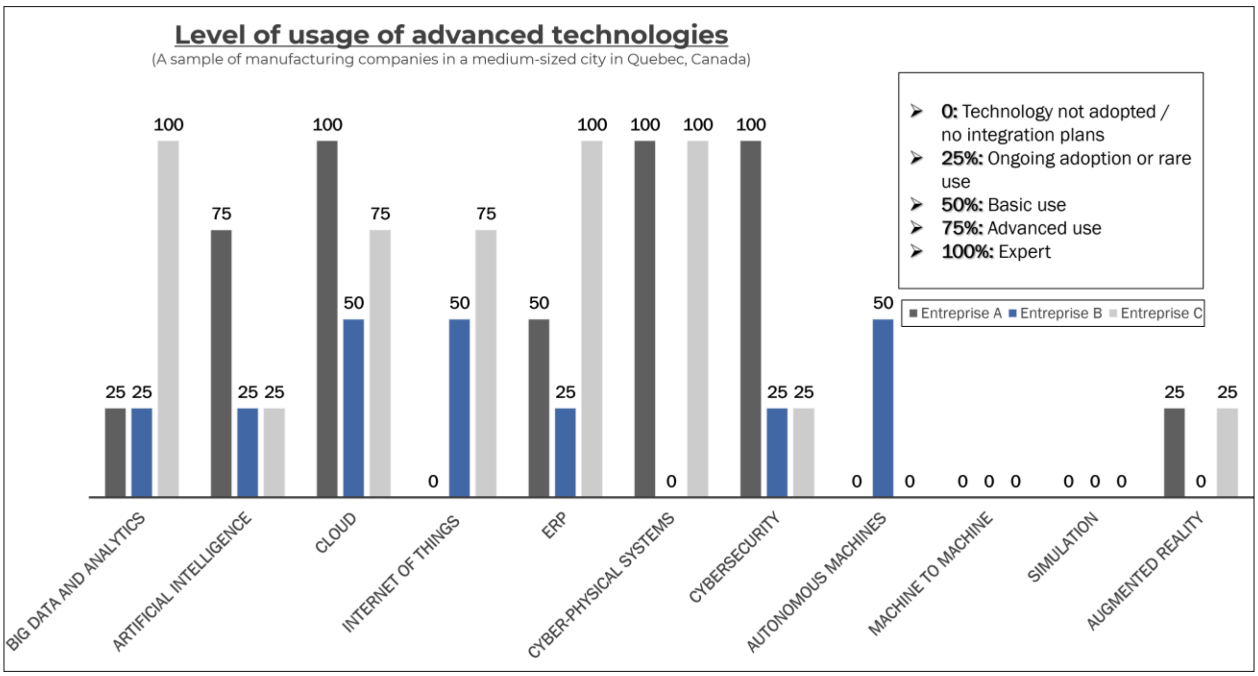


Figure 4.8 Level of usage of advanced technologies in manufacturing SMEs

These findings align with provincial trends (Statistics Canada, 2024), where business intelligence technologies (AI, analytics and security systems) are among the most implemented digital solutions. However, the level of advancement in usage remains uneven. Cloud computing, for example, is the most widely adopted technology, but its use is often limited to basic applications.

However, the highest rate in Statistics Canada's data corresponds to companies using advanced technologies in material handling, supply chain and logistics. Although tools like Enterprise Resource Planning (ERP) systems are not classified as emerging technologies (Danjou et al., 2017), they are still frequently cited by companies as key technology adoption. Yet, the use of ERPs also varies, indicating that value chain integration remains incomplete.

In contrast, more advanced technologies, such as the Internet of Things (IoT), cyber-physical systems (CPS), autonomous machines, augmented reality and digital twins, are still at early stages of adoption. These findings suggest that while foundational technologies like cloud computing and cybersecurity are increasingly adopted, more complex Industry 4.0 technologies are still not widely implemented across SMEs.

4.4.4 Obstacles to the adoption of advanced technologies

The study identifies several challenges contributing to the low adoption rates of Industry 4.0 technologies within SMEs, with human capital emerging as the most significant barrier.

Key obstacles (Figure 4.9) include resistance to change, lack of employee training and the complexity of integrating Industry 4.0 within existing processes. Additional challenges involve low return on investment or extended payback periods, compliance with effective data management, and priority management, where heavy workloads limit employees' ability to engage in digital training. Companies also face difficulties in recruiting qualified personnel, managing digital projects and effectively leveraging external support.

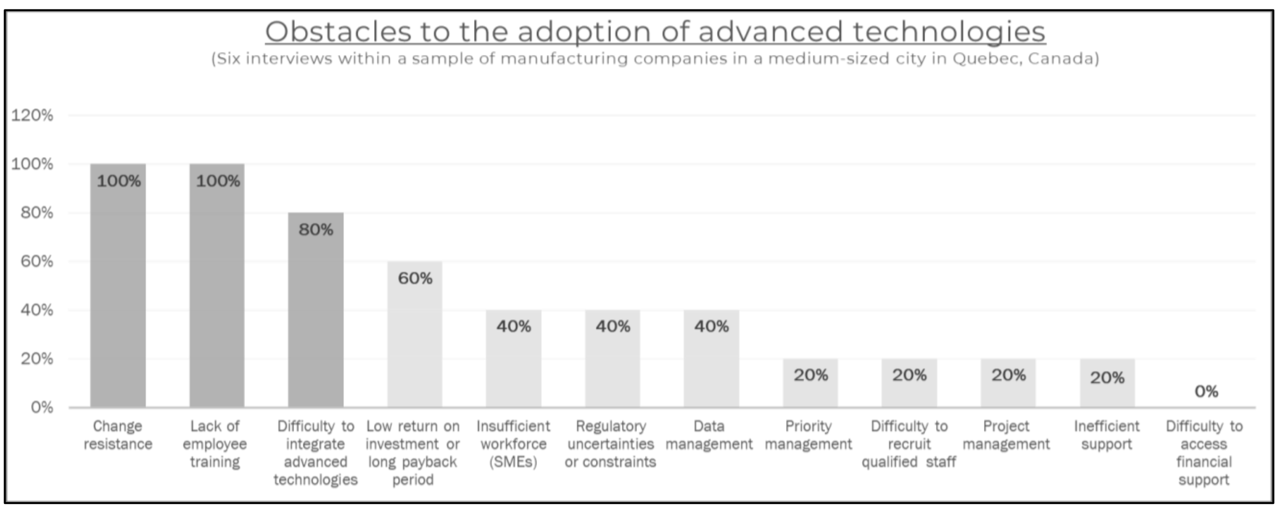


Figure 4.9 Obstacles to the adoption of advanced technologies in manufacturing SMEs

Overall, the findings highlight that organizational and operational factors, particularly those related to human resource development, remain the most persistent barriers to successful technology adoption.

4.4.5 Measures taken to reduce digital transformation obstacles

Recognizing human factors as the primary challenge to digital transformation, the participating SMEs have made considerable efforts to mitigate this obstacle. Data analysis revealed two predominant approaches (Figure 4.10), both of which are also reflected in national trends (Statistics Canada, 2023a):

- The deployment of employee training programs to enhance technical skills.
- The implementation of strategic partnerships including collaborations with technology providers, academic institutions (notably with university researchers involved in this study) and broader ecosystem engagement.

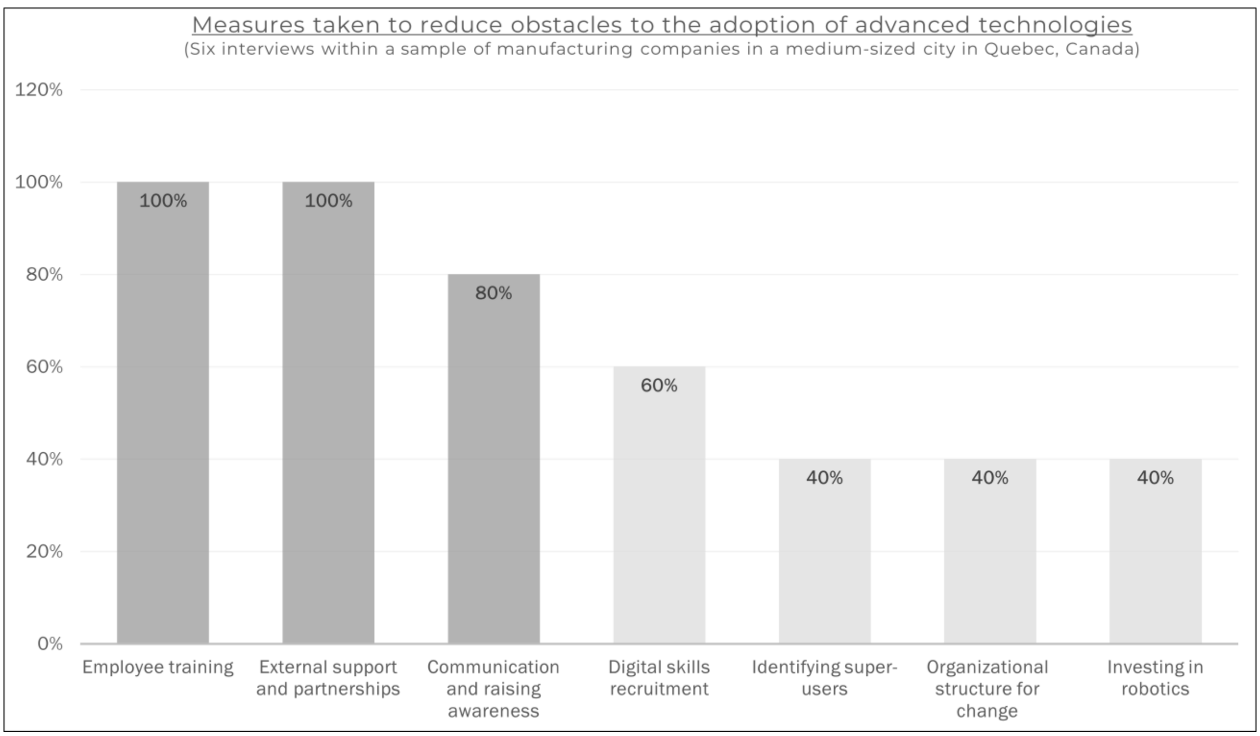


Figure 4.10 Measures taken to reduce digital technologies obstacles in manufacturing SMEs

These initiatives highlight the value of external expertise to effectively manage emergent technologies.

Furthermore, Figure 4.10 illustrates that effective communication and awareness raising efforts are essential for engaging employees in digital transformation, reducing resistance to change and fostering a culture of innovation. Rather than merely enduring change, employees are encouraged to take an active role in the transition process.

Other initiatives include recruiting professionals with digital skills, identifying internal "super-users" to strengthen team capabilities, adopting digital-friendly organizational structures and investing in automation to address labor shortages and transform the processes.

Together, these measures illustrate that successful digital transformation depends on both human capital development and organizational restructuring, with external partnerships acting as key enablers of technology adoption.

The findings from the multiple case studies provide a preliminary assessment of the digital maturity within the selected sample of the manufacturing SMEs in the Canadian context. The following section analyzes these results in relation to existing literature and discusses their implications for the development of the Digital Maturity Model.

4.5 Discussion and conclusion

The multiple case studies conducted with the manufacturing SMEs confirm the challenges and requirements identified in the literature on Industry 4.0 adoption. As previous research highlighted, SMEs struggle with limited financial resources, fragmented knowledge and constrained technological capabilities (Masood et al., 2020; Mittal et al., 2018). The case studies in this research validated these observations: although SMEs reveals a strong awareness of the strategic value of digital transformation and align their objectives with broader industrial strategies (Jayson Myers, 2019), they continue to face significant barriers especially regarding the organizational and human factors. Resistance to change, lack of engagement and limited digital readiness were recurrent themes across the participating firms. A clear gap persists between awareness and implementation demonstrated by the slow integration of available Industry 4.0 technologies. These findings corroborate the literature (Masood et al., 2020; Mittal et al., 2018) and align with national results identified by Supply Chain Canada (Chen et al., 2021; Supply Chain Canada (SCC) - National, 2023).

In line with the case study findings, several factors can be conceptualized as mediators and moderators influencing the relationship between technology adoption and digital transformation outcomes in SMEs. Mediators include human capital development, organizational culture and awareness, structured strategic planning and external partnerships, which facilitate the translation of technology adoption into operational and strategic benefits (Baojing et al., 2025; Kampoowale et al., 2025; Merín-Rodrigáñez et al., 2024; Sutrisno, 2023). Moderators include regulatory and compliance requirements, technology complexity, resource availability (particularly financial recourses), change management and existing operational infrastructure, which may strengthen or weaken the impact of technology adoption on transformation outcomes (Rahman et al., 2025; OECD, 2021; Succurro & Donati, 2025; Klarner et al., 2025). These insights highlight the importance of considering both internal and external factors when evaluating SME digital maturity.

Building on these observations, the interviewed SMEs recognize the challenges of digital transformation and are actively working to achieve higher maturity levels. This research contributes by providing guidance through this process, addressing the following research question: "***What are the key features of a Digital Maturity Model designed to reliably evaluate SMEs' digital maturity in the manufacturing sector?***" The findings from both the literature review and case studies converge on several essential features that our model incorporates.

First, the model integrates lower entry maturity levels, ensuring that SMEs beginning their digital journey can be reliably assessed. This addresses a major limitation of existing models, which often assume advanced digital capabilities (Mittal et al., 2018). The case studies revealed that SMEs frequently initiate digital adoption through incremental, short-term solutions rather than comprehensive strategies, highlighting the importance of capturing early stages of maturity within the assessment tool.

Second, the model adopts a multidimensional structure that covers strategy, governance, skills, technology, value chain integration, customers and products. The consolidation of dimensions, guided by the literature, was confirmed in practice through the case studies. This multidimensional view ensures that maturity is not assessed through technology alone, but also through organizational and cultural readiness, as recommended by prior critical reviews (Mittal et al., 2018; S. Mittal et al., 2018; Re et al., 2023).

Third, the model emphasizes practical usability and contextual relevance. The case studies refined its indicators and sub-dimensions to reflect the realities of the manufacturing SMEs. For example, indicators were added to the "Strategy and Governance" dimension to address the specific needs of manufacturing companies, while the "IT, Data and Security" dimension was revised to ensure comprehensive coverage of emerging technologies (Danjou et al., 2017). These refinements helped to enhance the model beyond theoretical frameworks and adapt it to the manufacturing SMEs. During pilot testing, question clarity, response options and additional guidance were improved, resulting in a final average completion time of 20 minutes, in line with standards for digital maturity assessments.

Fourth, the model advances beyond descriptive evaluation to provide prescriptive value (de Bruin et al., 2005). The developed DMM offers insights into an SME's current digital maturity but also provides a structured foundation for creating digital roadmaps using the objective assessment with ordinal scales and detailed response options that move beyond generic or opinion-based inputs to generate reliable maturity profiles. Future work will focus on developing a multi-criteria approach to calculate a digital maturity score, offering a comparative value to position SMEs within their ecosystem and support their digital transition journey.

The final version of the developed DMM consists of five dimensions, 34 sub-dimensions and 49 indicators transformed into a survey of 38 questions, with four additional questions to identify the participating company's characteristics. This structure is presented in Appendix B. The model is ready for dissemination to start the quantitative study phase.

From an academic perspective, this research provides a replicable and adaptable approach for evaluating digital maturity in SMEs and fostering innovation in manufacturing ecosystems. From a managerial perspective, it provides SMEs with a reliable, time-efficient and accessible tool to guide strategic decision-making in digital transformation.

However, the model still has some limitations. It was specifically designed for manufacturing SMEs, which may limit its applicability in more generic contexts. As a result, certain indicators may be less relevant or too simplistic for large enterprises. Another significant limitation relates to the emergence of the Fifth Industrial Revolution (Industry 5.0). While Industry 4.0 focuses on creating agile companies that leverage new technologies to adapt to changing environments, Industry 5.0 takes a different approach by considering human as the pillar of digital transformation and integrating social, societal and environmental considerations (Joblot et al., 2023). This raises an important research question: Would a company aligned with Industry 5.0 principles be more effective than one classified as a top performer in Industry 4.0?

Despite these limitations, the study presents a collaborative and holistic approach to develop a Digital Maturity Model capable of capturing the specific needs of SMEs. By explicitly incorporating their strategic and resources constraints, the model provides a basis for both assessing current maturity and guiding digital transformation.

CHAPITRE 5 ARTICLE 2: DESIGNING A MULTI-CRITERIA APPROACH TO MEASURE THE DIGITAL MATURITY SCORE OF MANUFACTURING SMES

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Authors' contributions: *Syrine Njah* led the conceptualization of the paper, the original draft writing, the literature review, the methodology design, the data collection and analysis, and the project administration. *Christophe Danjou* and *Fabiano Armellini* supervised the project and the paper, guided the development and the implementation of the methodology, validated the results and contributed to the writing of the original draft.

Abstract

Purpose: This study introduces a hybrid, reliable approach to digital maturity assessment in manufacturing SMEs. Existing Digital Maturity Models (DMMs) often rely on subjective evaluations and simplified scoring methods that overlook methodological rigor and interdependence between maturity dimensions. These limitations are critical for SMEs, navigating complex digital transitions with limited resources.

Design/methodology/approach: The study employs a Multi-Criteria Decision-Making (MCDM) approach, combining expert input and objective weighting. Eight qualitative criteria were identified through a literature review to assess five digital maturity dimensions, using a modified Delphi process. Expert evaluations were validated using the Rényi entropy method. Sensitivity analysis confirmed results robustness.

Findings: Findings show "Strategy and governance" and "HR and digital skills" as the most influential dimensions, representing over 50% of the maturity score, while "IT, data, and security" ranked lowest. Sustainability and innovation appeared underweighted, reflecting SMEs' short-term focus on efficiency and competitiveness.

Research limitations: The findings are limited by the SME specific context and expert panel composition. Researchers are encouraged to validate the approach in larger contexts.

Practical implications: For SMEs practitioners, this study provides a practical tool to assess digital maturity, identify gaps and prioritize transformation. With standardized dimensions and KPIs weights, it supports targeted resource allocation and digital roadmap design.

Originality/value: This research introduces a novel hybrid MCDM methodology, advancing digital maturity assessment by addressing the dual issues of subjectivity and methodological rigor that limit existing DMMs.

Keywords: Digital Maturity Model (DMM); Industry 4.0; Manufacturing SME; Multi-Criteria Decision-Making (MCDM); Modified Delphi; Rényi Entropy.

5.1 Introduction

In the Industry 4.0 era, organizations are increasingly challenged to implement complex digital transformations that demand both technological and organizational adaptation. For small and medium-sized enterprises (SMEs) in the manufacturing sector, this transformation is particularly problematic due to constrained financial and human resources, as well as limited strategic and technological flexibility (Mittal et al., 2018; Schumacher et al., 2016). As a result, assessing digital transformation progress has become a critical concern for both practitioners and researchers (Teichert, 2019).

Digital maturity has emerged as a key metric for evaluating and guiding digital transformation efforts. It reflects not only an organization's readiness to adopt advanced technologies but also its ability to integrate them across interconnected dimensions such as strategy, culture, operations, and technological infrastructure (Chanias et al., 2016; Rossmann, 2019). Assessing digital maturity offers a structured way to benchmark current capabilities, identify improvement areas and guide the progressive implementation of Industry 4.0 strategies (Mittal et al., 2018; Schumacher et al., 2019).

In this context, numerous Digital Maturity Models (DMMs) have been developed to support such assessments (Cognet et al., 2023; Colli et al., 2018; Gökalp et al., 2022). They typically decompose digital maturity into a set of dimensions and sub-dimensions, evaluated through measurable items or key performance indicators (KPIs) (Cognet et al., 2023). However, these components are highly interdependent and overlooking their interconnections risks producing fragmented insights that fail to capture all the aspects of Industry 4.0 (Cognet et al., 2023; Schumacher et al., 2019).

Despite their widespread adoption, existing DMMs exhibit notable methodological and practical limitations. Many provide descriptive frameworks that categorize organizations across maturity levels but lack quantitative rigor and theoretical grounding in their scoring methods (Bley et al., 2024; Cognet et al., 2023; Gökalp et al., 2022). Moreover, empirical studies reveal that only a minority of models provide post-assessment roadmaps or actionable recommendations (Gökalp et al., 2022; Mittal et al., 2018). The absence of objective scoring approaches and contextual sensitivity compromises the credibility of maturity evaluations (Gökalp et al., 2022).

For manufacturing SMEs, the Industry 4.0 strategies require approaches that are both resource-efficient and context-sensitive, while also delivering reliable maturity scores to help prioritize transformation initiatives (Mittal et al., 2018). Models that capture interdependencies across dimensions enable more holistic and objective assessments and the development of practical technological roadmaps (Schumacher et al., 2019).

To bridge these gaps, this study proposes a multi-criteria approach designed to generate reliable digital maturity scores for manufacturing SMEs. It conceptualizes maturity as interrelated dimensions and integrates subjective and objective weighting methods with sensitivity analysis to produce credible results.

The paper is structured as follows : **Section 5.2** reviews the theoretical foundations supporting the development of this approach. **Section 5.3** details the methodology used to create the scoring framework, which is applied to an existing DMM designed to assess manufacturing SMEs. **Section 5.4** presents the results of the weighting process, and **section 5.5** discusses the implications of the approach, as well as its limitations.

5.2 Theoretical background

5.2.1 Digital Maturity Models and their critical gaps

Maturity models are widely used instruments for assessing the extent to which an organization, process or a system has achieved a defined level of capability, completeness, or optimization with respect to a specific target state (Schumacher et al., 2016). DMMs serve as tools to assess how organizations leverage digital technologies to optimize processes, innovate, and align strategic goals with ongoing digital change (Aslanova et al., 2020; Kane, 2017, Njah et al, 2025)

Typically, DMMs examine multiple organizational dimensions, such as strategy, culture, technology infrastructure, processes, and workforce competencies, to provide a holistic perspective of the digital transformation stage (Cognet et al., 2023; Schumacher et al., 2019). These models allow organizations to benchmark their progress across incremental maturity levels and identify improvement areas (Berghaus et al., 2016; Haryanti et al., 2023). These levels generally describe a continuum from initial awareness or experimentation to full digital integration and optimization. For instance, the Industry 4.0 Readiness Online Self-Check for Business developed by the IMPULS Foundation of the German Engineering Federation (VDMA) evaluates an organization's readiness across six dimensions: "Strategy and Organization," "Smart Factory," "Smart Operations," "Smart Products," "Data-Driven Services," and "Employees". The tool positions firms from 0 (Outsider) to 5 (Top Performer), facilitating benchmarking and gap identification against peer organizations. Likewise, the Industry 4.0 Maturity Index (Schuh et al., 2020) delineates a six-phase trajectory from basic computerization to digital adaptability, structured around four pillars: "Resources," "Information Systems," "Organizational Structure," and "Culture".

