UNIVERSITA' DEGLI STUDI DI TORINO

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The role of performance, barriers, incentives and complexity in Industry 4.0

TESI PRESENTATA DA
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Thèse de doctorat

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Le rôle de la performance, des obstacles, des incitations et de la complexité dans l'industrie 4.0

The role of performance, barriers, incentives and complexity in Industry 4.0

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ÉCOLE DOCTORALE
Interfaces:
matériaux, systèmes, usages

UNIVERSITÀ DEGLI STUDI DI TORINO

Short abstracts

Italian short abstract

Titolo: Il ruolo di performance, barriere, incentivi e complessità nell'Industry 4.0

Parole chiave: Industry 4.0, Imprese manifatturiere, Performance, Barriere, Incentivi, Complessità

Sintesi: Negli ultimi dieci anni (2011-2021), la Quarta rivoluzione industriale, o Industry 4.0, ha trasformato ogni settore economico, specialmente quello manifatturiero dove il fenomeno ha avuto origine. Nonostante la grande attenzione sull'argomento posta da politici, manager e accademici, in impresa c'è ancora una limitata implementazione dell'Industry 4.0. Ciò è dovuto alla scarsa conoscenza delle performance reali, alla presenza di diverse barriere e alla maggiore complessità dei sistemi 4.0, tre limiti che non sempre sono superati con l'adozione di incentivi pubblici. Per questo motivo, la ricerca effettua in primo luogo un'analisi quantitativa su un campione statisticamente rappresentativo di 1331 unità locali manifatturiere, per individuare la reale relazione tra l'adozione dell'Industry 4.0 e le performance. In secondo luogo, lo studio approfondisce, attraverso un'analisi qualitativa, la percezione delle imprese su performance, barriere e incentivi. Successivamente, viene verificato empiricamente il ruolo di mediazione di barriere e incentivi sulla suddetta relazione, su un campione statisticamente rappresentativo di 1732 imprese manifatturiere. Infine, l'analisi approfondisce la percezione e la classificazione delle barriere ed esplora il ruolo della complessità nelle PMI attraverso un'analisi qualitativa. La tesi contribuisce alla letteratura, da un lato, identificando, classificando e misurando i principali concetti relativi all'Industry 4.0 e, dall'altro, testando soluzioni per l'implementazione dell'Industry 4.0 su più di 1300 imprese del settore manifatturiero, al fine di indirizzare meglio le politiche e le strategie di innovazione tecnologica.

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ÉCOLE DOCTORALE
Interfaces: matériaux, systèmes, usages

UNIVERSITÀ DEGLI STUDI DI TORINO

French short abstract

Titre: Le rôle de la performance, des obstacles, des incitations et de la complexité dans l'industrie 4.0

Mots-clés: Industry 4.0, Imprese manifatturiere, Performance, Barriere, Incentivi, Complessità