Despite their utility, existing DMMs exhibit notable conceptual and methodological limitations. Empirical studies reveal that only a minority of models provide post-assessment roadmaps or actionable recommendations, such as detailed transformation roadmaps or technology adoption paths, leaving SMEs without clear transformation pathways (Gökalp et al., 2022; Mittal et al., 2018). Consequently, organizations often receive maturity scores without concrete directions for capability development or prioritization of strategic initiatives.

Moreover, the scoring methodologies employed in most DMMs are oversimplified, relying on additive or ordinal averaging that fails to reflect the multidimensional and interdependent nature of digital maturity (Bley et al., 2024; Cognet et al., 2023; Gökalp et al., 2022). This simplicity not only undermines measurement precision but also limits model reliability and theoretical grounding. Teichert, (2019) also emphasized that many DMMs neglect qualitative dimensions such as organizational culture and employee engagement. Furthermore, Mittal et al., (2018) highlight that existing models are generic or sector-specific which lack contextual relevance for some companies, in particular SMEs. Additionally, Gökalp and Martinez, (2022) emphasize that few models are empirically validated or grounded in standardized measurement frameworks, resulting in limited credibility and replicability across contexts.

Recognizing these gaps, Njah et al, (2025) developed a tailored DMM for manufacturing SMEs. The model was empirically derived from a systematic comparative analysis of existing DMMs, where the integration of additional models was discontinued once redundancy among digital maturity dimensions was identified, thereby ensuring comprehensive yet non-redundant coverage

(Cognet et al., 2023). Their study also focused on capturing the contextual specificities of SMEs. Building on this foundation, the present study advances their work by employing their tailored DMM to address the absence of post-assessment improvement guidance and the reliance on oversimplified scoring methodologies.

5.2.2 Digital Maturity Models in guiding technological roadmaps

Prior to this study, a systematic review was conducted to confirm the need for a rigorous approach to quantify digital maturity components, enabling companies to gain a reliable digital assessment. The review addressed the research question: **"*What elements enable a Digital Maturity Model to effectively guide the design of a technological roadmap for Industry 4.0 strategy implementation?*".**

The review process followed the PRISMA methodology (Liberati et al., 2009) which ensures transparency and reproducibility in the reporting of systematic reviews. The process included four main phases: identification, screening, eligibility and inclusion, as illustrated in the PRISMA flow diagram (Figure 5.1).

In the identification phase, relevant records were retrieved from the Compendex and Web of Science databases using a search protocol combining keywords related to *Industry 4.0*, *digital maturity models*, *strategy* and *technological roadmap* (Table 5.1). Boolean operators and multiple search combinations were employed to maximize coverage and minimize bias. The inclusion criteria focused on journal articles or reviews and conference papers written in English that explicitly addressed how DMMs guide the design of technological roadmaps for Industry 4.0 implementation.

During the screening phase, duplicates were removed, and the remaining articles were assessed for relevance based on their titles and abstracts. Records that did not align with the research question or were not accessible were excluded according to the predefined exclusion criteria (Table 5.2).

In the eligibility phase, the full texts of the remaining studies were reviewed in depth to verify their alignment with the inclusion criterion (Table 5.2). This phase ensured that only studies focusing on the relationship between digital maturity assessment and strategic Industry 4.0 implementation through roadmaps were retained.

Finally, the inclusion phase resulted in a set of seven papers deemed most relevant.

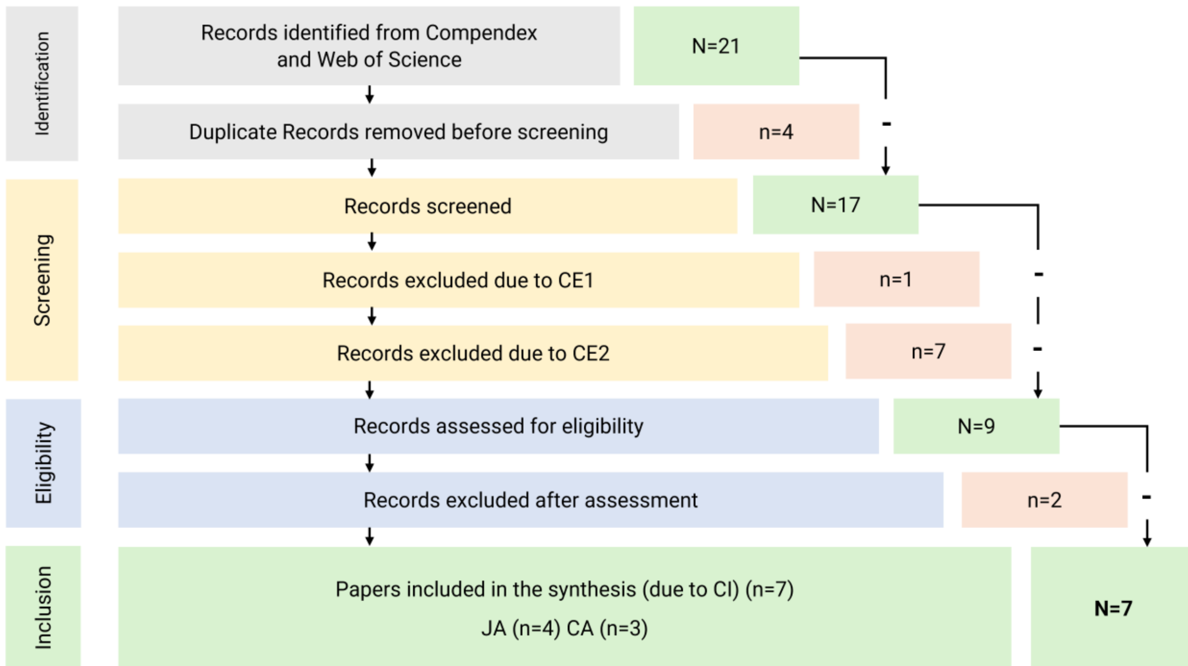

Figure 5.1 PRISMA flow diagram

Table 5.1 Search protocol

Search protocol	
Data information source	Compendex and Web of Science
Search terms	Industry 4.0 = ("Industrie 4.0" OR "Industry 4.0" OR "Industrial 4.0" OR "Industrial Internet" OR "Industrial Internet of things" OR "Smart production" OR "Manufacturing 4.0" OR "Smart factory" OR "smartfactoty" OR "Factor* of the future" OR "Advanced manufacturing" OR "Intelligent manufacturing" OR "Industri* of the future" OR "High value manufacturing" OR "Smart industry" OR "Integrated industry" OR "Digital factory" OR "Manufacturing renaissance" OR "Digital manufacturing" OR "Make in India" OR "Made-in-China 2025" OR "chinese Manufacturing 2025" OR "smart industry")
	Strategy = (strategic management or "strategic planning" or "strategic thinking" or "open strategy" or "technolog* + strategy" or "Business transformation")
	Roadmap = (Roadmap*)
	Digital maturity = (Digit* Maturity OR Digit* Transform* OR "Digit* Readiness" OR "Digit* Evolution" OR "Digit* Capabilit*" OR "Digit* Competence*" OR "IT Maturity" OR "Technolog* Maturity" OR "Industry 4.0 Maturity" OR “Industry 4.0 Readiness”)
	Model = (Model* OR "Tool" OR "Framework" OR "Instrument" OR "Questionnaire" OR "Survey" OR "Poll")
Documents type	Article (journal and conference) or review
Language	English

Table 5.2 Eligibility criteria for the systematic review

Criteria type	Code	Description
Exclusion	CE1	The full text of the document is not accessible.
	CE2	The paper doesn't fit the research scope
Inclusion	CI	A roadmap's design guided by a DMM to support Industry 4.0 strategy implementation is the main subject reviewed or discussed.

The retained papers presented in Table 5.3 consistently emphasize the critical need for more objective tools, such as DMMs, roadmaps and structured transition plans, to improve the reliability of digital maturity assessments and ensure effective digital transformation strategies.

Table 5.3 Reviewed papers and citations

Reference	Document Type	Citations
(Mittal et al., 2018)	JA*	1237
(Schumacher et al., 2019)	CA**	321
(Colli et al., 2019)	JA	173
(Ghobakhloo et al., 2022)	JA	153
(Kaya et al., 2023)	JA	5
(Norouzi et al., 2023)	CA	1
(Santiago & Silva, 2023)	CA	0

*JA: Journal Article ; **CA: Conference Article

Two common limitations were identified across studies. The first one is the lack of contextual validation mechanisms, where many existing DMMs fail to consider the specific context of organizations. Mittal et al., (2018) discuss industry-specific challenges, pointing out that the standardization of DMMs often conflicts with the realities faced by SMEs, including resource constraints, organizational structure and access to advanced technologies. Schumacher et al., (2019) and Colli et al., (2019) emphasize that without considering an organization's internal environment, such as its strategic goals or organizational culture, DMMs may not provide meaningful insights into aligning digital transformation efforts with long-term objectives.

The second common limitation is the lack of standardized quantitative measures. Mittal et al., (2018) highlight that many existing models rely on self-assessment methods that are inherently subjective. Such tools often fail to provide clear metrics or scoring systems, making it difficult to compare organizations or track progress. This issue is further confirmed by Ghobakhloo et al., (2022), Kaya et al., (2023) and Santiago and Silva, (2023), who note that the lack of standardized quantitative measures leaves organizations without clear guidance on where to focus their digital transformation efforts and that benchmarking against industry peers becomes a challenge.

Without the ability to accurately assess maturity, track progress and consider the company's context, organizations may face challenges in effectively implementing digital strategies (Mittal et al., 2018). They may struggle to identify the gaps that need to be addressed or fail to understand how well they are progressing toward Industry 4.0 (Schumacher et al., 2019).

This paper addresses one of the identified gaps in existing digital maturity assessment approaches and proposes the following research question: "***What methodological approach can be used to establish standardized quantitative measures for digital maturity?***" This question guides the development of a structured approach to quantify digital maturity, aiming to provide organizations with reliable and comparable metrics for Industry 4.0 implementation. The following section presents the digital maturity scoring methodologies currently used in the literature, highlighting their limitations and the resulting need for a more comprehensive and standardized methodology.

5.2.3 Digital Maturity scoring methodologies

While iterative evaluation processes could provide structured approaches for gap analysis and roadmap development, their effectiveness depends on robust scoring methods to accurately measure current and target maturity levels and define strategies that address the identified gaps (Colli et al., 2019; Norouzi et al., 2023; Schumacher et al., 2019).

Table 5.4 summarizes recent methodologies for calculating digital maturity scores, highlighting key variations in criteria identification (expert-driven, literature-based, or hybrid approaches), weight assignment (subjective or objective measurements), and validation using sensitivity analysis to ensure robustness.

As one can see, the Analytic Hierarchy Process (AHP) is the most widely used method in digital maturity research, appearing in six out of twelve reviewed studies. AHP is a structured MCDM approach that prioritizes digital maturity criteria through a hierarchical framework to determine their relative weights (Samaranayake et al., 2017).

However, this same table highlights a key limitation: AHP is predominantly subjective, which can introduce biases if not complemented with objective measures. To address this issue, researchers have increasingly integrated AHP with other methodologies to balance expert-driven qualitative insights with quantitative modeling, enhancing reliability. For example, Zhu et al., (2024) employed an AHP-DEMATEL (Decision-Making Trial and Evaluation Laboratory) hybrid approach to evaluate construction enterprises' digital maturity, deriving criteria weight through expert judgments and literature-based standards while mapping causal relationships between factors like digital strategy and organizational capabilities. Similarly, the Rényi Entropy method has been integrated into MCDM frameworks to address uncertainty in subjective evaluations. Görçün et al., (2024) combined entropy-derived weights, calculated from expert judgments and objective metrics, with fuzzy logic to create a hybrid maturity score. This approach mitigates biases inherent in subjective methods while incorporating measurable benchmarks, making it particularly effective for assessing digital maturity in dynamic environments. Another example is Durek et al., (2018) who integrated the Analytic Network Process (ANP) with the qualitative Decision Expert (DEX) method to assess higher education institutions, where quantitative weights from ANP were cross validated against qualitative decision rules to ensure robustness.

In conclusion, while commonly used MCDM methods remain predominantly subjective, relying heavily on expert panels or self-assessment surveys, recent frameworks increasingly aim to complement these with objective metrics. However, Table 5.4 shows that most of existing methodologies still fail to fully address the standardized quantitative measures necessary for calculating a reliable and comparable maturity score. This gap leaves organizations without clear benchmarks to track progress or compare their maturity levels against industry standards.

This paper proposes a refined scoring methodology that integrates a MCDM method based on the Brown-Gibson approach, (1972), combined with a modified Delphi study (Schneider et al., 2016; Shang, 2023), and the Rényi entropy method (Görçün et al., 2024). This approach integrates objective measures with subjective insights, leveraging criteria defined through a comprehensive literature review and validated by expert input. Furthermore, the methodology is refined through a sensitivity analysis to ensure the reliability and robustness of the resulting maturity score.

Table 5.4 Overview of existing digital maturity scoring methodologies

Reference	Sector	Used Method	Criteria Identification		Digital Maturity Measurement		Sensitivity Analysis
			Literature	Expert Opinion	Subjective Measurement	Objective Measurement	
(Samaranayake et al., 2017)	Manufacturing	Q-Sort + AHP	✓	✓	✓		
(Akman & Kökümer, 2023)	Home Appliances	MACBETH, EDAS + TOPSIS, VIKOR, SAW	✓	✓	✓	✓	
(Büyüközkan & Güler, 2018)	Banking	HFL, AHP and ARAS		✓	✓	✓	
(BENTAHER, 2023)	Automotive	Best-Worst	✓		✓		
(Zhu et al., 2024)	Construction	AHP-DEMATEL	✓		✓	✓	✓
(Durek et al., 2018)	Education	ANP-DEX	✓	✓	✓		
(Brodny & Tutak, 2021)	Country (Comparative)	Entropy + TOPSIS, MOORA, VIKOR	✓			✓	
(Büyüközkan et al., 2021)	Airline	AHP & VIKOR	✓	✓	✓		✓
(Martins et al., 2023)	Food Industry	AHP & TOPSIS	✓		✓		
(A. Mittal et al., 2022)	Manufacturing	AHP	✓		✓		
(Görçün et al., 2024)	Automotive	PFS, Renyi Entropy & CoCoSo	✓	✓	✓	✓	✓
(Kaya et al., 2023)	Manufacturing	DEMATEL, ANP & TOPSIS	✓	✓	✓	✓	✓
This study	**Manufacturing**	**Brown-Gibson, Modified Delphi, Rényi Entropy**	✓	✓	✓	✓	✓

5.3 Scoring Methodology

This study introduces a multi-criteria approach designed to calculate a reliable and robust digital maturity score. The score is derived from the weighted assessment of a DMM's dimensions and KPIs. The DMM used in this study (Njah et al., 2026), designed to assess manufacturing SMEs, comprises five core dimensions: (1) Strategy and governance, (2) Human Resources (HR) and digital skills, (3) Information technology (IT), data, and security, (4) Industrial systems and value chain, and (5) Portfolio, products, and services, integrating a total of 49 KPIs.

To determine the dimensions' weights, the Brown-Gibson method is employed. It's a multi-criteria decision-making approach designed to support complex decision-making involving both objective and subjective criteria. Initially developed to help organizations identify optimal facility or plant locations, the method integrates quantitative factors, such as labor costs and transportation logistics, with qualitative aspects like community support and environmental impact (Brown et al., 1972). Owing to its flexible mathematical structure and comprehensive integration of diverse criteria, the Brown-Gibson model has been adapted to various decision-making contexts across disciplines (Yimen et al., 2022). It has been effectively applied in fields such as engineering and management science, notably for project selection, resource allocation, and strategic planning where multifactorial analyses are essential (Yimen et al., 2022).

The novelty of this approach compared to other robust methodologies in the literature (e.g., Görçün et al. and Kaya et al., Table 5.4) lies in a systematic and transparent mechanism for integrating subjective and objective weights, ensuring a balanced and sensitive analysis. This prevents either type of data from dominating the final score, yielding a reliable evaluation. In contrast, studies that combine methods such as AHP and entropy, often lack a rigorous integration mechanism. The Brown-Gibson approach, however, provides explicit equations for combining measurements and incorporates sensitivity analysis to test result robustness. The modified Delphi method reinforces this approach by engaging experts to evaluate, compare and quantify criteria related to digital maturity, thereby enabling a structured assessment of each dimension's contribution to overall maturity (Linstone & Turoff, 1975). Subsequently, the Rényi entropy method is applied to convert subjective weights into objective measurements, ensuring that the final weights are unbiased and reducing the risk of over-reliance on subjective judgments (Görçün et al., 2024).

Although the Brown-Gibson approach, which relies on pairwise comparisons, is appropriate for evaluating the five dimensions, its direct application to all 49 KPIs would impose excessive demands on experts. Consequently, the KPIs' weights are assessed during the modified Delphi process using a 5-point Likert-scale to rate the importance of these items in evaluating their corresponding dimensions. The subjective results are subsequently refined through Rényi entropy to ensure objectivity and analytical robustness. Finally, the results from the modified Delphi process and Rényi entropy are integrated using the Brown-Gibson equations to calculate the combined weights of the DMM's dimensions and KPIs.

This integrated approach achieves a balanced evaluation that leverages the strengths of both qualitative and quantitative data. It is more comprehensive than methods that rely solely on one type of measurement, such as AHP, which is primarily subjective, or TOPSIS, which is primarily objective. By combining these techniques, the methodology ensures a holistic and reliable assessment of digital maturity. Figure 5.3 illustrates the methodology phases, which are detailed in the following sections.

5.3.1 Brown-Gibson methodology

The Brown-Gibson methodology, used for complex comparative evaluation problems, involves defining two types of criteria: objective criteria, which are based on measurable, factual and quantitative properties, and subjective criteria, which rely on judgments, interpretations, or expert opinions that reflect qualitative aspects of the elements being compared (Yimen et al., 2022). After identifying these criteria, the next step is to determine the weights of each criterion through expert consensus. The criteria weights are then used to measure and compare elements, typically by scoring each element according to its performance on every criterion and aggregating these scores using the assigned weights. This approach enables transparent and balanced decision-making that combines factual data with human expertise.

Since digital maturity is not typically associated with quantitative criteria (e.g., cost) in the literature, the Brown-Gibson Methodology was adapted for this study. Instead of identifying separate subjective and objective criteria, the research team defined qualitative criteria based on the literature and expert opinions. Subjective and objective weights were then calculated for these criteria to ensure a balanced evaluation. The steps of this adapted methodology are presented in Figure 5.3.

5.3.1.1 Selection of the decision-making committee

For this study, the decision-making committee was composed of experts specializing in Industry 4.0 and digital maturity, selected from LinkedIn to ensure domain expertise. The main criterion for inclusion was a minimum of four years of experience in the field and eligible experts should be academics, consultants and industrial practitioners to provide diverse perspectives. Their professional profiles were closely examined to verify the alignment of their competencies and professional backgrounds with the objectives of this research. Sixteen experts agreed to participate: five academics, five consultants and six industry practitioners ensuring diverse and credible input for the evaluation.

5.3.1.2 Selection of the evaluation criteria

Through a comprehensive literature review, eight key criteria influencing and reflecting digital maturity were identified. They can be considered as direct outcomes of digital maturity improvement. These criteria, derived from existing research, provide a foundation for evaluating and comparing the contributions of the different digital maturity dimensions. Each criterion is presented below with its relevance to digital maturity:

- **Improving competitiveness:** Enhancing competitiveness is a critical outcome of digital maturity, as it enables organizations to leverage digital tools and strategies to outperform competitors and to strengthen their market position (Dohale et al., 2023; Martincevic, 2022; Touijer & Elabjani, 2025). This criterion will help compare how different dimensions of digital maturity contribute to gaining a competitive edge.
- **Promoting innovation:** Digital maturity fosters innovation by enabling organizations to adopt advanced technologies and creative processes (Saad & Alnuiami, 2022; Sjodin et al., 2018; Zhou et al., 2024). This criterion will assess how digital maturity dimensions support innovation-driven growth.
- **Social sustainability:** Social sustainability focuses on the impact of digital transformation on employees, customers and communities (Ching et al., 2022; Ferreira et al., 2023; Müller et al., 2018; Sjodin et al., 2018). This criterion will evaluate how digital maturity dimensions contribute to ethical and socially responsible practices.
- **Environmental sustainability:** Environmental sustainability is increasingly important in digital transformation, as organizations strive to reduce their carbon footprint (Ching et al., 2022; Ferreira et al., 2023; Müller et al., 2018; Sjodin et al., 2018). This criterion will measure how digital maturity dimensions align with eco-friendly practices.
- **Process efficiency:** Process efficiency is a direct benefit of digital maturity, as it streamlines operations and reduces waste (Kaya et al., 2023; Sjodin et al., 2018; Wang &

Shao, 2024). This criterion will help compare how different dimensions enhance operational efficiency with minimal resources.

- **Lower operating costs:** Cost reduction is a key driver of digital transformation (Samaranayake et al., 2017; Schlaepfer & Koc, 2015; Sjodin et al., 2018). This criterion will evaluate how digital maturity dimensions lead to financial savings and resource optimization without affecting product or service quality.
- **Flexibility:** Flexibility is essential in the digital transformation era for organizations to adapt to changing market conditions, customer and environmental demands (Kaya et al., 2023; Schlaepfer et al., 2015). This criterion will measure how digital maturity dimensions enhance organizational flexibility.
- **Customer experience:** Improving customer experience is a primary goal of digital transformation (Kaya et al., 2023; Samaranayake et al., 2017; Schlaepfer et al., 2015). This criterion will assess how digital maturity dimensions contribute to better customer engagement and satisfaction throughout all interactions with a company, from first contact to post-purchase.

These criteria will be used to compare the digital maturity dimensions pairwise, ensuring a reliable weight for each dimension and ultimately, a robust maturity score.

5.3.1.3 Pairwise comparison

The criteria and dimensions pairwise comparison are conducted as follows:

Table 5.5 Example of criteria pairwise comparison

	Criterion 1	Criterion 2	Criterion 3	SCW_j
Criterion 1		0	0	0
Criterion 2	1		1	$\frac{\sum_u \mathbf{1}}{\sum_{ju} \mathbf{1}}$ =2/3
Criterion 3	1	0		1/3

The criteria binary matrix is created using the experts' opinions with:

- $p_{ju} = \begin{cases} 1 & \textit{if the } \text{Criterion j } \textit{is more important than the } \text{Criterion u} \\ 0 & \textit{otherwise or if the Expert has no preference} \end{cases}$
- SCW_j : the weighting of criterion j relative to all set of criteria

Table 5.6 Example of dimensions pairwise comparison

Based on Criterion j	Dimension 1	Dimension 2	Dimension 3	SW_{ij}
Dimension 1		1	1	2/3
Dimension 2	0		1	1/3
Dimension 3	0	0		0

The dimensions binary matrix is created using the experts' opinions with:

- $p_{ik} = \begin{cases} 1 & \textit{If the } \text{Dimension i } \textit{is more important than the } \text{Dimension k} \\ 0 & \textit{Otherwise or if the Expert has no preference} \end{cases}$
- SW_{ij} : the weighting of dimension i relative to all set of dimensions for the criterion j

This pairwise comparison methodology will be employed to design and guide the questionnaires administered to experts during the modified Delphi process.

5.3.1.4 Subjective weighting

SFM_i is the Subjective Factor Measure of dimension D_i ; with:

$$\boldsymbol{SFM_i = \sum_j SCW_j * SW_{ij} \quad ; \quad 0 \leq SFM_i \leq 1} \tag{1}$$

5.3.1.5 Objective weighting

OFM_i is the Objective Factor Measure of dimension D_i ; with:

$$\boldsymbol{OFM_i = \frac{1}{OW_i * \sum_j \frac{1}{OW_j}} \quad ; \quad 0 \leq OFM_i \leq 1} \tag{2}$$

$$\textit{With:} \quad \boldsymbol{OW_i = \sum_j OW_{ij}} \tag{3}$$

Where:

- OW_i : objective weight of each dimension D_i based on all the criteria
- OW_{ij} : objective weight of each dimension D_i based on the criterion C_j (calculated using Rényi Entropy)

5.3.1.6 Final combined weights and sensitivity analysis

M_i is the final weight (measure) of the dimension D_i combining the subjective and the objective measurements, with:

$$M_i = X * OFM_i + (1 - X) * SFM_i \quad ; \quad 0 \leq X \leq 1 \tag{4}$$

A sensitivity analysis is conducted to assess the robustness of the choice of X.

5.3.2 Modified Delphi process

To assign the subjective weights to the components (dimensions and KPIs) of the DMM, a modified Delphi process was employed, engaging 16 experts with specialized knowledge in Industry 4.0 and digital maturity, representing academia, industry, and consulting sectors.

Unlike a classical Delphi that typically involves multiple iterative rounds with controlled feedback and revision after each round, this modified Delphi was structured into distinct phases: data collection across the first two rounds and consensus-building in the final round. The rationale for adopting this modified approach was to structure an effective and faster consensus (Nasa et al., 2021). This modification also accounted for practical considerations, such as maintaining expert engagement and efficiently managing the complexity of the evaluated criteria and KPIs. This approach aligns with recent literature highlighting the flexibility of Delphi applications, which can deviate from the classical method to better suit specific research contexts (Schneider et al., 2016; Shang, 2023). These studies confirm that a consolidated feedback iteration after multiple independent questionnaire rounds can effectively achieve consensus while maintaining rigor and reducing attrition.

The modified process was organized as follows:

- **Round 1 - Criteria assessment:** Experts were asked to compare and evaluate the relative importance of the predefined criteria for digital maturity (detailed in section 5.3.1.2), according to the Brown-Gibson pairwise comparison method (detailed in section 5.3.1.3). Participants were also invited to propose any additional criteria they deemed relevant to the study, ensuring comprehensive coverage.
- **Round 2 – Dimensions and KPIs assessment:**

- ➢ ***Dimensions assessment:*** Experts performed pairwise comparisons of the dimensions based on the highest-priority criteria identified in Round 1, using the Brown-Gibson method. For instance, if six criteria were selected, six separate comparison matrices were presented, one per criterion.
- ➢ ***KPIs assessment:*** Using a 5-point Likert scale ranging from "Not at all important" to "Very important" (Figure 5.2), experts rated the importance of each KPI in relation to its respective dimension.

Question: On a scale from 1 to 5, how would you rate the importance of these indicators based on their contribution to the following dimension:

*__Information technology, data and security__: This dimension evaluates the company's IT infrastructure, adoption of advanced technologies, data management and cybersecurity practices.

Dimension	**Information technology, data and security***				
Level of importance: 5-point Likert scale**	**1**	**2**	**3**	**4**	**5**
High-performance IT infrastructure for digital transformation strategy support.					
Data collection and structuring (e.g. collect, aggregation, structuring, analysis, quality check).					
Cybersecurity implemented measures for data management (data integrity, confidentiality and availability)					

__** 5-Point Likert scale__

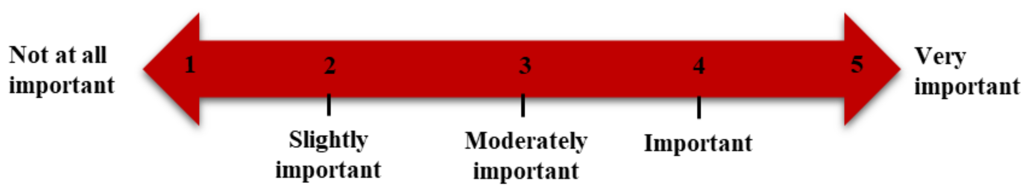

Figure 5.2 Example from the second modified Delphi's round

- **Round 3 - Controlled feedback and consensus:** An anonymized summary report presenting the statistical aggregation of group responses was shared with the experts. Participants were then invited to reflect on the collective results and revise their prior evaluations accordingly. This iterative process of reflection and adjustment, supported by anonymous and controlled feedback, was intended to promote convergence of opinions and facilitate consensus-building, in accordance with the core methodological principles of the Delphi technique (Hasson et al., 2025).

The modified Delphi process was conducted through video-conference interviews or self-administered questionnaires, depending on each expert's preference and logistical feasibility. Prior to participation, experts received a comprehensive guide detailing the study's objectives, the Delphi procedure (including all rounds), and definitions of key concepts to ensure a shared understanding and informed contributions. Prior informed consent was obtained from all experts before participation. All procedures were reviewed and approved under the university's ethical research protocols, ensuring compliance with institutional guidelines for human-subject research. Throughout the process, the research team remained available to clarify questions and methodological details, promoting transparency and expert engagement.

The final statistical aggregation of the experts' responses will determine each dimension's subjective weight. These measures will be then converted into objective weights using Rényi entropy (Figure 5.3).

5.3.3 Rényi Entropy method

The Rényi Entropy is an objective method used to determine the weights of criteria in MCDM processes. It evaluates the uncertainty associated with each criterion, assigning higher weights to criteria with less variability in responses, making them more discriminative.

In this study, the same principle is applied to the dimensions by assessing the dispersion of their subjective evaluations across 16 experts for each criterion. Since entropy measures variability, the expert evaluation matrix is organized so that each dimension is treated as a distribution of expert assessments under a given criterion. The methodology consists of the following steps (Görçün et al., 2024):

5.3.3.1 Matrix construction

For each criterion C_j, a matrix is constructed using the subjective weights (SW_{ijk}) where i=1...m indexes dimensions, j=1...n indexes criteria and k=1...K indexes experts. Each entry SW_{ijk} represents the assessment of dimension D_i by expert k for criterion C_j (see Table 5.7).

5.3.3.2 Matrix normalization

For each dimension D_i under criterion C_j, the subjective weights across experts are normalized to form a probability distribution:

$$\boldsymbol{P}_{\mathbf{ijk}} = \frac{\boldsymbol{SW}_{\boldsymbol{ijk}}}{\sum_{\boldsymbol{j=1}}^{\boldsymbol{K}} \boldsymbol{SW}_{\boldsymbol{ijk}}} \tag{5}$$

Where:

- P_{ijk}: Normalized subjective weight (probability)
- SW_{ijk}: Subjective weight of dimension D_i for criterion C_j provided by the expert E_k
- K: Number of experts

5.3.3.3 Calculation of Rényi entropy

The Rényi entropy for each dimension D_i under criterion C_j is calculated using the following formula:

$$\boldsymbol{H}_{\boldsymbol{\alpha}}(\boldsymbol{D}_{\boldsymbol{i}}, \boldsymbol{C}_{\boldsymbol{j}}) = \frac{\mathbf{1}}{\mathbf{1} - \boldsymbol{\alpha}} \mathbf{log}_{\mathbf{2}}(\sum_{\boldsymbol{j=1}}^{\boldsymbol{K}} \boldsymbol{p}_{\boldsymbol{ijk}}^{\boldsymbol{\alpha}}) \tag{6}$$

Where:

- $H_\alpha(p)$: Rényi entropy of dimension D_i under the criterion, measures the variability of expert assessments.
- α: Parameter that controls the sensitivity of the entropy to the probabilities; with $\alpha > 0$ and $\alpha \neq 0$.

Lower entropy corresponds to higher agreement among experts, indicating higher discriminative power.

The Rényi formulation introduces flexibility where the parameter α can adjust how the entropy reflects the distribution of probabilities. This makes the method more adaptable to different decision-making contexts than the standard Shannon entropy where $\alpha=1$. In this study the parameter $\alpha=2$ is adopted. It’s a frequent choice in MCDM applications known as collision entropy, which measures the probability that two independent identically distributed variables assume the same value (Wei et al., 2025).

5.3.3.4 Dispersion and objective weights

To reflect the discriminative power of each dimension (low variability among experts → high weight), the dispersion is calculated as:

$$\boldsymbol{d_i} = \mathbf{1} - \frac{\boldsymbol{H_\alpha(D_i, C_j)}}{\boldsymbol{H_\alpha^{max}}}\ ; \text{ with } \ \boldsymbol{H_\alpha^{max}} = \mathbf{log_2}(\boldsymbol{K}) \tag{7}$$

Where, H_α^{max} is the maximum possible Rényi entropy for K experts.

Then, the objective weight of the dimension D_i under criterion C_j $(\boldsymbol{OW_{ij}})$ is calculated by normalizing the dispersion values:

$$\boldsymbol{OW_{ij}} = \frac{\boldsymbol{d_{ij}}}{\sum_{i=1}^{m} \boldsymbol{d_{ij}}} \tag{8}$$

Where, “m” is the number of dimensions.

This approach ensures that dimensions with higher agreement among experts (lower entropy) receive higher objective weights, as they are considered more discriminative and informative.

Table 5.7 Demonstration of the objective weights’ matrix

For Criterion C_j :	**Dimension 1**	**Dimension 2**	**Dimension m**
Expert 1	SW_{1j1}	SW_{2j1}	SW_{mj1}
Expert 2	SW_{1j2}	SW_{2j2}	SW_{mj2}
Expert k	SW_{1jk}	SW_{2jk}	SW_{mjk}
Probabilities pi **With “K”: number of experts**	$\frac{\boldsymbol{SW_{1jk}}}{\sum_1^K \boldsymbol{SW_{ijk}}}$	$\frac{\boldsymbol{SW_{2jk}}}{\sum_1^K \boldsymbol{SW_{ijk}}}$	$\frac{\boldsymbol{SW_{mjk}}}{\sum_1^K \boldsymbol{SW_{ijk}}}$

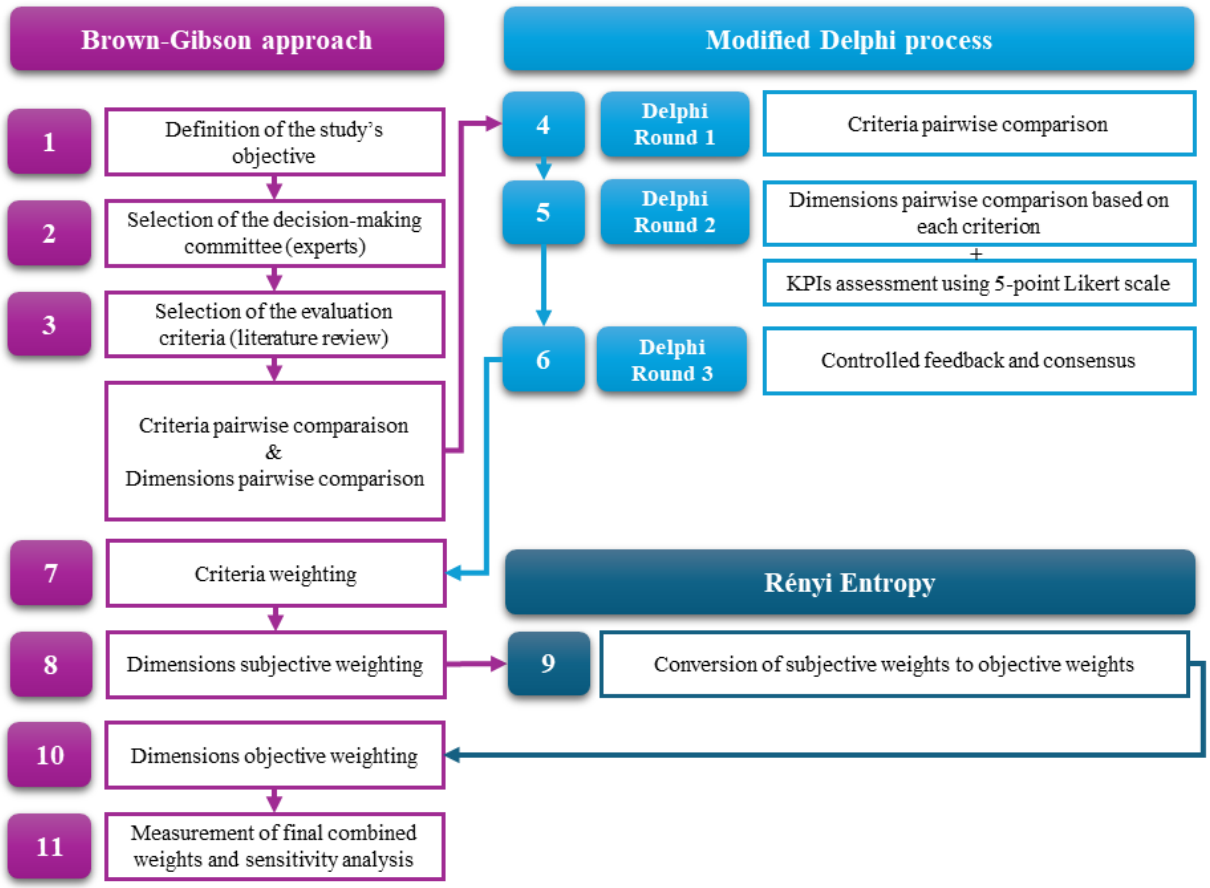

Figure 5.3 The Multi-Criteria Decision-Making approach

5.4 Results

5.4.1 Criteria assessment and weighting

The results of the Delphi's first round highlight that the experts prioritized criteria they perceived as the most immediate, measurable and performance-oriented drivers of digital maturity in the context of Industry 4.0. The consensus indicates that efficiency, competitiveness, customer value, cost reduction and flexibility represent the core elements shaping organizations' digital transformation trajectories, while innovation and sustainability-oriented criteria receive less weight.

As presented in Table 5.8, promoting innovation, social and environmental sustainability received the lowest relative importance scores, suggesting that stakeholders in academia, industry, and consulting do not rate them as critical or primary determinants when evaluating digital maturity in Industry 4.0 contexts.

Appendix D presents a sample of an individual expert's responses from the first Delphi's round, alongside the group's average as shown in the controlled feedback report provided to experts.

Including low-weighted criteria in the second round could dilute the dimensions' evaluation, as their impact would remain minimal while introducing additional complexity into the analysis. Therefore, the criteria weighted below 10% were excluded. The comparison thus focuses only on the six most influential criteria that experts agreed are most representative and impactful for assessing digital maturity.

Table 5.8 Criteria weights

Criteria	Weight	Normalized weight (SCW_j)
Process efficiency	17.35%	20.00%
Improving competitiveness	16.82%	19.39 %
Customer experience	15.95%	18.39%
Reducing operational costs	13.01%	15.00 %
Flexibility	12.93%	14.91 %
Promoting innovation	10.66%	12.29%
Social sustainability	7.49%	0%
Environmental sustainability	5.80%	0%

5.4.2 Dimensions assessment and weighting

In the second Delphi's round, experts evaluated the relative importance of the five digital maturity dimensions across the six criteria identified in Round 1. The aggregated results provided the subjective weights of the dimensions. Appendix D presents a sample of an individual expert's responses from this round, alongside the group average as reported in the controlled feedback summary. These subjective weights were subsequently refined by incorporating objective measures derived using Rényi entropy to calculate the final weights, with the calculation detailed in Appendix E. A sensitivity analysis was also performed to test the prioritization's robustness.

5.4.2.1 Dimensions subjective assessment

The calculation of the dimensions' subjective weights revealed different priority patterns depending on the evaluation criterion. As shown in Table 5.9, *"Strategy and governance"* consistently ranked highest for improving competitiveness (0.333), reducing operational costs (0.267), flexibility (0.279) and promoting innovation (0.328). *“HR and digital skills”* emerged as the top priority for process efficiency (0.289) and was generally ranked second across the remaining criteria. For improving customer experience, *“Portfolio, products, and services”* was identified as the most relevant dimension. In contrast, *“IT, data and security”* was consistently assigned the lowest importance across all six criteria.

When aggregating results across all criteria, *“Strategy and governance”* obtained the highest global subjective weight, followed by *“HR and digital skills”, “Industrial systems and value chains”, “Portfolio, products, and services”,* and *“IT, data and security”*.

Table 5.9 Dimensions’ subjective weights derived from expert assessments across criteria

Criteria / Dimensions	*Process efficiency*	*Improving competitiveness*	*Customer experience*	*Reducing operational costs*	*Flexibility*	*Promoting innovation*	Dimension subjective weight (Swij)
	20.00%	**19.39%**	**18.39%**	**15.00%**	**14.91%**	**12.29%**	
Strategy and governance	0.232	0.333	0.223	0.267	0.279	0.328	0.274
HR and digital skills	0.289	0.210	0.179	0.192	0.228	0.301	0.231
IT, data and security	0.115	0.130	0.143	0.172	0.140	0.121	0.136
Industrial systems and value chain	0.239	0.152	0.198	0.232	0.195	0.096	0.190
Portfolio, products and services	0.126	0.175	0.257	0.136	0.158	0.154	0.169

5.4.2.2 Dimensions final weights and sensitivity analysis

Objective dimensions weights were calculated using Rényi entropy to temper subjective input by emphasizing criteria with less variability in expert judgments. Dimensions with the least subjectivity or disagreement among the panel received higher objective weights. This mathematical correction reduces the influence of inconsistent evaluations, thereby improving reliability.

Integrating subjective and objective measures slightly adjusted the final prioritization (Table 5.10). Dimensions with lower variability across criteria, such as “*Strategy and governance”* and “*HR and* *digital skills*," received reinforced weights, whereas variable dimensions like "*IT, data and security"* were penalized. The combined measures and the sensitivity analysis confirmed the stability of the results (Figure 5.4): "*Strategy and governance"* and "*HR and digital skills*" are the most dominant dimensions, while "*IT, data and security"* remained the least important. Notably, the overall ranking of dimensions remained stable regardless of the weighting balance between subjective and objective measures, indicating the methodology's reliability and the expert consensus.

Table 5.10 Dimensions subjective-objective combined weights

Dimensions	**M_i**				
Sensitivity analysis (X)	**0 (SFM_i)**	**0.25**	**0.5**	**0.75**	**1 (OFM_i)**
Strategy and governance	0.274	0.270	0.266	0.263	0.259
HR and digital skills	0.231	0.245	0.259	0.273	0.287
Industrial systems and value chain	0.190	0.190	0.190	0.190	0.191
Portfolio, products and services	0.169	0.161	0.153	0.145	0.136
IT, data and security	0.136	0.134	0.132	0.130	0.128

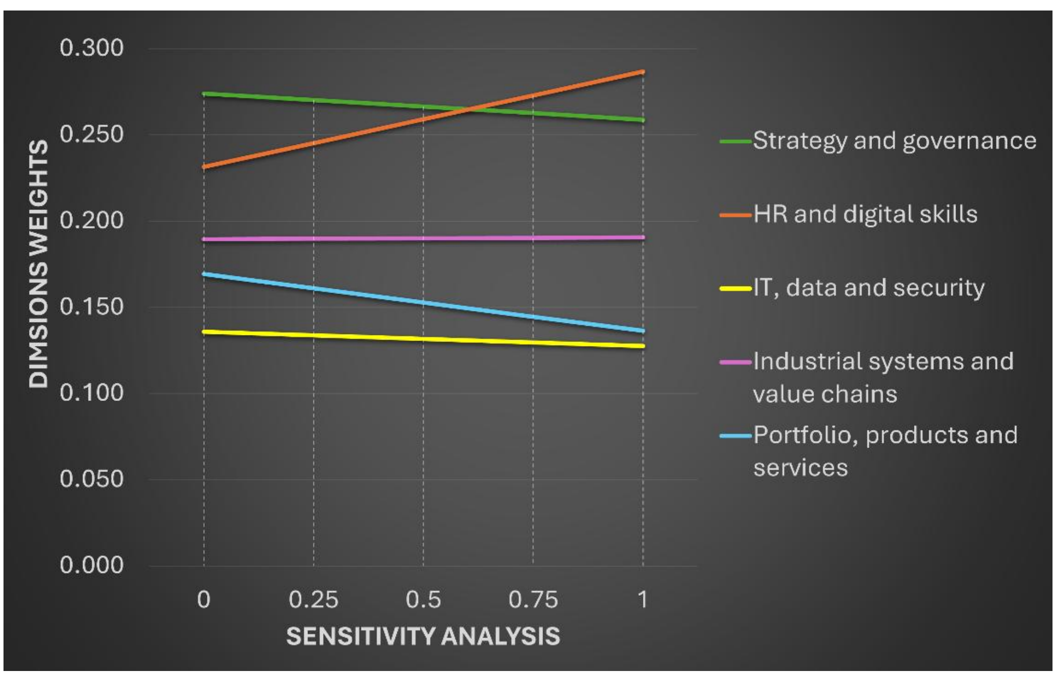

Figure 5.4 Sensitivity analysis of the final dimensions' weights

5.4.3 KPIs assessment and weighting

The evaluation of the KPIs within the dimensions was conducted using a 5-point Likert scale, allowing experts to rate their relative importance. To balance subjective assessments with consistency across experts, the final weighting of each KPI integrates subjective judgments with an objective correction factor and sensitivity analysis.

5.4.3.1 Strategy and governance KPIs

Table 5.11 presents the weighting results for the "Strategy and governance" KPIs. Overall, all KPIs were rated important, with similar evaluations across items. Objective measurements obtained using the Rényi entropy and Brown-Gibson methods refined the ranking for greater reliability. Thus, KPIs with high averages but strong disagreement among experts receive lower objective weights, reducing their influence in the overall assessment. For instance, "Availability of sponsors to support digital transformation projects" was rated high but received the lowest objective weight due to significant variability in responses, showing that experts diverged on its importance.