Résumé: Au cours des dix dernières années (2011-2021), la Quatrième révolution industrielle, ou Industrie 4.0, a transformé tous les secteurs industriels, en particulier le secteur manufacturier où la transformation a commencé. Malgré la grande attention portée par les politiques, les managers et les chercheurs académiques à ce sujet, la mise en œuvre de l'industrie 4.0 dans les entreprises reste limitée. Cela est dû à la connaissance limitée des performances réelles, à la présence de plusieurs barrières et à la complexité accrue des systèmes 4.0, trois causes qui ne sont pas toujours prises en compte par les incitations publiques. Pour cette raison, la recherche effectue d'abord une analyse quantitative pour identifier la relation réelle entre l'adoption de l'industrie 4.0 et la performance sur un échantillon statistiquement représentatif de 1331 unités locales de production. Par la suite, l'étude approfondit, par une analyse qualitative, la perception de la performance, des barrières et des incitations par les entreprises. Elle permet ensuite de vérifier quantitativement le rôle médiateur des barrières et des incitations sur la relation susmentionnée sur un échantillon statistiquement représentatif de 1732 entreprises manufacturières. Enfin, l'analyse porte sur la perception et la classification des obstacles et explore le rôle de la complexité dans les PME par le biais d'une analyse qualitative. La thèse contribue à l'enrichissement de la littérature, d'une part, en identifiant, classant et mesurant les principaux concepts liés à l'industrie 4.0 et, d'autre part, en testant des solutions pour la mise en œuvre de l'industrie 4.0 sur plus de 1300 entreprises du secteur manufacturier, en soulignant comment mieux cibler les politiques et les stratégies d'adoption des technologies. Au cours des dix dernières années (2011-2021), la Quatrième révolution industrielle, ou Industrie 4.0, a transformé tous les secteurs industriels, en particulier le secteur manufacturier où la transformation a commencé. Malgré la grande attention portée par les politiques, les managers et les chercheurs académiques à ce sujet, la mise en œuvre de l'industrie 4.0 dans les entreprises reste limitée. Cela est dû à la connaissance limitée des performances réelles, à la présence de plusieurs barrières et à la complexité accrue des systèmes 4.0, trois causes qui ne sont pas toujours prises en compte par les incitations publiques. Pour cette raison, la recherche effectue d'abord une analyse quantitative pour identifier la relation réelle entre l'adoption de l'industrie 4.0 et la performance sur un échantillon statistiquement représentatif de 1331 unités locales de production. Par la suite, l'étude approfondit, par une analyse qualitative, la perception de la performance, des barrières et des incitations par les entreprises. Elle permet ensuite de vérifier quantitativement le rôle médiateur des barrières et des incitations sur la relation susmentionnée sur un échantillon statistiquement représentatif de 1732 entreprises manufacturières. Enfin, l'analyse porte sur la perception et la classification des obstacles et explore le rôle de la complexité dans les PME par le biais d'une analyse qualitative. La thèse contribue à l'enrichissement de la littérature, d'une part, en identifiant, classant et mesurant les principaux concepts liés à l'industrie 4.0 et, d'autre part, en testant des solutions pour la mise en œuvre de l'industrie 4.0 sur plus de 1300 entreprises du secteur manufacturier, en soulignant comment mieux cibler les politiques et les stratégies d'adoption des technologies.

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UNIVERSITÀ DEGLI STUDI DI TORINO

English short abstract

Title: The role of performance, barriers, incentives and complexity in Industry 4.0

Keywords: Industry 4.0, Imprese manifatturiere, Performance, Barriere, Incentivi, Complessità

Abstract: Over the last ten years (2011-2021), the Fourth Industrial Revolution, or Industry 4.0, has disrupted every economic industry, especially the manufacturing, where the phenomenon was born. Despite the great attention on the topic paid by policy makers, managers and academics, there is still a limited implementation of Industry 4.0 in firms. This is due to limited knowledge on real performance, to several barriers, and to the increased complexity. These issues are not always covered by the adoption of public incentives. For this reason, the research firstly carries out a quantitative analysis to sort out the real relationship between Industry 4.0 adoption and performance on a statistically representative sample of 1331 manufacturing local units. Then, the study deeply scouts, through a quantitative analysis, firms' perception of performance, barriers and incentives and quantitatively verifies, on a statistically representative sample of 1732 manufacturing firms, the mediation role of barriers and incentives on the above mentioned relationship. Finally, the analysis deepens the perception and classification of barriers and explores the role of complexity in SMEs, through a qualitative analysis. The thesis contributes to enrich the literature by, on the one hand, identifying, classifying, and measuring key concepts related to Industry 4.0 and, on the other hand, testing solutions for Industry 4.0 implementation on more than 1,300 manufacturing firms, highlighting how to better target policies and technology adoption strategies. Over the last ten years (2011-2021), the Fourth Industrial Revolution, or Industry 4.0, has disrupted every economic industry, especially the manufacturing, where the phenomenon was born.

Despite the great attention on the topic paid by policy makers, managers and academics, there is still a limited implementation of Industry 4.0 in firms. This is due to limited knowledge on real performance, to several barriers, and to the increased complexity. These issues are not always covered by the adoption of public incentives. For this reason, the research firstly carries out a quantitative analysis to sort out the real relationship between Industry 4.0 adoption and performance on a statistically representative sample of 1331 manufacturing local units. Then, the study deeply scouts, through a quantitative analysis, firms' perception of performance, barriers and incentives and quantitatively verifies, on a statistically representative sample of 1732 manufacturing firms, the mediation role of barriers and incentives on the above mentioned relationship. Finally, the analysis deepens the perception and classification of barriers and explores the role of complexity in SMEs, through a qualitative analysis. The thesis contributes to enrich the literature by, on the one hand, identifying, classifying, and measuring key concepts related to Industry 4.0 and, on the other hand, testing solutions for Industry 4.0 implementation on more than 1,300 manufacturing firms, highlighting how to better target policies and technology adoption strategies.

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Long abstracts

Italian long abstract

La tesi analizza – sotto la duplice prospettiva manageriale e di ingegneria dei sistemi complessi – il contesto della Quarta rivoluzione industriale a dieci anni dal suo esordio. Nel 2011, infatti, il governo Tedesco ha varato il piano industriale *Industrie 4.0*, basato sull'adozione di nove categorie di tecnologie abilitanti nel settore manifatturiero, per aumentare la produttività e la competitività delle imprese. Successivamente, una serie di piani governativi e partnership pubblico-private a supporto dell'Industry 4.0 si sono sviluppati in numerosi paesi del mondo, trasformando non solo il settore manifatturiero, bensì tutti i settori economici, l'economia globale e la società nel suo insieme.

Le tecnologie 4.0 riguardano: la produzione automatizzata tramite l'intervento di robot collaborativi, droni e veicoli a guida autonoma (*advanced manufacturing*); la creazione di ambienti virtuali in grado di migliorare l'esperienza di acquisto dei clienti o la formazione dei dipendenti (*virtual/augmented/diminished reality*); la dotazione di macchinari e prodotti con sistemi e sensori in grado di comunicare da un lato con i dipendenti, per il monitoraggio dell'attività di produzione e di distribuzione, dall'altro con i client, fornendo loro informazioni utili in grado di accrescere il valore percepito del prodotto (*Internet of things*); la raccolta e l'analisi di grandi moli di dati sulle preferenze dei clienti, sull'andamento dei mercati e sul funzionamento dei macchinari interni alla fabbrica (*big data*); la conservazione virtuale di dati, facilitando l'accesso alle informazioni tramite piattaforme pubbliche o private (*cloud computing*); la possibilità di stampare prodotti finiti a partire da un design virtuale attraverso la stampante 3D, limitando lo spreco di materiale e velocizzando la prototipazione e la produzione (*additive manufacturing*); la simulazione in virtuale di scenari e prodotti, consentendo una riduzione dei tempi, dei costi e degli sprechi in fase di prototipazione (*simulation*); l'interconnessione di prodotti, macchinari, persone, imprese e sistemi (*horizontal and vertical integration*); la protezione della privacy dei dipendenti, dei clienti e delle imprese stesse, tramite sistemi di sicurezza informatica (*cyber security*). Tali tecnologie, accompagnate da sistemi di interconnessione tra la realtà fisica e la realtà virtuale (*Cyber Physical Systems*, CPSs), consentono alle imprese di ottenere molteplici performance legate a una maggiore efficienza in ogni fase della catena del valore.

Nonostante la forte attenzione sul tema posta a livello politico, manageriale e accademico, l'adozione di una o più tecnologie 4.0 in impresa risulta ancora limitata. Questo è dovuto principalmente alla mancanza di dati sul fenomeno – a causa del suo recente sviluppo – a una serie di barriere all'adozione dell'Industry 4.0 e alla complessità che la contraddistingue. Ad oggi, tali difficoltà non sono del tutto superate dall'adozione degli incenitvi messi a disposizione dei vari governi a livello macro (di ecosistema) e a livello micro (di impresa).

Per tale ragione, la tesi si propone di indagare, attraverso un approccio qualitativo e quantitativo, la percezione del fenomeno da parte delle imprese manifatturiere e le effettive relazioni esistenti tra Industry 4.0, performance, barriere, incenitvi e complessità.