The highest-ranked KPIs emphasize financial commitment, such as investments and access to public funding, as well as mechanisms like technological watch and benchmarking, underlining their central role in supporting digital transformation initiatives. Sensitivity analysis confirmed the stability of this ranking, showing minimal fluctuation when adjusting the balance between subjective and objective weights.

Table 5.11 KPIs weights in the "Strategy and governance" dimension

KPIs (Strategy and governance)	API /5-point*	M (KPI)				
Sensitivity analysis (X)		**0 (SFM)**	**0,25**	**0,5**	**0,75**	**1 (OFM)**
Financial investments (from the annual revenue) to support the digital strategy.	4.27	7.22%	8.55%	9.88%	11.22%	12.55%
Use of technological watch for decision-making.	3.87	6.54%	8.03%	9.53%	11.03%	12.52%
Access to public funding sources to support the digital transformation.	3.44	5.81%	7.61%	9.40%	11.19%	12.98%
Use of benchmarking for decision-making.	3.75	6.34%	7.13%	7.91%	8.70%	9.48%
Methods used to acquire and integrate advanced technologies.	3.75	6.34%	6.80%	7.27%	7.73%	8.19%

*Average Perceived Importance on the 5-point Likert scale

Table 5.11 KPIs weights in the "Strategy and governance" dimension (continued)

KPIs (Strategy and governance)	**API /5-point***	**M (KPI)**				
Sensitivity analysis (X)		**0 (SFM)**	**0,25**	**0,5**	**0,75**	**1 (OFM)**
Deployment of key performance indicators (KPIs) to monitor digital transformation.	4.50	7.61%	7.33%	7.04%	6.76%	6.47%
Integration of digital technology into the business model and the strategy.	4.88	8.24%	7.61%	6.97%	6.33%	5.70%
Involvement of managers to support the digital transformation projects.	4.75	8.03%	7.39%	6.74%	6.10%	5.45%
Management of identified challenges.	4.44	7.50%	6.89%	6.28%	5.67%	5.06%
Resistance to digital change management.	4.38	7.40%	6.81%	6.23%	5.65%	5.06%
Digital plan/technological roadmap to support the digital strategy.	4.63	7.82%	6.93%	6.03%	5.13%	4.24%
Identification of digital transformation challenges.	4.50	7.61%	6.79%	5.97%	5.16%	4.34%
Availability of sponsors to support the digital transformation projects.	4.38	7.40%	6.45%	5.49%	4.54%	3.59%
Promotion of collaborative versus hierarchical practices.	3.63	6.13%	5.69%	5.25%	4.80%	4.36%

5.4.3.2 HR and digital skills KPIs

Table 5.12 presents the weighting results for the "HR and digital skills" KPIs. These KPIs were all considered important based on their API (columns 2-3).

However, the transition from subjective to objective weighting leads to a significant shift in KPI rankings. At the purely subjective end, "Digital skills identification," "Digital skills consideration in hiring strategy," and "Digital skills training initiatives" are rated as most important, reflecting experts' perceived priorities for building a digitally capable workforce. In contrast, "Digital devices and alternative working modes" was ranked lowest.

As objective weights become dominant (columns 4-7), "Digital devices and alternative working modes" gains importance. This shift is due to the entropy approach that quantifies the variability and convergence in expert responses, not just their mean scores. KPIs with lower average scores, but higher consensus receive higher weights, indicating stability and agreement on their relevance.

Table 5.12 KPIs weights in the “HR and digital skills” dimension

KPIs (HR and digital skills)	API /5-point	M (KPI)				
Sensitivity analysis (X)		0 (SFM)	0,25	0,5	0,75	1 (OFM)
Digital skills identification.	4.69	27.68%	24.18%	20.69%	17.20%	13.71%
Digital skills consideration in the human resources hiring strategy.	4.44	26.20%	23.85%	21.50%	19.15%	16.80%
Digital skills training initiatives.	4.38	25.83%	23.54%	21.25%	18.96%	16.67%
Digital devices and alternative working modes to work remotely and promote mobility.	3.44	20.30%	28.43%	36.56%	44.69%	52.82%

5.4.3.3 IT, data and security KPIs

Table 5.13 presents the weighting results for the “IT, data and security” KPIs. The API values indicate that experts prioritized data reliability, structure and protection over emerging technologies. Highest subjective scores were attributed to “Data collection and structuring”, “Cybersecurity implemented measures for data management” and “High-performance IT infrastructure for digital transformation strategy support”, confirming that a robust and secure data foundation is essential for digital transformation.

However, the transition from subjective to objective weights reveals additional nuances. While subjective scores capture perceived importance, entropy-based weights refined the rankings to reflect experts’ variability. KPIs with higher agreement retain or gain weight, whereas those with dispersed opinions lose influence. For instance, both “Data collection and structuring” and “Cybersecurity implemented measures for data management”, show sharp reductions in objective weights, indicating that despite their importance, experts differed on their relative priority. In contrast, “Adoption of Internet of Things”, “Adoption of Cyber-Physical Systems”, and “Adoption of Autonomous Machines” gain weight, reflecting stronger consensus on their strategic role in ensuring operational continuity and automation.

Among the highest objective weights, “Adoption of Augmented Reality” and “Adoption of Machine-to-Machine” stand out. Although their subjective ratings were among the lowest, this inversion demonstrates how the Rényi entropy approach corrects for perceived bias by prioritizing KPIs with stronger consensus.

Table 5.13 KPIs weights in the "IT, data and security" dimension

KPIs (IT, data and security)	API /5-point	M (KPI)				
Sensitivity analysis (X)		**0 (SFM)**	**0,25**	**0,5**	**0,75**	**1 (OFM)**
Data collection and structuring (e.g. collect, aggregation, structuring, analysis, quality check).	4.75	6.93%	6.46%	5.99%	5.51%	5.04%
Cybersecurity implemented measures for data management (data integrity, confidentiality and availability)	4.63	6.75%	5.78%	4.81%	3.83%	2.86%
High-performance IT infrastructure for digital transformation strategy support.	4.56	6.66%	6.33%	6.00%	5.67%	5.34%
Data usage practices (e.g. predictive maintenance, automatic production, risk management, performances analysis, services, decision-making…)	4.56	6.66%	6.33%	6.00%	5.67%	5.34%
Digital compliance policy (laws and best practices)	4.56	6.66%	5.59%	4.51%	3.44%	2.37%
Adoption of Cybersecurity.	4.56	6.66%	5.73%	4.80%	3.86%	2.93%
Digital continuity between machines and production management systems	4.38	6.39%	6.13%	5.86%	5.60%	5.34%
Adoption of Internet Of Things (IoT).	3.88	5.66%	6.03%	6.41%	6.78%	7.15%
Adoption of Cyber-Physical Systems (CPS).	3.88	5.66%	5.83%	6.01%	6.19%	6.36%
Implementation of collaborative software and applications	3.81	5.57%	5.37%	5.16%	4.96%	4.76%
Adoption of Big Data and analytics.	3.81	5.57%	5.28%	5.00%	4.72%	4.43%
Adoption of CLOUD computing.	3.69	5.38%	5.43%	5.47%	5.51%	5.55%
Adoption of Artificial Intelligence (AI).	3.63	5.29%	5.36%	5.42%	5.49%	5.55%
Adoption of Autonomous machines.	3.63	5.29%	6.08%	6.86%	7.65%	8.43%
Adoption of Machine To Machine (M2M).	3.63	5.29%	6.73%	8.17%	9.61%	11.05%
Adoption of Simulation.	3.63	5.29%	5.65%	6.00%	6.35%	6.71%
Adoption of Augmented Reality (AR).	2.94	4.29%	5.91%	7.53%	9.15%	10.77%

5.4.3.4 Industrial systems and value chain KPIs

Table 5.14 presents the KPIs' evaluation within the "Industrial systems and value chain" dimension. Overall, experts strongly agree on the central role of process traceability and information systems such as ERP and MES. The API and sensitivity analysis show that experts consistently rated all KPIs as critical to digital transformation, with limited variation between items. These findings highlight data visibility, integration and process automation as key drivers for operational transparency and efficiency in the industrial value chain.

When shifting from subjective to objective weighting, KPI rankings remain relatively stable, confirming high expert consensus. “Traceability of internal and external processes” retains the highest weight, emphasizing its importance and strong agreement regarding its impact on industrial performance. By contrast, “Collaboration with external partners to support the digital transformation strategy” declines under objective weighting. Although initially rated relevant, the entropy adjustment indicates higher variability in expert opinions, suggesting less agreement about its impact within industrial value chain.

Table 5.14 KPIs weights in the “Industrial systems and value chain” dimension

KPIs (Industrial systems and value chains)	**API /5-point**	**M (KPI)**				
Sensitivity analysis (X)		**0 (SFM)**	**0,25**	**0,5**	**0,75**	**1 (OFM)**
Traceability of the internal and external processes for real-time monitoring.	4.31	12.00%	12.64%	13.29%	13.93%	14.58%
Production management and optimization (MES and smart equipment implementation)	4.19	11.65%	11.37%	11.09%	10.80%	10.52%
Processes digitalization for internal value chain management (ERP implementation).	4.13	11.48%	11.80%	12.11%	12.43%	12.75%
Use of information systems to manage selling/purchasing processes (ordering, quoting, shipping/receiving and billing/paying).	4.13	11.48%	11.56%	11.64%	11.71%	11.79%
Collaboration with the external partners (academics, suppliers, customers, subcontractors, etc.) to support the digital transformation strategy.	4.06	11.30%	10.14%	8.97%	7.81%	6.64%
Autonomous workpieces and self-guiding capacities through production.	3.81	10.61%	11.08%	11.55%	12.02%	12.49%
Inventory management strategy (WMS implementation).	3.81	10.61%	10.21%	9.81%	9.41%	9.01%
Production dynamic scheduling.	3.75	10.43%	10.42%	10.40%	10.38%	10.37%
Customer experience for product and service improvement processes (CRM implementation)	3.75	10.43%	10.79%	11.14%	11.50%	11.85%

5.4.3.5 Portfolio, products and services KPIs

Table 5.15 reports the weighting results for the "Portfolio, products and services" KPIs. Overall, the KPIs in this category were perceived important, highlighting experts' emphasis on customer-centric innovation and the integration of digital solutions for value creation.

When moving from subjective to objective weighting, KPI rankings show moderate adjustments. "Product lifecycle management" gains importance under objective weighting, reflecting strong expert consensus. In contrast, the weights of "Online sales platform with customer control over customization and order placement" and "Use of digital channels to manage customer relations" decrease, indicating higher variability in expert opinions regarding their impact.

Sensitivity analysis confirms that despite minor redistributions, KPI rankings remain relatively stable, demonstrating a consistent view among experts on the strategic role of smart, connected products and customer-oriented digital services in advancing digital maturity.

Table 5.15 KPIs weights in the "Portfolio, products and services" dimension

KPIs (Portfolio, products and services)	**API /5-point**	**M**				
Sensitivity analysis (X)		**0 (SFM)**	**0,25**	**0,5**	**0,75**	**1 (OFM)**
Products/services customization to enhance customer experience.	4.19	21.61%	21.29%	20.96%	20.63%	20.30%
Use of digital channels to manage customer relations while monitoring and controlling its digital footprint.	4.06	20.97%	20.10%	19.23%	18.37%	17.50%
Development of smart products and services based on data acquisition and exploitation (integrating additional functionalities (such as memorization, localization, self-reporting, tracking, and self-analysis) during both production and usage phases).	3.94	20.32%	19.81%	19.30%	18.79%	18.28%
Product lifecycle management.	3.63	18.71%	21.40%	24.09%	26.78%	29.47%
Online sales platform with customer control over customization and order placement.	3.56	18.39%	17.40%	16.42%	15.43%	14.45%

5.5 Discussion and conclusion

This study addresses the critical need for a reliable and comprehensive method to assess digital maturity, a key factor for organizations facing the challenges and the opportunities of Industry 4.0

and digital transformation. The DMM employed in this research was specifically designed for manufacturing SMEs. Findings of this study highlighted how digital maturity in these companies can be reliably assessed through a multi-criteria approach. By integrating subjective expert judgments from the modified Delphi process with objective weights derived from the Rényi entropy method, using the Brown-Gibson methodology, this study addresses two common limitations of existing DMMs: reliance on purely subjective assessments and lack of methodological rigor, which can lead to biased digital maturity scores (Gökalp et al., 2022; Kaya et al., 2023; Mittal et al., 2018).

The results of this approach identified "*Strategy and governance*" and "*HR and digital skills*" as the two most critical dimensions for assessing digital maturity, collectively accounting for over 50% of the final score. These dimensions were particularly relevant to key criteria, including process efficiency, competitiveness, customer experience enhancement, operational cost reduction, organizational flexibility, and the promotion of innovation.

These findings are consistent with the characteristics of SMEs, where strategic orientation and workforce competence are foundational enablers for successful Industry 4.0 adoption (Gamache et al., 2019). Tonder et al., (2024) through a systematic literature review of contemporary research on digital transformation in SMEs, confirmed that most studies emphasize strategy as a key dimension in assessing digital maturity. Similarly, another study highlighted that strategic vision and governance structures serve as the foundational catalysts for SMEs to progress beyond isolated technology adoption (Canhoto et al., 2021). Without such alignment, investments in advanced digital technologies risk producing only fragmented or short-term results.

The significance of "*HR and digital skills*" further reflects the findings of recent studies emphasizing the workforce as a critical factor for sustaining digital transformation (Bamidele Micheal Omowole et al., 2024; Tonder et al., 2024). Developing digital competencies through targeted hiring, continuous training, and integration into HR policies, enhances SMEs' capacity to leverage new technologies and adapt to dynamic market conditions (Jie et al., 2025). This factor is particularly crucial for SMEs, where maximizing human capital can often compensate for limitations in financial or technological resources (Jie et al., 2025; Mittal et al., 2018).

Another key finding is that the dimension "*IT, data, and security*" was rated as the least influential, despite being widely considered a cornerstone of digital transformation. This suggests a divergence between SMEs and larger firms regarding transformation priorities. For SMEs, the value of IT infrastructure remains instrumental but secondary, as they first require strong organizational commitment and skilled staff to leverage technological potential (Kaya et al., 2023). These results reflect the argument of Mittal et al. (2018) that SME-focused DMMs need to account for contextual realities: without leadership alignment and trained employees, investments in IT infrastructure alone cannot drive maturity. This finding does not diminish the importance of IT and data but indicates that SMEs should adopt IT infrastructure incrementally, after establishing the strategic and organizational capacities necessary for effective technology integration.

The study also revealed that sustainability-related aspects and innovation were deprioritized in digital maturity assessments. Experts tend to prioritize short-term efficiency, competitiveness and customer value over innovation and long-term social and environmental considerations. This does not imply that these factors are irrelevant; rather, it reveals an important gap: digital maturity benchmarking may underemphasize long-term and societal dimensions of transformation.

This gap reflects the characteristics of SMEs and many Industry 4.0 adopters who tend to prioritize short-term, tangible returns from digital investments. The literature confirms that SMEs tend to focus heavily on operational gains and short-term performance improvements, such as enhancing efficiency, reducing costs, and improving customer outcomes, because these benefits are measurable, directly linked to competitiveness, and easier to justify internally (OECD, 2021; Ojukwu et al., 2024). This is particularly pronounced in firms lacking advanced digital infrastructure or managerial capabilities, which naturally encourages them to favor incremental, efficiency-driven projects over longer-term and less tangible goals like sustainability and innovation.

However, digital transformation can significantly accelerate achieving sustainability goals and innovation (Ferreira et al., 2023; Mick et al., 2024; Zhou et al., 2024). Therefore, the relatively low weighting assigned to these criteria may stem from other underlying factors. For instance, policymakers and scholars have documented that the “social” pillar is often the least operationalized dimension of sustainability (Aichroth & Kempen, 2024; Colantonio, 2009). It is conceptually broad including multidimensional aspects such as well-being, inclusion, labor conditions and community impacts and it lacks standardized, commonly used KPIs in industrial digital transformation contexts (Aichroth et al., 2024). This conceptual ambiguity reduces its visibility in expert evaluations, making social sustainability less likely to be identified as a primary determinant of digital maturity, unless experts possess specific expertise or incentives related to social policy. This observation also helps explain our findings: the expert panel primarily comprises specialists in Industry 4.0 and digital maturity, whose professional backgrounds are strongly technical and performance oriented. This technical focus can unintentionally deprioritize social and environmental objectives that are more difficult to measure using conventional KPIs (Ferrari et al., 2022). Likewise, the low weighting of the environmental aspect reflects a broader challenge often characterized as the "twin transition" of digital and green transformations, where progress toward simultaneous technological and sustainability goals is difficult (Kovacic et al., 2024). Many organizations, especially SMEs with constrained resources, focus first on immediate competitive survival and operational efficiency, postponing deeper environmental commitments (Kannan & Gambetta, 2025).

Since its emergence, Industry 4.0 has been primarily technology and strategy centric, often overlooking human-centric, social and environmental considerations (Hein-Pensel et al., 2023). In contrast, the evolution toward Industry 5.0 represents a shift into a more transversal perspective, integrating human-centricity, sustainability and resilience alongside technological progress (Khan et al., 2023). Consequently, as organizations and assessment models increasingly adopt Industry 5.0 principles, it is likely that social and environmental factors, as well as long-term innovation, will gain greater weight in digital maturity assessments (Hein-Pensel et al., 2023; Khan et al., 2023).

This study contributes to both academic knowledge and practical application in the field of digital transformation. From an academic perspective, it introduces a novel MCDM approach that addresses gaps in existing methodologies. It provides a comprehensive approach that combines subjective expert input with objective measures and sensitivity analysis, resulting in digital maturity scores that are both reliable and theoretically robust. By ensuring balance and rigor in the evaluation process, the methodology provides a valuable foundation for future research in digital transformation measurement and benchmarking.

Building on this methodological contribution, the results highlight the specific impact of objective entropy weighting on expert prioritization. While subjective ratings capture participants' perspectives, applying entropy-based objective weights revealed narrow shifts in KPI rankings, particularly in cases of high or low expert variability. This effect is corroborated in the literature, which emphasizes that entropy-based weighting surfaces stable priorities that might not emerge through subjective ratings alone, making the method valuable in multidimensional digital maturity assessments with large sets of KPIs (Brodny et al., 2021; Görçün et al., 2024; Wei et al., 2025). The sensitivity analysis confirms that the final KPI scores reflect both qualitative intent and empirical agreement, while noting that, in this case, the high expert consensus suggests that subjective weights alone could also yield robust prioritization.

For industrial practitioners, especially within SMEs, the study delivers actionable, standardized weights for dimensions and KPIs that facilitate the identification of digital transition gaps and enable targeted, prioritized transformation initiatives. This method supports the efficient adoption of emerging technologies and promotes the strategic allocation of limited resources, ultimately strengthening SMEs' sustainable competitive advantage in the digital era.

For future research, the approach and findings supply a basis for designing tailored technological roadmaps, supporting incremental improvements by leveraging KPIs as precise, actionable milestones and driving holistic digital transformation efforts through the strategic weighting of dimensions.

While this study offers a robust approach for assessing digital maturity, it has certain limitations. First, the results may be constrained by the focus on SME-specific contexts and the particular set of criteria and dimensions chosen. Future research should aim to expand the contextual range and periodically update the criteria to reflect continual technological and organizational developments. Second, the composition of the expert panel may have influenced the relative underweighting of sustainability and social aspects. Including experts from broader fields such as sustainability, innovation management, and policy could provide a more balanced perspective.

CHAPITRE 6 CONCLUSION GÉNÉRALE

6.1 Synthèse de la recherche et complémentarité des articles

Ce mémoire s'inscrit dans une démarche de conception d'un modèle d'évaluation de la maturité numérique (DMM) spécifiquement adapté aux PME manufacturières. Il répond à deux problématiques : (1) proposer un modèle de maturité numérique intégrant les particularités des PMEs, et (2) opérationnaliser ce modèle à travers une approche quantitative permettant une mesure fiable et comparable du niveau de maturité numérique. L'objectif central était de proposer un outil capable de fournir un diagnostic détaillé pour soutenir le cycle de la transformation numérique des PME manufacturières afin d'alimenter le développement d'une feuille de route technologique.

L'organisation du travail en deux articles scientifiques a permis de répondre à ces deux volets complémentaires.

Le premier article, « *A Digital Maturity Model for assessing SMEs in the manufacturing sector* », a posé les fondements conceptuels du modèle. Par une revue de littérature et une étude de cas multiples, il a permis d'identifier les dimensions, sous-dimensions et indicateurs pour évaluer la maturité numérique des PME manufacturières. Cette première étape a conduit à la construction d'un modèle multidimensionnel composé de cinq dimensions : « Stratégie et gouvernance » ; « RH et compétences numériques » ; « TI, données et sécurité » ; « Systèmes industriels et chaîne de valeur » et « Portefeuille, produits et services », 35 sous-dimensions et 49 indicateurs.

Le second article, « *Designing a multi-criteria approach to measure the digital maturity score of manufacturing SMEs »*, a prolongé et opérationnalisé le modèle conceptuel. En intégrant une approche multicritère (MCDM) combinant une étude Delphi modifiée et la méthode d'entropie de Rényi, il a permis de transformer le modèle en un outil de mesure quantitatif robuste et reproductible. Cette approche atténue la subjectivité inhérente aux évaluations traditionnelles (Gökalp et al., 2022) en introduisant une pondération des dimensions et des KPIs selon leur contribution réelle à la maturité numérique. Elle vise ainsi à offrir une représentation plus fidèle du niveau de maturité numérique des PME.

Ainsi, les deux articles s'articulent de manière cohérente : le premier définit le « quoi », à travers les composantes structurelles de la maturité numérique, et le second précise le « comment », à travers la méthode de mesure et de calcul du score. Ensemble, ils fournissent un outil d'évaluation intégré, combinant diagnostic qualitatif et mesure quantitative. Cet outil constitue la base pour la conception de feuilles de route technologiques contextualisées, conformément à la logique méthodologique du mémoire.