Per conseguire tale finalità, la tesi è composta da tre articoli. Il primo indaga la relazione tra apertura all'Industry 4.0 e performance, attraverso un'analisi quantitativa su un campione statisticamente rappresentativo di 1331 unità locali manifatturiere in Piemonte (il database è frutto di una convenzione di ricerca tra l'Università degli Studi di Torino – Dipartimento di Management e di Scienze Economico-Sociali e Matematico-Statistiche – SAA School of Management e Unioncamere Piemonte). Il secondo articolo indaga la percezione delle performance, delle barriere e degli incentivi da parte delle imprese, attraverso un'analisi qualitativa (frutto di una collaborazione con istituzioni a supporto dello sviluppo dell'Industry 4.0 in impresa, quali il Competence Center CIM 4.0), e l'effetto mediatore di barriere e incentivi sulla relazione tra apertura all'Industry 4.0 e performance, attraverso un'analisi quantitativa su un campione statisticamente rappresentativo di 1732 unità locali manifatturiere in Piemonte (il database è frutto di una convenzione di ricerca tra l'Università degli Studi di Torino – Dipartimento di Management e di Scienze Economico-Sociali e Matematico-Statistiche – SAA School of Management e Unioncamere Piemonte). Infine, il terzo articolo si focalizza sulle piccole e medie imprese (PMI), che a causa di limitate risorse economiche, finanziarie e umane, riscontrano maggiori difficoltà nell'adozione dell'Industry 4.0. In tale contesto, il terzo articolo analizza la percezione delle barriere e la gestione della complessità nell'Industry 4.0, attraverso uno studio qualitativo (frutto di una collaborazione con istituzioni a supporto dello sviluppo dell'Industry 4.0 in impresa, quali il Competence Center CIM 4.0 e l'OPEO – operations & organisation).

In primo luogo, i risultati dello studio confermano empiricamente l'esistenza, evidenziata anche in letteratura, di una relazione positiva tra apertura all'Industry 4.0 e performance. In secondo luogo, l'analisi consente di integrare la letteratura sul tema verificando una relazione positiva tra: (i) apertura all'Industry 4.0 e percezione di barriere, legate alla mancanza di conoscenza, di risorse economico-finanziarie, di cultura dell'innovazione e a carenze dell'ecosistema di riferimento; (ii) percezione di barriere legate alla conoscenza del fenomeno e ad aspetti economico-finanziari e performance; (iii) apertura all'Industry 4.0 e adozione degli incentivi; (iv) adozione degli incentivi e performance. Infine, l'analisi consente di avviare una ricerca sulla gestione della complessità nelle PMI mostrando i limiti strutturali di questa categoria di imprese, che potrebbero talvolta limitare i potenziali benefici dell'Industry 4.0.

In conclusione, la ricerca contribuisce alla letteratura mappando, classificando e misurando i principali elementi connessi all'Industry 4.0 e testando soluzioni per l'adozione dell'Industry 4.0 su un campione di dati ampio e recente del settore manifatturiero, suggerendo potenziali strategie di governance e di government in ambito di adozione tecnologica, per garantire una migliore produttività e competitività delle imprese.

La tesi è strutturata come segue. Il primo capitolo riporta il primo articolo, intitolato *Smart factory performance and Industry 4.0* e pubblicato nel 2020 su *Technological Forecasting and Social Change*. Il secondo capitolo riporta il secondo articolo, intitolato *Openness to Industry 4.0 and performance: The impact of barriers and incentives* e pubblicato su *Technological Forecasting and Social Change* nel 2021. Il terzo capitolo riporta il terzo articolo, intitolato *Managing Complexity in Industry 4.0 Based Systems: A Qualitative Analysis*, presentato alla *Complex Systems Design and Management Conference* nel 2020 e in fase di pubblicazione come atto di convegno con ISBN. Infine, le conclusioni mettono in luce le principali implicazioni, i limiti e le prospettive di ricerca future.

French long abstract

La thèse analyse – sous la double perspective de la science de gestion et de l'ingénierie des systèmes complexes – le contexte de la Quatrième révolution industrielle dix ans après son lancement. En 2011, le gouvernement allemand a lancé le plan stratégique *Industrie 4.0*, basé sur l'adoption de neufs catégories de technologies habilitantes dans le secteur manufacturier, afin d'accroître la productivité et la compétitivité des entreprises. Par la suite, une série de plans gouvernementaux et de partenariats public-privé visant à soutenir l'industrie 4.0 se sont développés dans de nombreux pays du monde, transformant non seulement le secteur manufacturier, mais aussi tous les secteurs économiques, l'économie mondiale et la société dans son ensemble.

Les technologies 4.0 concernent: la production automatisée, grâce à l'intervention de robots collaboratifs, de drones et de véhicules à conduite autonome (*advanced manufacturing*) ; la création d'environnements virtuels pouvant améliorer l'expérience d'achat des clients ou la formation des employés (*virtual/augmented/diminished reality*) ; l'équipement des machines et des produits avec des systèmes et des capteurs capables de communiquer, d'une part, avec les employés pour surveiller les activités de production ou de distribution, et, d'autre part, avec les clients, en leur fournissant des informations utiles capables d'augmenter la valeur perçue du produit (*Internet of things*) ; la collecte et l'analyse de grandes quantités de données sur les préférences des clients, les tendances du marché et le fonctionnement des machines à l'intérieur de l'usine (*big data*) ; le stockage de données et d'informations sous forme virtuelle, facilitant les communications par l'intermédiaire de plateformes publiques ou privées (*cloud computing*) ; la possibilité d'imprimer des produits finis à partir d'un design virtuel au moyen d'une imprimante 3D, limitant le gaspillage de matériaux et accélérant le prototypage et la production elle-même (*additive manufacturing*) ; la simulation de scénarios et de produits physiques, permettant une réduction du temps, des coûts et des boucles dans la phase de prototypage (*simulation*) ; l'interconnexion des produits, des machines, des personnes, des entreprises et des systèmes (*horizontal and vertical integration*) ; la protection de la vie privée des employés, des clients et des entreprises elles-mêmes, grâce à des systèmes de cybersécurité (*cyber security*). Ces neufs technologies, accompagnées de systèmes d'interconnexion entre la réalité physique et la réalité virtuelle (*Cyber Physical Systems*, CPSs), permettent aux entreprises d'atteindre de multiples performances liées à une plus grande efficacité de chaque phase de la chaîne de valeur.

Malgré la forte attention portée à ce sujet au niveau politique, managérial et académique, l'adoption d'une ou plusieurs technologies 4.0 dans l'entreprise reste limitée. Ceci est principalement dû au manque de données sur le phénomène, en raison de son développement recent, d'un certain nombre d'obstacles à son adoption et de sa complexité. À ce jour, ces difficultés ne sont pas entièrement surmontées par l'adoption des incitations mises à disposition par les différents gouvernements aux niveaux macro (écosystème) et micro (entreprise).

Pour cette raison, la thèse vise à étudier, par une approche qualitative et quantitative, la perception du phénomène par les entreprises manufacturières et les relations réelles existant entre l'industrie 4.0, la performance, les barrières, les incitations et la complexité.

Pour atteindre cet objectif, la thèse est composée de trois articles. Le premièr étudie la relation entre l'ouverture à l'industrie 4.0 et la performance, à travers une analyse quantitative d'un échantillon statistiquement représentatif de 1331 unités locales manufacturières du Piémont – Italie du Nord (l'échantillon est résultat d'un accord de recherche entre Università degli Studi di Torino – Département de Management et de