6.2 Positionnement du nouvel outil par rapport aux modèles existants

L'outil de mesure de la maturité numérique développé pour les PME manufacturières se distingue d'abord par la transparence méthodologique de sa méthode de calcul du score qui présente un équilibre entre subjectivité et objectivité, assurant une image fiable de la réalité des entreprises évaluées. Il se différencie notamment de modèles tels que « Industry 4.0 Readiness (IMPULS)» de Lichtblau et al. (2015) et l'« Industrie 4.0 Maturity Index » d'Acatech (Schuh et al., 2020), dont les méthodes de calcul ne sont pas explicitement présentées et dont l'auto-évaluation est sujette à des biais. Cette critique est corroborée par Gökalp et al. (2022), qui montrent que ces modèles ne satisfont pas aux critères « description de la méthode d'évaluation » et « objectivité de la méthode d'évaluation ». Les modèles qui satisfaisaient ces critères soit manquent de couverture dimensionnelle complète, comme le « Maturity and Readiness Model of Industry 4.0 Strategy » d'Akdil et al. (2018), soit ils sont spécifiques à un secteur d'activité donné, par exemple le secteur bancaire (Bandara et al., 2019) ou le secteur des télécommunications (Valdez-de-Leon, 2016). Le DX-CMM de Gökalp & Martinez (2022) répond à tous les critères d'évaluation et vise l'applicabilité intersectorielle, mais son application suit la norme ISO 330xx, nécessitant une équipe d'audit distincte (auditeurs internes formés ou consultants externes certifiés), ce qui le rend inadapté à l'auto-évaluation autonome des PME et requiert une expertise pour son transfert au contexte manufacturier.

À l'opposé, le modèle de maturité numérique développé dans le cadre de cette étude assume un périmètre volontairement restreint aux PME manufacturières, intégrant un niveau bas d'entrée (absence de démarche numérique) et des indicateurs opérationnels compréhensibles par ces entreprises. Bien que Ganzarain & Errasti (2016) et S. Mittal et al. (2020) ciblent aussi les PME, leurs modèles ne présentent pas d'approche d'évaluation de la maturité numérique.

Par ailleurs, cet outil s'appuie sur une base dimensionnelle robuste définies par Cognet et al. (2023). La revue de littérature systématique réalisée par Tonder et al. (2024) confirme l'exhaustivité des dimensions retenues, où elle a défini les dimensions clés permettant de mesurer le niveau de maturité numérique des (PME) à savoir : stratégie, leadership, culture, organisation, personnes, technologie, processus, produits, clients.

Enfin, l'outil pour PME combine (i) une base de contenu consolidée et adaptée aux contraintes spécifiques des PME, (ii) une méthode fiable de calcul du score, et (iii) un diagnostic détaillé des réponses, exploitable pour orienter le développement de la stratégie de transformation numérique.

6.3 Implications de l'étude pour les PME manufacturières

Le modèle d'évaluation de la maturité numérique proposé fournit aux PME manufacturières un diagnostic structuré et opérationnel de leur transformation numérique, couvrant de manière intégrée les dimensions organisationnelles, technologiques et industrielles. Il permet d'analyser l'intégration du numérique dans la stratégie d'affaires, le rôle des dirigeants et des gestionnaires, la gestion du changement et des obstacles, ainsi que le développement des compétences numériques. Parallèlement, il renseigne sur la qualité de l'infrastructure TI, l'interopérabilité des systèmes, la gouvernance des données, la cybersécurité et l'adoption de technologies avancées. Sur le plan opérationnel, le modèle évalue également la transformation numérique de la chaîne de valeur, incluant l'automatisation de la production, la gestion des stocks, l'intégration des partenaires, ainsi que l'évolution de l'offre vers des produits et services intelligents et personnalisés. L'ensemble de ces items produit des scores par dimension et un score global, permettant aux entreprises de se positionner sur un continuum de maturité numérique.

La pondération des dimensions et des indicateurs constitue un élément central de la valeur ajoutée du modèle, dans la mesure où elle reconnaît que tous les aspects de la transformation numérique n'ont pas le même poids stratégique. En accordant une importance relative plus élevée à certaines dimensions ou à certains leviers jugés structurants (par exemple l'usage des données, l'intégration des systèmes ou la cybersécurité), le score agrégé reflète davantage les priorités réelles de la compétitivité des PME manufacturières plutôt qu'une simple moyenne uniforme des pratiques observées. Cette logique de pondération permet ainsi de distinguer les entreprises qui sont véritablement avancées sur les facteurs critiques de celles qui présentent essentiellement des progrès diffus ou superficiels.

Dans cette perspective, l'outil d'évaluation constitue une base solide pour le développement de feuilles de route technologiques, en fournissant des indicateurs précis et contextualisés qui alimentent la perspective technologique et de recherche du cadre de roadmapping proposé par

Phaal et al. (2013). Il se prête particulièrement à une approche de poussée technologique « Technology push », qui est particulièrement pertinente pour les PME, puisqu'elle repose sur l'exploitation des ressources, compétences et technologies déjà disponibles afin d'atteindre un niveau de maturité cible (Caetano & Amaral, 2011). Cette approche permet aux PME de structurer leur feuille de route sur les opportunités technologiques internes, plutôt que de se limiter à une réponse réactive à la demande du marché ou aux tendances externes (Arshed et al., 2012; Caetano et al., 2011).

L'intégration conjointe de la dimension technologique, la perspective commerciale et stratégique, ainsi que la perspective de conception, développement et production, permet d'assurer la cohérence des feuilles de route et de répondre à l'absence fréquente de mécanismes de validation contextuelle des outils de maturité numérique (limite méthodologique identifiée dans la revue systématique du deuxième article (section 5.2.2)).

Selon les travaux de Colli et al. (2019), Norouzi et al. (2023), et Schumacher et al. (2019), la mise en œuvre de méthodes itératives et participatives, notamment à travers des ateliers collaboratifs au sein des entreprises réunissant experts, dirigeants et employés, permet de mobiliser les outils d'évaluation pour déterminer l'écart entre le niveau de maturité actuel et le niveau cible et identifier les priorités d'amélioration. Durant ces ateliers, les environnements interne et externe de l'entreprise sont examinés de manière croisée, à partir les perspectives technologiques, organisationnelles et stratégiques des différents participants. Ce processus itératif et collaboratif assure une actualisation continue de la pertinence des plans d'action issus des feuilles de route et permet d'évaluer régulièrement leur impact sur la progression de la maturité numérique des PME.

6.4 Principaux résultats

6.4.1 Facteurs médiateurs et modérateurs de la transformation numérique des PME manufacturières

L'analyse des cas du premier article a révélé que la relation entre l'adoption technologique et les résultats de la transformation numérique est influencée par un ensemble de médiateurs et de modérateurs.

Les médiateurs identifiés incluent :

- Le développement du capital humain et la formation numérique continue ;

- La culture organisationnelle ouverte à l'innovation ;
- La planification stratégique structurée ;
- Les partenariats externes favorisant le transfert de connaissances.

Ces médiateurs traduisent le rôle central des ressources humaines et de la gouvernance dans la transformation des investissements technologiques en bénéfices tangibles, rejoignant les conclusions de Baojing et al. (2025) et Kampoowale et al. (2025).

Cette constatation est en cohérence avec les résultats du deuxième article, où les résultats ont mis en évidence le rôle central des dimensions « Stratégie et gouvernance » et « RH et compétences numériques », qui représentent plus de la moitié du score global. Ceci confirme que la réussite de la transformation numérique repose d'abord sur la vision stratégique et le développement des compétences, avant l'intégration technologique (Canhoto et al., 2021; Jie et al., 2025; Tonder et al., 2024)

Les modérateurs, quant à eux, incluent :

- les contraintes financières;
- la complexité technologique;
- la gestion du changement;
- les exigences réglementaires.

Ces variables externes ou structurelles modulent la capacité des PME à convertir leurs efforts numériques en résultats stratégiques.

Ainsi, la maturité numérique des PME ne dépend pas uniquement du niveau technologique, mais d'un équilibre entre facteurs humains, organisationnels et environnementaux, confirmant la nature multidimensionnelle du concept (Masood et al., 2020; OECD, 2021).

Les médiateurs et modérateurs mentionnés ci-dessus ont été identifiés de manière inductive à partir de l'analyse itérative des entrevues semi-structurées menées dans le cadre de l'article 1, selon une approche hybride déductive-inductive. Leur identification repose sur la récurrence des relations perçues dans les discours des répondants, mises en évidence lors du codage axial et de la comparaison inter-cas. Ces relations ont été triangulées avec des sources secondaires, telles que les observations, les documents des entreprises et les sites web, et corroborées par les études existantes sur la transformation numérique. Dans le cadre des perspectives de cette recherche, une étude quantitative est suggérée afin de valider formellement ces relations.

6.4.2 Priorités stratégiques

Les résultats du second article mettent en évidence que, dans le contexte des PME manufacturières comme dans d'autres types d'entreprises, les priorités stratégiques traduisent une orientation vers l'efficacité des processus, l'amélioration de la compétitivité, la réduction des coûts opérationnels, l'amélioration de l'expérience client et la flexibilité organisationnelle, des objectifs concrets, immédiats et mesurables. À l'inverse, les aspects liés à la durabilité environnementale, à la responsabilité sociétale et à l'innovation à long terme ont été faiblement pondérés. Cette tendance illustre une priorisation des gains économiques à court terme au détriment des objectifs durables.

Les travaux de Aichroth & Kempen (2024) et Colantonio (2009) montrent que la dimension sociale de la durabilité est souvent la moins opérationnalisée dans les contextes industriels, faute d'indicateurs normalisés. De même, la transition « double » numérique et écologique (twin transition) demeure difficile à concilier (Kovacic et al., 2024).

Ces résultats suggèrent que, la transformation numérique demeure largement technocentrée et orientée vers la performance immédiate, confirmant les limites observées par Hein-Pensel et al. (2023) et Khan et al. (2023) dans les modèles d'Industrie 4.0. Cela souligne la nécessité d'une évolution vers les principes d'Industrie 5.0, intégrant les dimensions humaines, durables et résilientes.

6.5 Limites et perspectives de la recherche

La validation du modèle pour les PME manufacturières demeure principalement qualitative. Des travaux futurs visent une validation quantitative afin de confirmer la fiabilité du modèle et sa robustesse contextuelle.

Une fois cette validation quantitative établie, le modèle, initialement conçu pour les PME manufacturières, présente un potentiel d'adaptation à d'autres secteurs (services, agroalimentaire, technologies). Cette adaptation pourrait s'appuyer sur une recalibration des dimensions et des indicateurs au moyen d'un processus Delphi impliquant des experts sectoriels. Elle impliquerait l'ajustement des indicateurs opérationnels (par exemple, la substitution d'indicateurs liés à la production par des indicateurs de personnalisation, de qualité de service ou d'intensité relationnelle avec le client) ainsi qu'une révision des pondérations relatives, de façon à refléter les déterminants spécifiques de la performance numérique dans chaque secteur. Les dimensions transversales, telles que la stratégie et les compétences numériques, resteraient applicables quel que soit le contexte sectoriel, garantissant la cohérence conceptuelle du modèle. Enfin, la transférabilité de l'outil devrait être éprouvée par un test pilote auprès d'un échantillon restreint d'organisations du secteur ciblé, permettant d'évaluer la pertinence des indicateurs, la robustesse du score obtenu et l'utilité opérationnelle du diagnostic avant un déploiement à plus grande échelle.

D'autre part, le positionnement du modèle dans le paradigme de l'Industrie 4.0 limite son intégration des dimensions sociales et durables. Il serait pertinent de réfléchir à l'évolution et au maintien de l'outil, afin de l'adapter aux transformations actuelles du monde numérique, en particulier vers l'Industrie 5.0, centrée sur l'humain, la résilience et la durabilité (Hein-Pensel et al., 2023; Khan et al., 2023).

Enfin, dans une perspective de continuité de la recherche, les résultats obtenus ouvrent la voie à l'intégration du modèle au sein d'un processus de planification stratégique fondé sur des feuilles de route technologiques. Une telle approche permettrait d'articuler le diagnostic de maturité avec la priorisation des actions stratégiques, afin de guider de manière structurée la progression vers des niveaux de maturité numérique ciblés. Ce cadre pourrait être appliqué aussi bien aux PME qu'aux grandes entreprises, à condition que l'outil soit préalablement testé et jugé pertinent pour ce type d'organisation.

RÉFÉRENCES

Aichroth, L. S., & Kempen, R. (2024). Social sustainability and digital transformation - two birds with one stone? A concept paper for a mixed methods research design. *Procedia Computer Science*, *246*, 362-370. 10.1016/j.procs.2024.09.415

Akdil, K. Y., Ustundag, A., & Cevikcan, E. (2018). Maturity and Readiness Model for Industry 4.0 Strategy. Dans A. Ustundag & E. Cevikcan (édit.), *Industry 4.0: Managing The Digital Transformation* (p. 61-94). Springer International Publishing. 10.1007/978-3-319-57870-5_4

Akman, G., & Kökümer, Z. (2023). Evaluation of digital transformation competency in the white-goods sector in the context of Industry 4.0 by MACBETH and EDAS methods. *Journal of the Faculty of Engineering and Architecture of Gazi University*, *38*(4). 10.17341/gazimmfd.981824

Arshed, N., Finch, J., & Bunduchi, R. (2012). *Technology roadmapping and SMEs: A literature review*. https://www.research.ed.ac.uk/files/17718212/Technology_Roadmapping_and_SMEs_A_Literature_Review.pdf

Aslanova, I. V., & Kulichkina, A. I. (5 mai 2020). *Digital Maturity: Definition and Model*. 2nd International Scientific and Practical Conference "Modern Management Trends and the Digital Economy: from Regional Development to Global Economic Growth" (MTDE 2020) (p. 443-449). Atlantis Press. 10.2991/aebmr.k.200502.073

Bamidele Micheal Omowole, Amarachi Queen Olufemi-Phillips, Onyeka Chrisanctus Ofodile, Nsisong Louis Eyo-Udo, & Somto Emmanuel Ewim. (2024). Barriers and drivers of digital transformation in SMEs: A conceptual analysis. *International Journal of Scholarly Research in Science and Technology*, *5*(2), 019-036. 10.56781/ijsrst.2024.5.2.0037

Bandara, O., Vidanagamachchi, K., & Wickramarachchi, R. (2019). A Model for Assessing Maturity of Industry 4.0 in the Banking Sector.

Baojing, Z., Alias, N., & Yaacob, M. H. (2025). The relationship between organizational culture and digital transformation in SMEs: A systematic review. *Multidisciplinary Reviews*, *8*(5), 2025162-2025162.

Barry, A. S., Assoul, S., & Souissi, N. (2022). *Benchmarking of digital maturity models according to the dimension component* (p. 1-8). IEEE. https://ieeexplore.ieee.org/abstract/document/9737781/

Barry, A. S., Assoul, S., & Souissi, N. (2023). Strengths and Weaknesses of Digital Maturity Models. *J. Comput. Sci*, *19*, 727-738.

Becker, J., Knackstedt, R., & Pöppelbuß, J. (2009). Developing Maturity Models for IT Management. *Business & Information Systems Engineering*, *1*(3), 213-222. 10.1007/s12599-009-0044-5

BENTAHER, C. (2023). The assessment of the key success factors for digital transformation based on MCDM method: The case study of an automotive company. *International Journal of Economic Studies and Management (IJESM)*, *3*, 13-27. 10.5281/zenodo.7552619

Berghaus, S., & Back, A. (2016). Stages in digital business transformation: Results of an empirical maturity study. https://aisel.aisnet.org/cgi/viewcontent.cgi?article=1022&context=mcis2016

Bley, K., Pappas, I., & Strahringer, S. (2024). A Configurational Approach to Maturity Model Development – Using fsQCA to Build a Multiple-Pathway Maturity Model. *Communications of the Association for Information Systems*, *54*(1), 75-132. 10.17705/1CAIS.05405

Brodeur, J., Pellerin, R., & Deschamps, I. (2021). Collaborative approach to digital transformation (CADT) model for manufacturing SMEs. *Journal of Manufacturing Technology Management*, *33*(1), 61-83. 10.1108/JMTM-11-2020-0440

Brodny, J., & Tutak, M. (2021). Assessing the level of digital maturity of enterprises in the Central and Eastern European countries using the MCDM and Shannon's entropy methods. *PLOS ONE*, *16*(7), e0253965. 10.1371/journal.pone.0253965

Brown, P. A., & Gibson, D. F. (1972). A Quantified Model for Facility Site Selection-Application to a Multiplant Location Problem. *A I I E Transactions*, *4*(1), 1-10. 10.1080/05695557208974822

Büyüközkan, G., & Güler, M. (2018). Analysis of companies' digital maturity by hesitant fuzzy linguistic MCDM methods. *Journal of Intelligent & Fuzzy Systems*, *38*(1), 1119-1132. 10.3233/JIFS-179473

Büyüközkan, G., Havle, C. A., & Feyzioğlu, O. (2021). Digital competency evaluation of low-cost airlines using an integrated IVIF AHP and IVIF VIKOR methodology. *Journal of Air Transport Management*, *91*, 101998. 10.1016/j.jairtraman.2020.101998

Caetano, M., & Amaral, D. C. (2011). Roadmapping for technology push and partnership: A contribution for open innovation environments. *Technovation*, *31*(7), 320-335. 10.1016/j.technovation.2011.01.005

Canhoto, A. I., Quinton, S., Pera, R., Molinillo, S., & Simkin, L. (2021). Digital strategy aligning in SMEs: A dynamic capabilities perspective. *The Journal of Strategic Information Systems*, *30*(3), 101682. 10.1016/j.jsis.2021.101682

Chanias, S., & Hess, T. (2016). How digital are we? Maturity models for the assessment of a company's status in the digital transformation. *Management Report / Institut Für Wirtschaftsinformatik Und Neue Medien*, (2), 1-14.

Chen, C.-L., Lin, Y.-C., Chen, W.-H., Chao, C.-F., & Pandia, H. (2021). Role of Government to Enhance Digital Transformation in Small Service Business. *Sustainability*, *13*(3), 1028. 10.3390/su13031028

Ching, N. T., Ghobakhloo, M., Iranmanesh, M., Maroufkhani, P., & Asadi, S. (2022). Industry 4.0 applications for sustainable manufacturing: A systematic literature review and a roadmap to sustainable development. *JOURNAL OF CLEANER PRODUCTION*, *334*, 130133. 10.1016/j.jclepro.2021.130133

Chonsawat, N., Sopadang, A., & Ouzrout, Y. (2023). Decision-making methods for selecting the best strategy for Industry 4.0. *International Journal of Manufacturing Technology and Management*, *37*(5-6), 538-562. 10.1504/IJMTM.2023.133699

Cognet, B., Pernot, J.-P., Rivest, L., & Danjou, C. (2023). Systematic comparison of digital maturity assessment models. *Journal of Industrial and Production Engineering*, *40*(7), 519-537. 10.1080/21681015.2023.2242340

Colantonio, A. (2009). Social sustainability: a review and critique of traditional versus emerging themes and assessment methods. https://eprints.lse.ac.uk/35867

Colli, M., Berger, U., Bockholt, M., Madsen, O., Moller, C., & Waehrens, B. V. (2019). A maturity assessment approach for conceiving context-specific roadmaps in the Industry 4.0 era. *Annual Reviews in Control*, *48*, 165-77. 10.1016/j.arcontrol.2019.06.001

Colli, M., Madsen, O., Berger, U., Møller, C., Wæhrens, B. V., & Bockholt, M. (2018). Contextualizing the outcome of a maturity assessment for Industry 4.0. *IFAC-PapersOnLine*, *51*(11), 1347-1352. 10.1016/j.ifacol.2018.08.343

Creswell, J. W., & Creswell, J. D. (2017). *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. SAGE Publications.

Danjou, C., Pellerin, R., & Rivest, L. (2017). *Le passage au numérique : Industrie 4.0 : des pistes pour aborder l'ère du numérique et de la connectivité* [Rapport technique]. Centre francophone d'informatisation des organisations (CEFRIO). http://www.cefrio.qc.ca/publications/numerique-entreprise/le-passage-au-numerique/

de Bruin, T., Rosemann, M., Freeze, R., & Kulkarni, U. (2005). *Understanding the main phases of developing a maturity assessment model*. Sydney, NSW, Australia. Association for Information Systems.

DeJonckheere, M., & Vaughn, L. M. (2019). Semistructured interviewing in primary care research: a balance of relationship and rigour. *Family Medicine and Community Health*, *7*(2), e000057. 10.1136/fmch-2018-000057

Dohale, V., Verma, P., Gunasekaran, A., & Akarte, M. (2023). Manufacturing strategy 4.0: a framework to usher towards industry 4.0 implementation for digital transformation. *Industrial Management and Data Systems*, *123*(1), 10-40. 10.1108/IMDS-12-2021-0790

Durek, V., Kadoic, N., & Begičević Ređep, N. (mai 2018). *Assessing the digital maturity level of higher education institutions*. 2018 41st International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO) (p. 0671-0676). 10.23919/MIPRO.2018.8400126

European Commission. (2003). *SME definition*. https://single-market-economy.ec.europa.eu/smes/sme-fundamentals/sme-definition_en

Fantoni, G., Coli, E., Jorg, O., Tosello, G., & Calaon, M. (2025). Roadmapping Research and Development Initiatives in Digital Transformation of Industrial and Manufacturing Operations. *Applied Sciences*, *15*(13), 7172. 10.3390/app15137172

FCEI, F. canadienne de l'entreprise indépendante. (29 septembre 2025a). *L'adoption des technologies numériques et de l'IA est rentable pour les PME, mais inégale*. https://www.cfib-fcei.ca/fr/medias/ladoption-des-technologies-numériques-et-de-lia-est-rentable-pour-les-pme-mais-inégale

FCEI, F. canadienne de l'entreprise indépendante. (29 septembre 2025b). *Transformation numérique : Comment les PME canadiennes exploitent l'IA et les technologies pour* *stimuler leur croissance et leur productivité*. https://www.cfib-fcei.ca/fr/rapports-de-recherche/transformation-numerique-comment-les-pme-canadiennes-exploitent-lia-et-les-technologies-pour-stimuler-leur-croissance-et-leur-productivite

Ferrari, A., Bacco, M., Gaber, K., Jedlitschka, A., Hess, S., Kaipainen, J., … Brunori, G. (2022). Drivers, barriers and impacts of digitalisation in rural areas from the viewpoint of experts. *Information and Software Technology*, *145*, 106816. 10.1016/j.infsof.2021.106816

Ferreira, J. J., Lopes, J. M., Gomes, S., & Rammal, H. G. (2023). Industry 4.0 implementation: Environmental and social sustainability in manufacturing multinational enterprises. *Journal of Cleaner Production*, *404*, 136841. 10.1016/j.jclepro.2023.136841

Flick, U. (2022). An Introduction to Qualitative Research, 1-100.