Scienze Economico-Sociali e Matematico-Statistiche – SAA School of Management et Unioncamere Piemonte). Le deuxième article étudie la perception de la performance, des barrières et des incitations par les entreprises, par le biais d'une analyse qualitative (résultat d'une collaboration avec des institutions soutenant le développement de l'industrie 4.0 dans l'entreprise, telles que le Competence Center CIM 4.0). Par le biais d'une analyse quantitative sur un échantillon statistiquement représentatif de 1732 unités manufacturières locales du Piémont – Italie du Nord (l'échantillon est résultat d'un accord de recherche entre Università degli Studi di Torino – Département de Management et de Scienze Economico-Sociali e Matematico-Statistiche – SAA School of Management et Unioncamere Piemonte), le deuxième article démontre l'effet médiateur des barrières et des incitations sur la relation entre l'ouverture à l'industrie 4.0 et la performance. Enfin, le troisième article se concentre sur les petites et moyennes entreprises (PME) qui, en raison de ressources économiques, financières et humaines limitées, éprouvent davantage de difficultés à adopter l'industrie 4.0. Dans ce contexte, le troisième article analyse la perception des obstacles et de la gestion de la complexité dans l'industrie 4.0, à travers une étude qualitative (résultat d'une collaboration avec des institutions soutenant le développement de l'industrie 4.0 dans l'entreprise, telles que le centre de compétences CIM 4.0 et l'OPEO - operations & organisation).

Les résultats de l'ensemble de nos travaux confirment l'existence, mise en évidence dans la littérature, d'une relation positive entre l'ouverture à l'industrie 4.0 et la performance. Ensuite, l'analyse permet d'intégrer la littérature sur le sujet en vérifiant une relation positive entre : (i) l'ouverture à l'industrie 4.0 et la perception des barrières, liées au manque de connaissances, de ressources économico-financières, de culture de l'innovation et aux déficiences de l'écosystème de référence ; (ii) la perception des barrières liées à la connaissance du phénomène et aux aspects économico-financiers et la performance ; (iii) l'ouverture à l'industrie 4.0 et l'adoption de mesures incitatives ; (iv) l'adoption de mesures incitatives et la performance. Enfin, l'analyse permet d'entamer une recherche sur la gestion de la complexité dans les PME en montrant les limites structurelles de cette catégorie d'entreprises, qui pourraient parfois limiter les bénéfices potentiels de l'industrie 4.0.

En conclusion, la recherche contribue à la littérature en identifiant, classant et mesurant les principaux éléments liés à l'industrie 4.0 et en testant des solutions pour l'adoption de l'industrie 4.0 sur un échantillon de données important et récent du secteur manufacturier.

Une perspective de nos travaux est de continuer la réflexion sur les stratégies potentielles de gouvernance et de gouvernement dans le domaine de l'adoption des technologies pour assurer une meilleure productivité et compétitivité des entreprises.

La thèse est structurée comme suit. Le premier chapitre rend compte du premier article, intitulé *Smart factory performance and Industry 4.0* et publié sur *Technological Forecasting and Social Change* en 2020. Le deuxième chapitre rend compte du deuxième article, intitulé *Openness to Industry 4.0 and performance: The impact of barriers and incentives* et publié sur *Technological Forecasting and Social Change* en 2021. Le troisième chapitre rend compte du troisième article, intitulé *Managing Complexity in Industry 4.0 Based Systems : A Qualitative Analysis*, présenté à la conférence *Complex Systems Design and Management* en 2020 et en cours de publication avec ISBN. Enfin, les conclusions soulignent les implications principales, les limites et les perspectives de recherches futures.

English long abstract

The thesis analyzes – under the dual perspective of management and complex systems engineering – the context of the Fourth industrial revolution ten years after its beginning. In 2011, in fact, the German government launches the industrial plan *Industrie 4.0*, based on the adoption of nine categories of enabling technologies in the manufacturing sector, to increase productivity and competitiveness of firms. Subsequently, several industrial plans and public-private partnerships to support Industry 4.0 are developed in numerous countries worldwide, transforming not only the manufacturing sector, but all the economic industries, the global economy and society as a whole.

The 4.0 technologies involve: automated production, through the intervention of collaborative robots, drones and self-driving vehicles (*advanced manufacturing*); the creation of virtual environments, that can improve user experience or employee training (*virtual/augmented/diminished reality*); the equipping of machinery and products with systems and sensors capable of communicating from one side with employees, to monitor production or distribution activities, and from the other side with customers, providing them with useful information capable of increasing the perceived value of products (*Internet of Things*); the collection and analysis of large amounts of data on customer preferences, market trends and on the operation of machinery inside the factory (*big data*); the virtual storage of data and information through public or private platforms, facilitating communications (*cloud computing*); the ability to print finished products from a virtual design through a 3D printer, limiting material waste and speeding up prototyping and production (*additive manufacturing*); the virtual simulation of scenarios and physical products, reducing times, costs and waste in phase of prototyping (*simulation*); the interconnection of products, machineries, people, enterprises and systems (*horizontal and vertical integration*); the protection of the privacy of employees, customers and firms (*cyber security*). These technologies, accompanied by systems of interconnection between physical reality and virtual reality (*Cyber Physical Systems*, CPSs), allow companies to achieve multiple performances related to greater efficiency in each phase of the value chain.