Fortier, J., Gamache, S., & Fonrouge, C. (2025). Integrating Sustainable Performance into the Digital Maturity Models for SMEs in Manufacturing. *Applied Sciences*, *15*(7), 4041. 10.3390/app15074041

Gamache, S., Abdul-Nour, G., & Baril, C. (2019). Development of a Digital Performance Assessment Model for Quebec Manufacturing SMEs. *Procedia Manufacturing*, *38*, 1085-1094. 10.1016/j.promfg.2020.01.196

Ganzarain, J., & Errasti, N. (2016). Three stage maturity model in SME's toward industry 4.0. *Journal of Industrial Engineering and Management*, *9*(5), 1119. 10.3926/jiem.2073

Ghobakhloo, M., Iranmanesh, M., Vilkas, M., Grybauskas, A., & Amran, A. (2022). Drivers and barriers of Industry 4.0 technology adoption among manufacturing SMEs: a systematic review and transformation roadmap. *Journal of Manufacturing Technology Management*, *33*(6), 1029-1058. 10.1108/JMTM-12-2021-0505

Gökalp, E., & Martinez, V. (2022). Digital transformation maturity assessment: development of the digital transformation capability maturity model. *International Journal of Production Research*, *60*(20), 6282-6302. 10.1080/00207543.2021.1991020

Görçün, Ö. F., Mishra, A. R., Aytekin, A., Simic, V., & Korucuk, S. (2024). Evaluation of Industry 4.0 strategies for digital transformation in the automotive manufacturing industry using an integrated fuzzy decision-making model. *Journal of Manufacturing Systems*, *74*, 922-948. 10.1016/j.jmsy.2024.05.005

Government of Canada, S. C. (24 janvier 2022a). *NAICS 2022 Version 1.0 - 31-33 - Manufacturing*. https://www23.statcan.gc.ca/imdb/p3VD.pl?Function=getVD&TVD=1369825&CVD=1369826&CPV=31-33&CST=27012022&CLV=1&MLV=5

Government of Canada, S. C. (25 janvier 2022b). *Introduction to the North American Industry Classification System (NAICS) Canada 2022 Version 1.0*. https://www.statcan.gc.ca/en/subjects/standard/naics/2022/v1/introduction

Government of Canada, S. C. (28 juillet 2023). *Obstacles to the adoption of advanced technologies, by industry and enterprise size*. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2710039201

Guest, G., Namey, E., & Chen, M. (2020). A simple method to assess and report thematic saturation in qualitative research. *PLOS ONE*, *15*(5), e0232076. 10.1371/journal.pone.0232076

Haryanti, T., Rakhmawati, N. A., & Subriadi, A. P. (2023). The Extended Digital Maturity Model. *Big Data and Cognitive Computing*, *7*(1). 10.3390/bdcc7010017

Hasson, F., Keeney, S., & McKenna, H. (2025). Revisiting the Delphi technique - Research thinking and practice: A discussion paper. *International Journal of Nursing Studies*, *168*, 105119. 10.1016/j.ijnurstu.2025.105119

Hein-Pensel, F., Winkler, H., Brückner, A., Wölke, M., Jabs, I., Mayan, I. J., … Zinke-Wehlmann, C. (2023). Maturity assessment for Industry 5.0: A review of existing maturity models. *Journal of Manufacturing Systems*, *66*, 200-210. 10.1016/j.jmsy.2022.12.009

Hlel, J., Yahia, N. B., & Saoud, N. B. B. (2025). Explainable Assessment Model for Digital Transformation Maturity. https://www.scitepress.org/Papers/2025/134593/134593.pdf

Innovation, F., Science, & Canada, E. D. (1 avril 2025). *Key Small Business Statistics 2024*. Innovation, Science and Economic Development Canada. https://ised-isde.canada.ca/site/sme-research-statistics/en/key-small-business-statistics/key-small-business-statistics-2024

ISDE, I., Sciences et Développement économique Canada. (11 janvier 2024). *Principales statistiques relatives aux petites entreprises 2022*. Innovation, Sciences et Développement économique Canada. https://ised-isde.canada.ca/site/recherche-statistique-pme/fr/principales-statistiques-relatives-aux-petites-entreprises/principales-statistiques-relatives-aux-petites-entreprises-2022

Jayson Myers. (2019). *Next Generation Manufacturing Canada Advanced Manufacturing Supercluster Five-Year Strategy*. Next Generation Manufacturing Canada (NGen). https://www.ngen.ca/hubfs/Documents/NGenFiveYearStrategy_EN_V1.0.pdf?hsLang=en

Jie, H., Gooi, L. M., & Lou, Y. (2025). Digital maturity, dynamic capabilities and innovation performance in high-tech SMEs. *International Review of Economics & Finance*, *99*, 103971. 10.1016/j.iref.2025.103971

Joblot, L., Florian, M., Rosin, F., Pellerin, R., & Passalacqua, M. (juin 2023). *Protocole expérimental visant l'étude de l'IA centrée sur l'humain dans le contexte de l'Industrie 5.0 : Application en réalité augmentée*. Trois Rivières, Canada. https://hal.science/hal-04142374

Kampoowale, I., Hussien Musa, A. M., Adam Abdalla, A. A., Iftikhar, H., Abdelraheem, A. A. E., & Elamin Elboukhari, Y. A. (2025). Assessing the mediating role of human capital in the relationship between digital transformation and firm performance. *Journal of Manufacturing Technology Management*, 1-22. 10.1108/JMTM-02-2025-0122

Kane, G. C. (4 avril 2017). *Digital Maturity, Not Digital Transformation*. MIT Sloan Management Review. https://sloanreview.mit.edu/article/digital-maturity-not-digital-transformation/

Kane, G. C., Palmer, D., & Phillips, A. N. (2017). *Achieving Digital Maturity* [Technical Report]. MIT Sloan Management Review. https://sadil.ws/handle/123456789/1453

Kannan, S., & Gambetta, N. (2025). Technology-driven Sustainability in Small and Medium-sized Enterprises: A Systematic Literature Review. *Journal of Small Business Strategy*, *35*(1), 129-157. 10.53703/001c.126636

Kanyepe, J., Musasa, T., & Wilbert, M. (2025). Supply chain risk factors, technological capabilities, and firm performance of small to medium enterprises (SMEs). *Journal of Small Business Strategy*, *35*(1), 115-128.

Kaya, hsan, Karaan, A., Guvercin, O., lbahar, E., & Baracli, H. (2023). Appraisal of smart factory design for advance manufacturing plants based on transition strategies by using an integrated fuzzy decision-making methodology. *International Journal of Computer Integrated Manufacturing*, *36*(8), 1153-1177. 10.1080/0951192X.2023.2177735

Khan, M., Haleem, A., & Javaid, M. (2023). Changes and improvements in Industry 5.0: A strategic approach to overcome the challenges of Industry 4.0. *Green Technologies and Sustainability*, *1*(2). 10.1016/j.grets.2023.100020

Khatami, F., De Bernardi, P., Vilamová, Š., Cagno, E., & Ricciardi, F. (2024). Innovation ecosystem for smart product: empirical quantification of its key dimensions in SMEs of 21 European countries. *Review of Managerial Science*, *18*(9), 2723-2748. 10.1007/s11846-024-00763-z

Klarner, L., Řehoř, P., Vrchota, J., & Maříková, M. (2025). Change management in SMEs in the Era of Industry 4.0. *Procedia Computer Science*, *256*, 1451-1458. 10.1016/j.procs.2025.02.278

Kovacic, Z., García Casañas, C., Argüelles, L., Yáñez Serrano, P., Ribera-Fumaz, R., Prause, L., & March, H. (2024). The twin green and digital transition: High-level policy or science fiction? *Environment and Planning E: Nature and Space*, *7*(6), 2251-2278. 10.1177/25148486241258046

Krippendorff, K. (2018). *Content Analysis: An Introduction to Its Methodology*. SAGE Publications.

Kumar, R., Singh, R. Kr., & Dwivedi, Y. Kr. (2020). Application of industry 4.0 technologies in SMEs for ethical and sustainable operations: Analysis of challenges. *Journal of Cleaner Production*, *275*, 124063. 10.1016/j.jclepro.2020.124063

Kumar, S., Raut, R. D., Aktas, E., Narkhede, B. E., & Gedam, V. V. (2023). Barriers to adoption of industry 4.0 and sustainability: a case study with SMEs. *International Journal of Computer Integrated Manufacturing*, *36*(5), 657-677. 10.1080/0951192X.2022.2128217

Leso, B. H., Cortimiglia, M. N., & Ghezzi, A. (2023). The contribution of organizational culture, structure, and leadership factors in the digital transformation of SMEs: a mixed-methods approach. *Cognition, Technology & Work*, *25*(1), 151-179. 10.1007/s10111-022-00714-2

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P. A., … Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration. *BMJ*, *339*, b2700. 10.1136/bmj.b2700

Lichtblau, K., Stich, V., Bertenrath, R., Blum, M., Bleider, M., Millack, A., … Schröter, M. (2015). Industrie 4.0-Readiness (IMPULS). https://epub.fir.de/frontdoor/index/index/docId/2569

Linstone, H. A., & Turoff, M. (1975). *The delphi method*. Addison-Wesley Reading, MA. https://www.academia.edu/download/29694542/delphibook.pdf

Marcos, S., Reis, J., Pereira, R. H., & P, I. A. (2024). Digital Maturity Model for Industries SMEs: A Systematic Literature Review. *CAPSI 2024 Proceedings*. https://aisel.aisnet.org/capsi2024/5

Martincevic, I. (2022). The Correlation Between Digital Technology and Digital Competitiveness. *INTERNATIONAL JOURNAL FOR QUALITY RESEARCH*, *16*(2), 541-558. 10.24874/IJQR16.02-13

Martins, F. S., Fornari Junior, J. C. F. B., Mazieri, M. R., & Gaspar, M. A. (2023). A fuzzy AHP analysis of potential criteria for initiatives in digital transformation for agribusiness. *RAM. Revista de Administração Mackenzie*, *24*, eRAMR230055. https://doi.org/10.1590/1678-6971/eRAMR230055.en

Masood, T., & Sonntag, P. (2020). Industry 4.0: Adoption challenges and benefits for SMEs. *Computers in Industry*, *121*, 103261. 10.1016/j.compind.2020.103261

Merín-Rodrigáñez, J., Dasí, À., & Alegre, J. (2024). Digital transformation and firm performance in innovative SMEs: The mediating role of business model innovation. *Technovation*, *134*, 103027. 10.1016/j.technovation.2024.103027

Mick, M. M. A. P., Kovaleski, J. L., & Chiroli, D. M. de G. (2024). Sustainable Digital Transformation Roadmaps for SMEs: A Systematic Literature Review. *Sustainability*, *16*(19), 8551. 10.3390/su16198551

Mittal, A., Kumar, V., Verma, P., & Singh, A. (2022). Evaluation of organizational variables of quality 4.0 in digital transformation: the study of an Indian manufacturing company. *The TQM Journal*, *36*(1), 178-207. 10.1108/TQM-07-2022-0236

Mittal, Muztoba Ahmad Khan, David Romero, & Thorsten Wuest. (2018). A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs). *JOURNAL OF MANUFACTURING SYSTEMS*, *49*, 194-214. 10.1016/j.jmsy.2018.10.005

Mittal, S., Khan, M. A., Purohit, J. K., Menon, K., Romero, D., & Wuest, T. (2020). A smart manufacturing adoption framework for SMEs. *International Journal of Production Research*, *58*(5), 1555-1573. 10.1080/00207543.2019.1661540

Mittal, S., Romero, D., & Wuest, T. (2018). Towards a Smart Manufacturing Maturity Model for SMEs (SM3E). Dans I. Moon, G. M. Lee, J. Park, D. Kiritsis, & G. Von Cieminski (édit.), *Advances in Production Management Systems. Smart Manufacturing for Industry 4.0* (vol. 536, p. 155-163). Springer International Publishing. 10.1007/978-3-319-99707-0_20

Müller, J. M., Kiel, D., & Voigt, K.-I. (2018). What Drives the Implementation of Industry 4.0? The Role of Opportunities and Challenges in the Context of Sustainability. *Sustainability*, *10*(1), 247. 10.3390/su10010247

Nasa, P., Jain, R., & Juneja, D. (2021). Delphi methodology in healthcare research: How to decide its appropriateness. *World Journal of Methodology*, *11*(4), 116-129. 10.5662/wjm.v11.i4.116

Njah, S., Danjou, C., Armellini, F., Beaudry, C., & Mosconi, E. (2026). A digital maturity model for assessing SMEs in the manufacturing sector. *Digital Engineering*, *9*, 100084. 10.1016/j.dte.2025.100084

Norouzi, H., ElMaraghy, W., & ElMaraghy, H. (2023). *A Maturity Assessment Model for Digital Twin-Value Stream Technology in Greenhouses*. Bologna, Italy (p. 725-734). Springer Science and Business Media Deutschland GmbH. 10.1007/978-3-031-34821-1_79

O'Connor, C., & Joffe, H. (2020). Intercoder Reliability in Qualitative Research: Debates and Practical Guidelines. *International Journal of Qualitative Methods*, *19*, 1609406919899220. 10.1177/1609406919899220

OECD. (2021). *The Digital Transformation of SMEs*. https://doi.org/10.1787/bdb9256a-en.

Ojukwu, P. U., Omokhoa, H. E., Odionu, C. S., Azubuike, C., & Sule, A. K. (2024). Digital transformation and optimization framework for advancing SME growth and operational effectiveness. *International Journal of Research and Innovation in Social Science*, *8*(12), 4607-4628.

Orzes, G., Rauch, E., Bednar, S., & Poklemba, R. (décembre 2018). *Industry 4.0 Implementation Barriers in Small and Medium Sized Enterprises: A Focus Group Study*. 2018 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM) (p. 1348-1352). 10.1109/IEEM.2018.8607477

Palinkas, L. A., Horwitz, S. M., Green, C. A., Wisdom, J. P., Duan, N., & Hoagwood, K. (2015). Purposeful sampling for qualitative data collection and analysis in mixed method implementation research. *Administration and policy in mental health*, *42*(5), 533-544. 10.1007/s10488-013-0528-y

Pelletier, C., & Cloutier, L. M. (2019). Conceptualising digital transformation in SMEs: an ecosystemic perspective. *Journal of Small Business and Enterprise Development*, *26*(6-7), 855-876. 10.1108/JSBED-05-2019-0144

Petrou, A. P., Hadjielias, E., Thanos, I. C., & Dimitratos, P. (2020). Strategic decision-making processes, international environmental munificence and the accelerated internationalization of SMEs. *International Business Review*, *29*(5), 101735. 10.1016/j.ibusrev.2020.101735

Phaal, R., Farrukh, C., & Probert, D. (2001). Technology Roadmapping: linking technology resources to business objectives. *Centre for Technology Management, University of Cambridge*, 1-18.

Phaal, R., Farrukh, C., & Probert, D. R. (2013). *Technology Management and Roadmapping at the Firm Level*. M. G. Moehrle, R. Isenmann, & R. Phaal (édit.), Berlin, Heidelberg (p. 13-29). Springer. 10.1007/978-3-642-33923-3_2

Pierre-Olivier Bédard-Maltais. (2017). *Industry 4.0: the new industrial revolution Are Canadian manufacturers ready?* the Business Development Bank of Canada (BDC). https://www.bdc.ca/en/about/analysis-research/industry-4-new-industrial-revolution

Pissareva, L., Bernal, M. S., Trapasso, R., & Velayos, J. (2025). Equipping SMEs with the skills to navigate the twin transition. *OECD SME and Entrepreneurship Papers*. https://search.proquest.com/openview/97bd1ad0f21ca29a37dcf434094aca51/1?pq-origsite=gscholar&cbl=6245956

Quenum, G. G. Y., Vallée, S., & Ertz, M. (2025). *The Digital Maturity of Small- and Medium-Sized Enterprises in the Saguenay-Lac-Saint-Jean Region* [Article publié dans une revue avec comité d'évaluation]. Machines. 10/1/machines-13-00835.pdf

Rahman, S. A., Taghizadeh, N. S., Tipu, S. A. A., & Far, S. M. (2025). Leveraging dynamic capabilities for digital transformation: Exploring the moderating role of cost in environmental performance of SMEs. *Journal of Open Innovation: Technology, Market, and Complexity*, *11*(2), 100523. 10.1016/j.joitmc.2025.100523

Re, N. U., Ghezzi, A., Balocco, R., & Rangone, A. (2023). *Modelling Digital Maturity for SMEs.* (p. 538-545). https://www.scitepress.org/Papers/2023/118282/118282.pdf

Rossmann, A. (1 janvier 2019). *Digital Maturity: Conceptualization and Measurement Model*.

Saad, S. M., & Alnuiami, S. (2022). *Development of a Digital Innovation Framework that is Renowned Globally*. Linz, Austria (vol. 217, p. 895-903). Elsevier B.V. 10.1016/j.procs.2022.12.286

Saldana, J. (2021). The Coding Manual for Qualitative Researchers, 1-440.

Saldana, J., & Omasta, M. (2016). *Qualitative Research: Analyzing Life*. SAGE Publications.

Samaranayake, P., Ramanathan, K., & Laosirihongthong, T. (décembre 2017). *Implementing industry 4.0 — A technological readiness perspective*. 2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Singapore (p. 529-533). IEEE. 10.1109/IEEM.2017.8289947

Santiago, S. B., & Silva, J. R. (2023). *Strategic Roadmap for Digital Transformation Based on Measuring Industry 4.0 Maturity and Readiness*. Berlin, Germany (p. 336-47). Springer Nature. 10.1007/978-3-031-49339-3_21

Schlaepfer, D. R. C., & Koc, M. (2015). Deloitte AG, Industry 4.0: Challenges and Solutions for the Digital Transformation and Use of Exponential Technologies, Audit, Tax, Consulting. *Corporate Finance*.

Schneider, P., Evaniew, N., Rendon, J. S., McKay, P., Randall, R. L., Turcotte, R., … Ghert, M. (2016). Moving forward through consensus: protocol for a modified Delphi approach to determine the top research priorities in the field of orthopaedic oncology. *BMJ Open*, *6*(5), e011780. 10.1136/bmjopen-2016-011780

Schuh, G., Anderl, R., Dumitrescu, R., & Krüger, A. (2020). *Industrie 4.0 Maturity Index Managing the Digital Transformation of Companies*.

Schumacher, A., Erol, S., & Sihn, W. (2016). A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises. *6th International Conference on Changeable, Agile, Reconfigurable and Virtual Production, CARV 2016, September 4, 2016 - September 6, 2016*, *52*, 161-166. 10.1016/j.procir.2016.07.040

Schumacher, A., Nemeth, T., & Sihn, W. (2019). *Roadmapping towards industrial digitalization based on an Industry 4.0 maturity model for manufacturing enterprises* (vol. 79, p. 409-414). 10.1016/j.procir.2019.02.110

Schwab, K. (2017). *The fourth industrial revolution. Currency*. World Economic Forum.

Scremin, L., Armellini, F., Brun, A., Solar-Pelletier, L., & Beaudry, C. (2018). Towards a Framework for Assessing the Maturity of Manufacturing Companies in Industry 4.0 Adoption. Dans *Analyzing the Impacts of Industry 4.0 in Modern Business Environments* (p. 224-254). IGI Global. 10.4018/978-1-5225-3468-6.ch012

Shahzad, K., & Hafeez, S. (2022). *Digitalization of SMEs : an ecosystem-based perspective*. Lappeenranta University of Technology. https://osuva.uwasa.fi/handle/11111/2626

Shang, Z. (2023). Use of Delphi in health sciences research: A narrative review. *Medicine*, *102*(7), e32829. 10.1097/MD.0000000000032829

Sjodin, D. R., Parida, V., Leksell, M., & Petrovic, A. (2018). Smart Factory Implementation and Process Innovation A Preliminary Maturity Model for Leveraging Digitalization in Manufacturing. *RESEARCH-TECHNOLOGY MANAGEMENT*, *61*(5), 22-31. 10.1080/08956308.2018.1471277

Statistics Canada. (28 juillet 2023a). Measures taken to reduce obstacles to the adoption of advanced technologies in Canada and Quebec - Table 27-10-0393-01. https://doi.org/10.25318/2710039301-eng

Statistics Canada. (1 août 2023b). Objectives of adopting advanced technologies for manufacturing SMEs in Canada -Table 27-10-0391-01. https://doi.org/10.25318/2710039101-eng

Statistics Canada. (30 avril 2024). Use of advanced or emerging technologies in Canada and Quebec - Table 27-10-0367-01. https://doi.org/10.25318/2710036701-eng

Succurro, M., & Donati, C. (2025). The role of the regulatory framework in enhancing SMEs' digital transformation. *International Review of Law and Economics*, *83*, 106263. 10.1016/j.irle.2025.106263

Supply Chain Canada (SCC) - National. (2023). *Adopting Digitization and Its Impact on Skills*. https://www.supplychaincanada.com/media/files/supply-chain-trends-precis.pdf

Sutrisno, S. (2023). The role of partnerships and business networks in the growth of MSMEs in the digital age. *Technology and society perspectives (TACIT)*, *1*(3), 122-131.

Swain, J. (2018). A Hybrid Approach to Thematic Analysis in Qualitative Research: Using a Practical Example. *Sage Research Methods*. http://doi.org/10.4135/9781526435477

Teichert, R. (2019). Digital Transformation Maturity: A Systematic Review of Literature. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, *67*, 1673-1687. 10.11118/actaun201967061673

Tonder, C. van, Bossink, B., Schachtebeck, C., & Nieuwenhuizen, C. (2024). Key Dimensions That Measure The Digital Maturity Levels Of Small And Medium-Sized Enterprises (SMEs). *Journal of Technology Management and Innovation | Innovation for Social and Sustainable Progress*, *19*(1), 110-130. 10.4067/S0718-27242024000100110

Touijer, M. N., & Elabjani, A. (2025). A Delphi study on digital maturity and digital competitiveness in the context of digital transformation. *JOURNAL OF ENTERPRISING COMMUNITIES-PEOPLE AND PLACES IN THE GLOBAL ECONOMY*. 10.1108/JEC-05-2024-0088

Valdez-de-Leon, O. (2016). A Digital Maturity Model for Telecommunications Service Providers. *Technology Innovation Management Review*, *6*(8).

Verhoef, P. C., Broekhuizen, T., Bart, Y., Bhattacharya, A., Qi Dong, J., Fabian, N., & Haenlein, M. (2021). Digital transformation: A multidisciplinary reflection and research agenda. *Journal of Business Research*, *122*, 889-901. 10.1016/j.jbusres.2019.09.022

Vial, G. (2019). Understanding digital transformation: A review and a research agenda. *The Journal of Strategic Information Systems*, *28*(2), 118-144. 10.1016/j.jsis.2019.01.003

Wang, D., & Shao, X. (2024). Research on the impact of digital transformation on the production efficiency of manufacturing enterprises: Institution-based analysis of the threshold effect. *International Review of Economics & Finance*, *91*, 883-897. 10.1016/j.iref.2024.01.046

Wei, L., Wang, D., & Wang, Y. (2025). Generalized relative entropy: New look at Rényi entropy and its exploration from complexity measures to sparsity measures with applications in machine condition monitoring. *Mechanical Systems and Signal Processing*, *223*, 111917. 10.1016/j.ymssp.2024.111917

Weiner, E. S., & Simpson, J. A. (1989). The Oxford English Dictionary. *Oxford*, *21989*, 65.

Wendler, R. (2012). The maturity of maturity model research: A systematic mapping study. *Information and Software Technology*, *54*(12), 1317-1339. 10.1016/j.infsof.2012.07.007

Westerman, G., Bonnet, D., & McAfee, A. (2014). *Leading Digital: Turning Technology Into Business Transformation*. Harvard Business Press.

Williams, C., Krumay, B., Schallmo, D., & Scornavacca, E. (2024). Digital Maturity Model for SMEs: Validation Through a Mixed-Method Approach. *Pacific Asia Journal of the Association for Information Systems*, *16*(1). 10.17705/1pais.16102

Xu, X., Lu, Y., Vogel-Heuser, B., & Wang, L. (2021). Industry 4.0 and Industry 5.0—Inception, conception and perception. *Journal of Manufacturing Systems*, *61*, 530-535. 10.1016/j.jmsy.2021.10.006

Yimen, N., Tchotang, T., Kanmogne, A., Adamu, Y., Fon, F. L., & Dagbasi, M. (2022). Brown–Gibson Model as a Multi-criteria Decision Analysis (MCDA) Method: Theoretical and Mathematical Formulations, Literature Review, and Applications. Dans A. J. Kulkarni (édit.), *Multiple Criteria Decision Making: Techniques, Analysis and Applications* (p. 169-191). Springer Nature. 10.1007/978-981-16-7414-3_9

Yin, R. K., Campbell, D. T. (Donald T., & Sage Publications. (2018). *Case study research and applications: design and methods* (Sixth edition). SAGE Publications, Inc.

Zhou, Y., Yang, C., Liu, Z., & Gong, L. (2024). Digital technology adoption and innovation performance: a moderated mediation model. *Technology Analysis & Strategic Management*, *36*(11), 3341-3356. 10.1080/09537325.2023.2209203

Zhu, H., Wang, L., Li, C., Philbin, S. P., Li, H., Li, H., & Skitmore, M. (2024). Building a Digital Transformation Maturity Evaluation Model for Construction Enterprises Based on the Analytic Hierarchy Process and Decision-Making Trial and Evaluation Laboratory Method. *Buildings*, *14*(1), 91. 10.3390/buildings14010091

ANNEXE A QUALITATIVE DATA STRUCTURE AND CODES

Table A.1 Qualitative data structure and codes

1st Order code	2nd Order code	Category
Process adaptability; Operational agility	Improving flexibility of processes and operations	Objectives of adopting advanced technologies
Structural adaptation; Knowledge transfer; Change readiness	Improving organizational flexibility	
Increasing market share; Competitive differentiation	Improving competitiveness	
Improving productivity; Improving service quality; Improving product quality	Performance enhancement	
Sustainability; Short-term versus long-term vision	Business sustainability	
Agility; Adaptability; Reactivity	Resilience	
Best practices in SMEs; Industry standards in large companies; Industry 4.0 opportunities for SMEs; Market positioning	Competitive benchmarking	Strategic planning tools
Market demand; Customer expectations	Customer needs analysis	
Risk evaluation in collaborations; Partners assessment	Partners assessment	
Human resources assessment; Technological resources assessment; Financial resources assessment	Internal resource assessment	
Corrective actions after audits	Audit-Based Strategic Planning	
Ad-hoc planning; Experience-based strategy; Hypothesis-driven strategy; Creativity; Leadership insights	Intuitive thinking	
Board-driven decisions; Vertical decision-making; CEO's role	Executive committee meetings	
Roadmap	Roadmapping	
Predictive analytics; Data insights; Real-time analytics	Big Data and analytics	Use of advanced technologies
Cloud infrastructure; Scalability; Cloud storage	Cloud	
Data protection; System security; Threats	Cybersecurity	
Business process integration; Supply chain management; Resource planning; Enterprise software	Enterprise Resource Planning (ERP)	
Artificial Intelligence	Artificial Intelligence	
Smart sensors; Internet Of Things	Internet Of Things	
Automation; Robotics	Autonomous machines	
Interactive visualization	Augmented reality (AR)	
Embedded systems	Cyber-physical systems (CPS)	

Table A.1 Qualitative data structure and codes (continued)

1st Order code	2nd Order code	Category
Difficulty identifying appropriate technologies for existing systems and processes; Difficulty integrating new technologies into existing systems and processes; Complexity of new technologies; Data security and privacy concerns; Lack of IT infrastructure readiness; Data management and interoperability	Technological integration challenges	Obstacles to the adoption of advanced technologies
Low return on investment (ROI); Long payback period; High cost of technologies; Limited access to funding or financial resources; Uncertainty about cost-benefit outcomes	Financial challenges	
Priority management; Resource allocation; Project management; Lack of clear digital strategy; Short-term focus over long-term planning	Strategic constraints	
Difficulty in finding or interpreting regulatory standards; Difficulty in integrating regulatory standards; Compliance complexity; Rapidly changing regulations	Regulatory uncertainties or constraints	
Ineffective external support when buying technologies; Poor after-sales support or training; Lack of reliable technology vendors or consultants	Ineffective external support	
Lack of digital skills; Lack of employee training; Resistance to change; Shortage of manpower; Low digital literacy among staff; Limited internal knowledge transfer	Human Resource and Skills Challenges	
Dedicated digital team; Inter-departmental collaboration; Change management processes; Clear roles and responsibilities; Standardization of digital workflows	Organizational and Governance Initiatives	Measures taken to reduce digital transformation obstacles
Employee training programs; Identification of super-users; Recruiting digital skills; Communication and awareness-raising; Digital literacy development	Human Resource and Skills Development	
Investment in automation; Implement security policies to protect data; Adoption of cloud-based solutions; Collect digital data for decision-making and predictive analytics	Technology and Process Implementation	
Engage specialist consultants or external suppliers to solve digital problems; Collaboration with partners; Participation in industry networks; Benchmarking best practices with peers	External Support and Collaboration	
Encourage innovation and experimentation; Performance bonuses; Access to public or private funding opportunities for digital projects; Resource prioritization for high-impact digital initiatives	Innovation and Resource Management	

ANNEXE B DMM'S DIMENSIONS, SUB-DIMENSIONS AND KPIS

Table B.1 DMM's dimensions, sub-dimensions and KPIs

Dimension	Sub-dimension	KPI
Strategy and governance	Business model & Digital strategy	Ability of the organization to integrate digital technology into its business model and strategy.
	Digital implementation monitoring	Deployment of key performance indicators (KPIs) to assess the implementation of the digital transformation.
	Digital plan & roadmap	Availability of a documented, reviewed and communicated digital plan/technological roadmap to support the digital strategy.
	Digital leadership	Availability of sponsors to support the digital transformation projects.
		Involvement of managers to support the digital transformation projects.
	Digital challenges	Ability of the organization to identify the digital transformation obstacles (Lack of digital skills; employee resistance to digital change; customer resistance to digital change; low return on investment or long payback period; difficulty accessing financial support; difficulty integrating new technologies into existing systems and processes; production disruption when integrating new technologies; difficulty ensuring data security and confidentiality; regulatory constraints or uncertainties, or other)
	Management modes	Existence of a mitigation plan for identified obstacles.
		Ability of the organization to promote collaborative versus hierarchical practices.
		Ability of the organization to manage resistance to digital changes to support the organization's digital transformation.
	Technological watch & Benchmarking	Ability of the organization to leverage the results of technological watch for decision-making.
		Ability of the organization to leverage the results of benchmarking for decision-making.
	Investment	Adequacy of financial investments to support the organization's digital strategy and the digital transformation projects.
	Funding	Ability of the organization to understand and leverage available funding sources to support the organization's digital transformation.
	Technology adoption methods	Methods used to acquire and integrate advanced technologies.
Human Resources and digital skills	Skills & expertise	Availability of an appropriate structuring of the digital competencies to support the organization's digital transformation.
	Hiring	Adequacy of the human resources hiring strategy to support the organization's digital transformation.
	Training	Adequacy of the resources for the employees to train and acquire the digital competencies required for the organization's digital transformation.
	Work modes	Ability of the organization to leverage digital devices and alternative working modes to work remotely and promote mobility.

Table B.1 DMM's dimensions, sub-dimensions and KPIs (continued)

Dimension	Sub-dimension	KPI
Industrial systems and value chain	Traceability	Availability of traceability for real-time monitoring of the organization's internal and external processes.
	Internal value chain management	Ability of the organization to digitalize processes for internal value chain management (ERP implementation).
	Production digitalization	Ability of the organization to implement workpiece's autonomous and self-guiding capacities through production
		Ability of the organization to digitalize equipment and processes in order to monitor, control, optimize and automate production (e.g. loading/unloading, operation, transportation, quality checks) (MES and smart equipment implementation).
	Agility	Ability of the organization to efficiently manage small batch sizes and dynamically adapt the production to varying requests and manufacturing conditions.
	Inventory	Ability of the organization to leverage digital technologies for inventory management (WMS implementation).
	External collaboration	Ability of the organization to collaborate with external partners (academics, suppliers, customers, subcontractors, etc.) in order to support the implementation and deployment of its digital transformation projects.
	Customer experience	Ability of the organization to leverage the customer experience as part of product and service improvement processes.
	Selling & purchasing	Ability of the organization to integrate and leverage software tools and IT technologies within the selling/purchasing processes (ordering, quoting, shipping/receiving and billing/paying).
Portfolio, products and services	Smart products & services	Ability of the organization to develop smart products and services based on data acquisition and exploitation (integrating additional functionalities (such as memorization, localization, self-reporting, tracking, and self-analysis) during both production and usage phases).
	Lifecycle simulation	Ability of the organization to model and simulate the entire product lifecycle from early design to recycling.
	Customization	Ability of the organization to enhance customer experience by means of products/services customization.
	Online sales	Availability of online sales platform that enables customer-controlled product customization and direct order placement.
	Communication & marketing	Ability of the organization to leverage multiple communication/marketing channels (e.g. website, social media) and software tools to interact and engage with customers, while monitoring and controlling its digital footprint.

Table B.1 DMM's dimensions, sub-dimensions and KPIs (continued)

Dimension	**Sub-dimension**	**Indicator**
Information technology (IT), data and security	Infrastructure	Availability of high-performance IT infrastructure for digital transformation strategy support.
	Software tools	Ability of the organization to leverage software tools and systems to foster collaboration and collective intelligence.
		Ability of the organization to leverage digital continuity between machines and production management systems.
	Data acquisition & processing	Ability of the organization to efficiently collect and leverage digital data (e.g. collect, aggregation, structuring, analysis, quality check).
	Data usage	Ability of the organization to leverage digital data to support its activities (e.g. predictive maintenance, automatic production, risk management, performances analysis, production campaign adaptation, services, decision-making, product development and improvement, changes, services creation, dashboard creation, self-diagnosing, self-scheduling).
	Digital security	Ability of the organization to implement Cybersecurity solutions for data integrity, confidentiality and availability throughout the organization.
	Digital compliance	Ability of the organization to ensure that the digital compliance policy (laws and best practices) is understood and respected.
	Adoption of advanced technologies	Adoption of Big Data and analytics.
		Adoption of Artificial Intelligence (AI).
		Adoption of CLOUD computing.
		Adoption of Internet Of Things (IoT).
		Adoption of Cyber-Physical Systems (CPS).
		Adoption of Cybersecurity.
		Adoption of Autonomous machines.
		Adoption of Machine To Machine (M2M).
		Adoption of Simulation.
		Adoption of Augmented Reality (AR).

ANNEXE C SUPPLEMENTARY MATERIAL - INTERVIEW GUIDE

(A French version is provided below – La version française est fournie ci-dessous.)

I. Interview protocol

1. **General information**

You are invited to participate in the research project "Assessment of Digital Maturity in manufacturing SMEs", conducted by a team of researchers from a university in Quebec, Canada.

This interview aims to explore the experiences of manufacturing SMEs in the Industry 4.0 era. It focuses on their objectives in adopting digital transformation, the strategic planning tools they employ, the advanced technologies they use, the challenges they face, and the strategies they put in place to address them.

The insights gathered will contribute to the development of a Digital Maturity Model designed to assess manufacturing SMEs in light of their unique characteristics. This model will provide a reliable overview of their current maturity level and offer guidance on how they can progress to higher levels of digital maturity.

This study specifically targets senior executives, operation managers and digital technology managers working in manufacturing SMEs comprising less than 499 employees or that generate annual revenues less than $20,000,000.

2. **Research question**

This study aims to assess the digital maturity of manufacturing SMEs, considering technological, managerial, and organizational dimensions, in order to identify their special needs and guide them in their Industry 4.0 transition journey.

3. **Type of participation**

- Your participation will be based on an interview that lasts approximately 60 minutes.
- The interview will be conducted in person or online at a convenient time.
- The interview will be recorded to facilitate a thorough analysis of the information gathered.

4. Data privacy policy

This study has received ethical approval from the university's research ethics committee for studies involving human participants. You are required to read and sign the information and consent form before the start of the interview.

Key Points on Data Privacy:

- Participation is voluntary and you may stop the interview at any time.
- Your responses will remain anonymous and no personal information will be collected.
- All recordings and data will be kept strictly confidential and accessible only to the research team.
- Data will be summarized and coded so that no individual or company can be identified.
- The information collected will be used only for the purposes of this project and for scientific communication.

II. Interview procedure

Preliminary information:

- ***Name of the interviewer:***
- ***Name of the interviewee or the company involved:***
- ***Date and time:***
- ***Did the interviewee agree to record this interview?***

1. Initial contact

The objective of this initial phase is to create a comfortable atmosphere for participants during the interview and establish a trusting relationship. The interviewer will begin by introducing himself/herself, restating the purpose of the interview, and ensuring that the participant understands that all information given during the interview will be treated confidentially (Yin et al., 2018).

It is crucial, in this part, to have a good understanding of the interviewee's background and familiarity with their company to establish a strong basis for effective communication and a productive collaboration throughout the interview (DeJonckheere & Vaughn, 2019).

Question (1.1): Before we begin, could you please introduce yourself?

- Could you tell us about your academic and professional background?
- What is your position in the company and could you briefly describe it to us?
- Do you currently use technology and digital tools to support your work?

Question (1.2): Could you briefly introduce your company?

- What are your company's core activities?
- What are the key products or services that your company offers?
- What is your company's size in terms of employees and revenues?

Question (1.3): Do you have any specific concerns or questions about this interview?

* This question aims to clarify the participant's expectations.

2. Objectives of adopting advanced technologies

Question (2.1): Company's vision (Inspired by Canhoto et al., 2021)

- What is the long-term vision of your company?
- What are your objectives regarding digital transformation?
- How are these objectives aligned with your company's overall strategy?
- How does your company determine its "optimal" level of digital maturity?
- Are there any digital transformation projects currently underway?
- How do you prioritize between different potential digital initiatives (examples: efficiency, customer service, innovation)?

Question (2.2): Perceived value of digitalization (Inspired by Canhoto et al., 2021; OECD, 2021)

- How would you rate your company's digital maturity level?
- What impact has digital transformation had on: Operational efficiency/Productivity/ Customer satisfaction/Data management...
- Do you have a concrete example of a digital initiative you've implemented with positive results?
- Have you noticed any competitive advantages that digitalization has brought to your company?
- What are the main expected benefits from digitalization in the next 3-5 years?

3. Strategic planning tools

Question (3.1): Strategic management (Inspired by Petrou et al., 2020)

- What tools or methods do you use for planning and implementing corporate strategies?
- How frequently is strategic planning conducted within your organization, and how is the planning horizon defined?
- How is strategic planning structured within your organization? Is there a dedicated department or team responsible for strategy formulation, implementation, monitoring, and follow-up?
- How is the planning process formalized?
- How are strategic objectives communicated across the organization?
- Do you use digital tools (dashboards, software, platforms) to support strategic planning?
- How do you benchmark your digital maturity against competitors or industry standards?

Question (3.2): Collaborations and partnerships (Inspired by Kanyepe et al., 2025; Sutrisno, 2023)

- How does your company collaborate with external partners (e.g., startups, experts) to foster digital innovation?
- What digital tools or platforms do you use to enhance exchanges with partners and customers?
- As part of your policy, what share of your budget is allocated to innovation and digital investment?
- Have you established formal partnerships with universities, research institutes, or government programs to support your digital strategy?

Question (3.3): Innovation ecosystem (Inspired by (Khatami et al., 2024; Pelletier & Cloutier, 2019; Shahzad & Hafeez, 2022)

- How does your company take its innovation ecosystem into account when managing strategy?
- How does your company define its innovation ecosystem?
- Have you developed roadmaps to guide your strategy?

- How do you position yourself compared to competitors, suppliers, and customers in terms of digital adoption?
- How important are collaborations within your ecosystem to achieving your digital objectives?

4. <u>Adoption and challenges of advanced technologies</u>

Question (4.1): Internal organization and skills (Inspired by Leso et al., 2023; Pissareva et al., 2025)

- How are the leaders of your organization involved in the implementation of the digital strategy?
- What is your team's overall attitude toward digital technologies?
- Do you have a dedicated team for digital transformation?
- What are your company's needs in terms of digital skills?
- Do you rely on external support or consulting to carry out digital projects?
- What initiatives has your company undertaken to develop employees' digital skills?

(Examples may include training and professional development, awareness and communication, mentoring and coaching, cross-functional collaboration, online learning resources, experimental projects, or recruitment based on digital competencies. Do not provide these examples before allowing the participant to respond.)

Question (4.2): Digital audit (Inspired by Cognet et al., 2023)

- Has your company already conducted a digital audit to diagnose its business processes, assess its digital maturity and have a formal digital plan?

If the answer is "YES":

- What is your company's position in a digitalizing market?
- Which areas do you think you need to focus on to improve your digital performance or reinforce your strengths in order to outperform your competitors?
- In general, how is supported the information management of your company's various processes?

If "NO":

- Have you implemented or planned any measures to assess the company's digital maturity?
- Is there a clear understanding of the company's strengths and weaknesses in terms of digital transformation?
- Which departments and processes do you think require digital improvement most?

Question (4.3): Data management (Inspired by OECD, 2021)

- Are data accessible within your company? If so, what tools do you use to collect and store them? (examples: connected sources, interoperability platforms)
- How are the collected and analyzed data used to support strategic decision-making in your company? (examples: local use, data lake deployment, archiving, or deletion practices)
- Have you implemented data security policies to protect your information? If yes, please specify which measures apply:
  - Isolated industrial network with controlled internal access
  - Secure remote connections through firewall and VPN with strong or multi-factor authentication
  - Employee training in cybersecurity
  - Data encryption and implementation of a threat/incident/attack management system
  - Defense-in-depth approach (reliable intrusion detection and prevention system)

Question (4.4): Over the past *three years, have you encountered the following obstacles (Government of Canada, 2023) **when adopting the ten groups of emerging technologies?**

* We will set the period at three years, as the surveys of advanced technologies and business innovation from Statistics Canada and several OECD countries use the same period to assess the adoption of advanced technologies and the readiness of companies to innovate.

This question is designed to simultaneously assess the level of adoption and the specific challenges faced for each technology group, thereby providing a diagnostic view of both technological transition and barriers encountered by SMEs.

Table C.1 Obstacles to the adoption of the ten groups of emerging technologies

Technology groups *(Danjou et al., 2017)*	Big Data and analysis	AI[1]	CLOUD	IoT[2]	CPS[3]	Cyber security	Autonomous machines	M2M[4]	Simulati-on	AR[5]
** Lack of employee skills*										
** Resistance to digital change (by employees, customers or suppliers)*										
** Difficulty in recruiting qualified staff*										
** Low return on investment or long payback period*										
** Difficulty in accessing financial support*										
** Difficulty integrating or identifying appropriate new technologies to existing systems, standards and processes*										
** Production disruption due to integration of new technologies*										
**Organizational difficulties*										
** Ensuring data security and confidentiality*										
** Regulatory constraints or uncertainties*										

AI[1] : Artificial Intelligence; IoT[2]: Internet of Things; CPS[3]: Cyber-Physical Systems; M2M[4]: Machine to Machine; AR[5]: Augmented Reality

Question (4.5): According to you, have these obstacles and unexpected events delayed or completely blocked the completion of your digitalization plan over the past three years?

5. Mitigation plans

Question (5.1): What actions has your company carried out over the last three years to reduce barriers to digital transformation? (Statistics Canada, 2023a)

The answer to this question should reveal whether the company is pursuing planned, clear and proactive strategies towards digitization, or, instead, is only reacting to problems as they occur.

Table C.2 Measures taken to reduction the digital transformation obstacles

Actions	☑
% Organizational and managerial actions *Example: Adopt a digital transformation organizational structure (dedicated digital transformation team, inter-departmental collaboration, training and skills development, communication and awareness).	
% Innovation initiatives *Example: Encourage innovation and experimentation (performance bonuses, availability of resources, etc.)	
% Digital integration actions *Example: Engage specialist consultants or external suppliers to solve digital problems.	
% Security policy actions *Example: Implement security policies to protect data.	
% Governance actions *Example: Implement digital systems integration governance.	
% Data usage *Example: Collect digital data for use in decision-making and predicting future trends.	
% Financial investments *Example: Establish a financing strategy for digital transformation projects	
% External support *Examples: Consulting firms / Collaborations with universities, research institutions / Government support…	
Other (specify)	
No action taken	

Question (5.2): Which of these actions do you consider the most effective?

6. Interview closure

At the end of the interview, participants will have the opportunity to ask further questions or provide additional information they consider relevant to the research project.

Guide d’entrevue (Version française)

I. Protocole de l’entrevue

1. Informations générales

Vous êtes invité à participer au projet de recherche « Évaluation de la maturité numérique des PME manufacturières », mené par une équipe de chercheurs d'une université du Québec, au Canada.

Cette entrevue vise à explorer les expériences des PME manufacturières à l'ère de l'Industrie 4.0. Elle se concentre sur leurs objectifs en matière de transformation numérique, les outils de planification stratégique qu'elles utilisent, les technologies de pointe qu'elles adoptent, les défis auxquels elles sont confrontées et les stratégies qu'elles mettent en place pour les relever.

Les informations recueillies contribueront au développement d'un modèle de mesure de la maturité numérique conçu pour évaluer les PME manufacturières en prenant en considération leurs caractéristiques uniques. Ce modèle fournira un aperçu fiable de leur niveau de maturité actuel et permettra de guider leur progression vers des niveaux de maturité numérique plus élevés.

Cette étude s’adresse aux hauts dirigeants, les directeurs des opérations ou les responsables des technologies numériques travaillant dans des PME manufacturières comptant moins de 499 employés ou générant un chiffre d'affaires annuel inférieur à 20 000 000 $.

2. Question de recherche

Cette étude vise à évaluer la maturité numérique des PME manufacturières, en prenant en considération les dimensions technologiques, managériales et organisationnelles, afin d'identifier leurs besoins spécifiques et de les guider dans leur transition vers l'Industrie 4.0.

3. Nature de participation

- Votre participation consistera en une entrevue d’une durée de 60 minutes environ.
- Cette entrevue s’effectuera en personne ou en ligne à un moment qui vous conviendra.
- L’entrevue sera enregistrée pour faciliter une analyse rigoureuse des informations recueillies.

4. Confidentialité des données

Cette étude a reçu les certifications éthiques du comité d'éthique pour la recherche avec les êtres humains de l'université. Vous devez lire et signer le formulaire d'information et de consentement avant le début de l'entrevue.

Principaux aspects de la confidentialité des données :

- Votre participation demeure volontaire et vous pouvez quitter l'entrevue à tout moment.
- Vos réponses resteront anonymes et aucune information personnelle ne sera collectée.
- Tous les enregistrements et toutes les données resteront strictement confidentiels et ne seront accessibles qu'à l'équipe de recherche.
- Les données seront résumées et codées et il ne sera pas possible d'identifier aucune personne ou entreprise.
- Les informations recueillies seront utilisées uniquement dans le cadre de ce projet et à des fins de communication scientifique.

II. Déroulement de l'entrevue

Informations préliminaires:

- ***Nom de l'intervieweur:***
- ***Nom de la personne interrogée ou de l'entreprise concernée:***
- ***Date et heure:***
- ***La personne interrogée a-t-elle accepté que cette entrevue soit enregistrée?***

1. Prise de contact

L'objectif de cette phase initiale est de créer une atmosphère confortable pour les participants pendant l'entrevue et d'établir une relation de confiance. L'intervieweur commencera par se présenter, rappeler l'objectif de l'entrevue et s'assurer que le participant comprend que toutes les informations fournies seront traitées de manière confidentielle (Yin et al., 2018).

Dans cette partie, il est essentiel de bien comprendre le parcours de la personne interrogée et sa position au sein de l'entreprise afin d'établir une base solide pour une communication efficace tout au long de l'entrevue (DeJonckheere et al., 2019).

Question (1.1): Avant de débuter, pourriez-vous vous présenter ?

- Pourriez-vous nous parler de votre parcours académique et professionnel ?
- Quel est votre poste au sein de l'entreprise et pourriez-vous nous le décrire brièvement ?
- Utilisez-vous actuellement des technologies et des outils numériques dans vos tâches ?

Question (1.2): Pourriez-vous nous parler brièvement de votre entreprise ?

- Quelles sont les activités principales de votre entreprise ?
- Quels sont les principaux produits ou services proposés par votre entreprise ?
- Quelle est la taille de votre entreprise en termes d'employés et de chiffre d'affaires ?

Question (1.3): Avez-vous des préoccupations ou des questions spécifiques concernant cette entrevue ? *Cette question sert à clarifier les attentes du participant.

2. <u>Objectifs de l'adoption de technologies numériques</u>

Question (2.1): Vision de l'entreprise (Inspirée par Canhoto et al., 2021)

- Quelle est la vision à long terme de votre entreprise ?
- Quels sont les objectifs de votre entreprise en termes de transformation numérique ?
- Comment ces objectifs sont-ils alignés avec la stratégie globale de votre entreprise ?
- Comment votre entreprise définit-elle le niveau « optimal » de maturité numérique ?
- Est-ce qu'il y a des projets de transformation numérique en cours d'exécution ?
- Comment définissez-vous les priorités entre les différentes initiatives numériques potentielles (exemples : efficacité, service à la clientèle, innovation) ?

Question (2.2): Valeur perçue de la transformation numérique (Inspirée par Canhoto et al., 2021; OECD, 2021)

- Comment jugez-vous le niveau de maturité numérique de votre entreprise ?
- Quel impact la transformation numérique a-t-elle eu sur : l'efficacité opérationnelle, la productivité, la satisfaction client, la gestion des données... ?
- Avez-vous un exemple concret d'initiative numérique que vous avez mise en œuvre et qui a donné des résultats positifs ?
- Avez-vous remarqué des avantages concurrentiels que la transformation numérique a apportés à votre entreprise ?

- Quels sont les principaux avantages attendus de la transformation numérique au cours des 3 à 5 prochaines années ?

3. <u>Outils de planification stratégique</u>

Question (3.1): Gestion stratégique (Inspirée par Petrou et al., 2020)

- Quels outils ou méthodes utilisez-vous pour planifier et mettre en œuvre les stratégies d'entreprise ?
- À quelle fréquence la planification stratégique est-elle effectuée au sein de votre organisation, et comment l'horizon de planification est-il défini ?
- Comment la planification stratégique est-elle structurée au sein de votre organisation ? Avez-vous un service ou une équipe dédié(e) à la formulation, à la mise en œuvre, au suivi et au contrôle de la stratégie ?
- Comment le processus de planification est-il formalisé ?
- Comment les objectifs stratégiques sont-ils communiqués au sein de l'organisation ?
- Utilisez-vous des outils numériques (tableaux de bord, logiciels, plateformes) pour soutenir la planification stratégique ?
- Comment évaluez-vous votre maturité numérique par rapport à vos concurrents ou aux normes du secteur ?

Question (3.2): Collaborations et partenariats (Inspirée par Kanyepe et al., 2025; Sutrisno, 2023)

- Comment votre entreprise collabore-t-elle avec les partenaires externes (par exemple, des start-ups, des experts) pour favoriser l'innovation numérique ?
- Quels outils ou plateformes numériques utilisez-vous pour améliorer les échanges avec vos partenaires et vos clients ?
- Dans le cadre de votre politique, quelle part de votre budget est allouée à l'innovation et à l'investissement numérique ?
- Avez-vous établi des partenariats officiels avec des universités, des instituts de recherche ou des programmes gouvernementaux afin de soutenir votre stratégie numérique ?

Question (3.3): Écosystème d'innovation (Inspirée par Khatami et al., 2024; Pelletier & Cloutier, 2019; Shahzad & Hafeez, 2022)

- Comment votre entreprise tient-elle compte de son écosystème d'innovation dans la gestion de sa stratégie ?
- Comment votre entreprise définit-elle son écosystème d'innovation ?
- Avez-vous élaboré des feuilles de route pour orienter votre stratégie ?
- Comment vous vous positionnez par rapport à vos concurrents, fournisseurs et clients en termes d'adoption du numérique ?
- Quelle est l'importance des collaborations au sein de votre écosystème pour atteindre vos objectifs numériques ?

4. <u>Adoption et défis des technologies avancées</u>

Question (4.1): Organisation interne et compétences (Inspirée par Leso et al., 2023; Pissareva et al., 2025)

- Comment les dirigeants de votre organisation participent-ils à la mise en œuvre de la stratégie numérique ?
- Quelle est l'attitude générale de votre équipe envers les technologies numériques ?
- Disposez-vous d'une équipe dédiée à la transformation numérique ?
- Quels sont les besoins de votre entreprise en matière de compétences numériques ?
- Faites-vous appel à une aide ou à des conseils externes pour mener à bien vos projets numériques ?
- Quelles initiatives votre entreprise a-t-elle prises pour développer les compétences numériques de ses employés ?

(Les exemples peuvent inclure la formation et le développement personnel, la sensibilisation et la communication, mentoring et coaching, collaboration interfonctionnelle, ressources d'apprentissage en ligne, projets d'expérimentations, processus de recrutement basé sur les aptitudes numériques…). * Ne pas donner les exemples avant de laisser la liberté au participant de répondre.

Question (4.2): Audit numérique (Inspirée par Cognet et al., 2023)

- Votre entreprise a-t-elle déjà réalisé un audit numérique afin d'évaluer sa maturité numérique et d'élaborer un plan numérique formel ?

Si la réponse est « OUI » :

- Quelle est la position de votre entreprise sur le marché numérique ?
- Selon vous, quels domaines devraient être priorisés pour améliorer vos performances numériques ou consolider vos points forts afin de surpasser vos concurrents ?
- De manière générale, comment votre entreprise gère-t-elle les informations liées à ses différents processus ?

Si « NON » :

- Avez-vous mis en œuvre ou prévu des mesures pour évaluer la maturité numérique de l'entreprise ?
- Les forces et les faiblesses de l'entreprise en matière de transformation numérique sont-elles clairement comprises ?
- Selon vous, quels services ou processus nécessitent le plus d’améliorations sur le plan numérique ?

Question (4.3): Gestion des données (Inspirée par OECD, 2021)

- Les données sont-elles accessibles au sein de votre entreprise ? Si oui, quels outils utilisez-vous pour les collecter et les stocker ? (Exemples: sources connectées, plateformes d'interopérabilité)
- Comment les données collectées et analysées sont-elles utilisées pour soutenir la prise de décisions stratégiques dans votre entreprise ? (Exemples: utilisation locale, déploiement d'un lac de données, archivage ou pratiques de suppression)
- Avez-vous mis en place des politiques de sécurité des données pour protéger vos informations ? Si oui, veuillez préciser les mesures qui s’appliquent :
  - Réseau industriel isolé et accès internes contrôlés
  - Connexions à distance sécurisés via un pare-feu et un VPN avec authentification forte / multi facteurs
  - Formation du personnel en cybersécurité
  - Cryptage des données et mise en place d'un système de gestion des menaces/incidents/attaques
  - Approche de défense en profondeur (Système fiable de détection et de prévention des intrusions).

Question (4.4): Au cours des trois dernières années, avez-vous rencontré les obstacles suivants (Government of Canada, 2023) **lors de l'adoption des dix groupes de technologies émergentes ?**

* Nous fixerons la période à trois ans, car les enquêtes sur les technologies de pointe et l'innovation dans les entreprises menées par Statistique Canada et plusieurs pays de l'OCDE utilisent la même période pour évaluer l'adoption des technologies de pointe et la propension des entreprises à innover.

Cette question vise à évaluer simultanément le niveau d'adoption et les défis spécifiques rencontrés pour chaque groupe technologique, fournissant ainsi une vision diagnostique à la fois de la transition technologique et des obstacles rencontrés par les PME.

Tableau C.3 Obstacles à l'adoption des dix groupes de technologies émergentes

Groupes technologiques *(Danjou et al., 2017)*	Données massives et analytique	IA[1]	CLOUD	IoT[2]	CPS[3]	Cyber-sécurité	Machines autonomes	M2M[4]	Simulati-on	RA[5]
** Manque de compétences des employés*										
** Résistance au changement numérique (employés, clients ou fournisseurs)*										
** Difficulté à recruter du personnel qualifié*										
** Faible retour sur investissement ou longue période de récupération*										
** Difficulté à accéder à un soutien financier*										
** Difficulté à intégrer ou à identifier les nouvelles technologies appropriées aux systèmes, normes et processus existants*										
** Perturbation de la production due à l'intégration de nouvelles technologies*										
** Difficultés organisationnelles*										
** Garantir la sécurité et la confidentialité des données*										
** Contraintes ou incertitudes réglementaires*										

IA[1] : Intelligence Artificielle; IoT[2]: Internet des objets; CPS[3]: Systèmes cyber-physiques; M2M[4]: Machine to Machine; AR[5]: Réalité augmentée

Question (4.5): Selon vous, ces obstacles et événements imprévus ont-ils retardé ou complètement bloqué la réalisation de votre plan numérique au cours des trois dernières années ?

5. <u>Plans de mitigation</u>

Question (5.1): Quelles mesures votre entreprise a-t-elle prises au cours des trois dernières années pour réduire les obstacles à la transformation numérique ? (Statistics Canada, 2023a)

La réponse à cette question devrait révéler si l'entreprise poursuit des stratégies planifiées, claires et proactives en matière de transformation numérique ou si, au contraire, elle se contente de réagir aux problèmes à mesure qu'ils se présentent.

Tableau C.4 Mesures prises pour réduire les obstacles à la transformation numérique

Actions	☑
% Mesures organisationnelles et managériales * Exemple : Adopter une structure organisationnelle adaptée à la transformation numérique (équipe dédiée à la transformation numérique, collaboration interdépartementale, formation et développement des compétences, communication et sensibilisation).	
% Initiatives en matière d'innovation * Exemple : Encourager l'innovation et l'expérimentation (primes de rendement, mise à disposition de ressources, etc.)	
% Actions d'intégration numérique * Exemple : faire appel à des consultants spécialisés ou à des fournisseurs externes pour résoudre les problèmes numériques.	
% Mesures relatives à la politique de sécurité *Exemple : mettre en œuvre des politiques de sécurité pour protéger les données.	
% Mesures de gouvernance *Exemple : mettre en œuvre une gouvernance de l'intégration des systèmes numériques.	
% Utilisation des données *Exemple : collecter des données numériques à utiliser dans la prise de décision et la prévision des tendances futures.	
% Investissements financiers *Exemple : établir une stratégie de financement pour les projets de transformation numérique	
% Soutien externe *Exemples : cabinets de conseil / collaborations avec des universités, des instituts de recherche / soutien gouvernemental...	
Autre (précisez)	
Aucune mesure prise	

Question (5.2): Laquelle de ces actions considérez-vous comme la plus efficace ?

6. <u>Clôture de l'entrevue</u>

À la fin de l'entrevue, les participants auront la possibilité de poser d'autres questions ou de fournir des informations supplémentaires qu'ils jugent pertinentes pour le projet de recherche.

ANNEXE D SAMPLE OF CRITERIA & DIMENSIONS ASSESSMENT

Table D.1 Example of criteria assessment (individual expert's responses - Delphi Round 1)

	Improving competitiv--eness	Environmental sustainability	Social sustainability	Promoting innovation	Process efficiency	Reducing operational costs	Customer experience	Flexibility	Criterion weight (SCWj) (Individ--ual)	Criterion weight (All experts)
Improving competitiveness		1	1	0	0	0	0	1	10.71%	16.82%
Environmental sustainability	0		0	0	0	0	0	0	0.00%	5.80%
Social sustainability	0	1		0	0	0	0	0	3.57%	7.49%
Promoting innovation	1	1	1		0	1	0	0	14.29%	10.66%
Process efficiency	1	1	1	1		1	0	0	17.86%	17.35%
Reducing operational costs	1	1	1	0	0		0	0	10.71%	13.01%
Customer experience	1	1	1	1	1	1		1	25.00%	15.95%
Flexibility	0	1	1	1	1	1	0		17.86%	12.93%

Table D.2 Example of dimensions' assessment under the criterion C1 "Improving competitiveness" (individual expert's responses - Delphi Round 2)

Improving competitiveness	Strategy and governance	HR and digital skills	IT, data and security	Industrial systems and value chain	Portfolio, products and services	Dimension's weight (SWi1) (Individual)	Dimension's weight (All experts)
Strategy and governance		1	0	0	0	0.143	0.333
HR and digital skills	0		0	0	0	0	0.210
IT, data and security	1	1		0	0	0.286	0.130
Industrial systems and value chain	1	1	0		0	0.286	0.152
Portfolio, products and services	1	1	0	0		0.286	0.175

Table D.3 Example of dimensions' assessment under the criterion C2 "Process efficiency" (individual expert's responses - Delphi Round 2)

Process efficiency	Strategy and governance	HR and digital skills	IT, data and security	Industrial systems and value chain	Portfolio, products and services	Dimension's weight (SWi2) (Individual)	Dimension's weight (All experts)
Strategy and governance		1	0	0	1	0.250	0.232
HR and digital skills	0		1	0	0	0.125	0.289
IT, data and security	0	0		0	0	0	0.115
Industrial systems and value chain	1	1	0		1	0.375	0.239
Portfolio, products and services	0	1	1	0		0.250	0.126

Table D.4 Example of dimensions' assessment under the criterion C3 "Improving customer experience" (individual expert's responses - Delphi Round 2)

Improving customer experience	Strategy and governance	HR and digital skills	IT, data and security	Industrial systems and value chain	Portfolio, products and services	Dimension's weight (SWi3) (Individual)	Dimension's weight (All experts)
Strategy and governance		1	1	0	0	0.200	0.223
HR and digital skills	0		1	0	0	0.100	0.179
IT, data and security	0	0		0	0	0	0.143
Industrial systems and value chain	1	1	1		0	0.300	0.198
Portfolio, products and services	1	1	1	1		0.400	0.257

Table D.5 Example of dimensions' assessment under the criterion C4 "Reducing operational costs" (individual expert's responses - Delphi Round 2)

Reducing operational costs	Strategy and governance	HR and digital skills	IT, data and security	Industrial systems and value chain	Portfolio, products and services	Dimension's weight (SWi4) (Individual)	Dimension's weight (All experts)
Strategy and governance		1	1	0	1	0.429	0.267
HR and digital skills	0		0	0	1	0.143	0.192
IT, data and security	0	1		0	1	0.286	0.172
Industrial systems and value chain	0	0	0		1	0.143	0.232
Portfolio, products and services	0	0	0	0		0	0.136

Table D.6 Example of dimensions' assessment under the criterion C5 "Improving flexibility" (individual expert's responses - Delphi Round 2)

Improving flexibility	Strategy and governance	HR and digital skills	IT, data and security	Industrial systems and value chain	Portfolio, products and services	Dimension's weight (SWi5) (Individual)	Dimension's weight (All experts)
Strategy and governance		0	1	1	1	0.600	0.279
HR and digital skills	0		1	0	0	0.200	0.228
IT, data and security	0	0		0	0	0	0.140
Industrial systems and value chain	0	0	0		0	0	0.195
Portfolio, products and services	0	1	0	0		0.200	0.158

Table D.7 Example of dimensions' assessment under the criterion C6 "Promoting innovation" (individual expert's responses - Delphi Round 2)

Promoting innovation	Strategy and governance	HR and digital skills	IT, data and security	Industrial systems and value chain	Portfolio, products and services	Dimension's weight (SWi6) (Individual)	Dimension's weight (All experts)
Strategy and governance		0	1	1	1	0.429	0.328
HR and digital skills	1		1	0	0	0.286	0.301
IT, data and security	0	0		0	0	0	0.121
Industrial systems and value chain	0	0	0		0	0	0.096
Portfolio, products and services	0	1	1	0		0.286	0.154

Table D.8 Subjective dimensions' weights based on all criteria (SFMi) (individual expert's responses)

	Dimension's subjective weight (SFMi) (individual)	Dimension's subjective weight (All experts)
Strategy and governance	0.321	**0.274**
HR and digital skills	0.130	**0.231**
IT, data and security	0.098	**0.136**
Industrial systems and value chain	0.207	**0.190**
Portfolio, products and services	0.244	**0.169**

ANNEXE E DIMENSIONS' OBJECTIVE WEIGHTS CALCULATION

Table E.1 Experts' assessments for all dimensions under the criterion Cj (Improving competitiveness)

	Strategy and governance	HR and digital skills	IT, data and security	Industrial systems and value chain	Portfolio, products and services
Expert 1	0.400	0.300	0.200	0.100	0
Expert 2	0.429	0.286	0.143	0.143	0
Expert 3	0.400	0.100	0.100	0.200	0.200
Expert 4	0.500	0	0.250	0.125	0.125
Expert 5	0.300	0.300	0.200	0.100	0.100
Expert 6	0.100	0.200	0.100	0.200	0.400
Expert 7	0.100	0.400	0.100	0.100	0.300
Expert 8	0.400	0.200	0.200	0.200	0
Expert 9	0.400	0	0.100	0.300	0.200
Expert 10	0.400	0.200	0	0.100	0.300
Expert 11	0.400	0.200	0	0.200	0.200
Expert 12	0.143	0	0.286	0.286	0.286
Expert 13	0.364	0.273	0	0.182	0.182
Expert 14	0.200	0.200	0.100	0.100	0.400
Expert 15	0.400	0.300	0.200	0.100	0
Expert 16	0.300	0.400	0	0.100	0.200

Table E.2 Normalized matrix (Pijk) and objective weight calculation

	Strategy and governance	HR and digital skills	IT, data and security	Industrial systems and value chain	Portfolio, products and services
Expert 1	0.076	0.089	0.101	0.039	0
Expert 2	0.082	0.085	0.072	0.056	0
Expert 3	0.076	0.030	0.051	0.079	0.069
Expert 4	0.096	0	0.126	0.049	0.043
Expert 5	0.057	0.089	0.101	0.039	0.035
Expert 6	0.019	0.060	0.051	0.079	0.138
Expert 7	0.019	0.119	0.051	0.039	0.104
Expert 8	0.076	0.060	0.101	0.079	0
Expert 9	0.076	0	0.051	0.118	0.069
Expert 10	0.076	0.060	0	0.039	0.104
Expert 11	0.076	0.060	0	0.079	0.069
Expert 12	0.027	0	0.144	0.113	0.099
Expert 13	0.069	0.081	0	0.072	0.063
Expert 14	0.038	0.060	0.051	0.039	0.138
Expert 15	0.076	0.089	0.101	0.039	0
Expert 16	0.057	0.119	0	0.039	0.069
$\sum (P_{ijk})$	1.000	1.000	1.000	1.000	1.000
$\sum (P_{ijk}^2)$	0.071	0.085	0.096	0.073	0.096
Rényi Entropy (Hα=2 (Di,Cj))	3.816	3.560	3.386	3.771	3.386
Dispersion (di)	0.046	0.110	0.154	0.057	0.153
Objective Weight (Owij)	0.089	0.211	0.295	0.110	0.295

The same procedure was applied to the five remaining criteria to convert the dimensions' subjective assessments to objective weights (OWij) across all criteria using the Rényi Entropy method. The final objective measure was then computed using the Brown-Gibson method and is presented in the table below.

Table E.3 Dimensions Final Objective Measures (OFMi)

Dimensions	OWi1	OWi2	OWi3	OWi4	OWi5	OWi6	OWi	1/OWi	OFMi
Strategy and governance	0.089	0.195	0.138	0.133	0.227	0.052	0.139	7.188	0.259
HR and digital skills	0.211	0.064	0.186	0.129	0.150	0.014	0.126	7.963	0.287
IT, data and security	0.295	0.297	0.274	0.265	0.209	0.353	0.282	3.544	0.128
Industrial systems and value chain	0.110	0.119	0.207	0.201	0.186	0.311	0.189	5.292	0.191
Portfolio, products and services	0.295	0.326	0.194	0.273	0.227	0.270	0.264	3.786	0.136
							∑ (1/OWi)	27.772	