Despite the interest on the topic paid by policy makers, managers and academia, the adoption of one or more 4.0 technologies in the firms is still limited. This is mainly caused by a lack of data on the phenomenon – due to its recent development – by a number of barriers to its adoption and to its complexity. To date, these difficulties are not completely overcome through the adoption of incentives made available by worldwide governments at macro (ecosystem) and micro (firms) levels.

For this reason, the thesis aims to investigate, through a qualitative and a quantitative approach, the perception of the phenomenon by manufacturing firms and the empirical relationships between Industry 4.0, performance, barriers, incentives and complexity.

To achieve this aim, the thesis is composed of three articles. The first one investigates the relationship between openness to Industry 4.0 and performance, through a quantitative analysis on a statistically representative sample of 1331 manufacturing local units in Piedmont – Northern Italy (the database comes from of a research agreement between Università degli Studi di Torino – Department of Management and of Scienze Economico-Sociali e Matematico-Statistiche – SAA School of Management and Unioncamere Piemonte). The second article investigates firms' perceptions on performance, barriers and incentives, through a qualitative analysis (result of a collaboration with institutions supporting the development of Industry 4.0 in the enterprise such as the Competence Center CIM 4.0), and the mediating effects of barriers and incentives on the relationship between openness to Industry 4.0 and performance,

through a quantitative analysis on a statistically representative sample of 1732 manufacturing local units in Piedmont (the database comes from a research agreement between Università degli Studi di Torino – Department of Management and of Scienze Economico-Sociali e Matematico-Statistiche – SAA School of Management and Unioncamere Piemonte). Finally, the third article focuses on small and medium-sized enterprises (SMEs), which experience more difficulties in adopting Industry 4.0, due to limited economic, financial and human resources. In this context, the third article analyzes the perception of barriers and the management of complexity in Industry 4.0, through a qualitative study (result of a collaboration with institutions supporting the development of Industry 4.0 in the enterprise such as the Competence Center CIM 4.0 and the OPEO - operations & organization).

Firstly, the results of the study confirm the existence, highlighted in the literature, of a positive relationship between openness to Industry 4.0 and performance. Secondly, the analysis allows to integrate the literature on the topic, verifying a positive relationship between: (i) openness to Industry 4.0 and perceived barriers related to lack of knowledge on the topic, lack of economic-financial resources, lack of culture of innovation and lack of a strong ecosystem; (ii) perceived barriers related to knowledge and economic-financial aspects and performance; (iii) openness to Industry 4.0 and adoption of incentives; (iv) adoption of incentives and performance. Finally, the analysis opens up a research on complexity management in SMEs, showing the structural limits of this category of firms, which could sometimes limit the potential benefits of Industry 4.0.

In conclusion, the research contributes to the literature by mapping, classifying and measuring the main elements related to Industry 4.0 and testing solutions for the adoption of Industry 4.0 on a large and recent data sample of the manufacturing sector. Therefore, the study suggests potential governance and government strategies in the field of technology adoption to ensure better productivity and competitiveness of firms.

The thesis is structured as follows. The first chapter reports the first article, titled *Smart factory performance and Industry 4.0* and published on *Technological Forecasting and Social Change* in 2020. The second chapter reports the second article, titled *Openness to Industry 4.0 and performance: The impact of barriers and incentives* and published in Technological Forecasting and Social Change in 2021. The third chapter reports the third article, titled *Managing Complexity in Industry 4.0 Based Systems: A Qualitative Analysis*, presented at the *Complex Systems Design and Management Conference* in 2020 and being published as conference proceeding with ISBN. Finally, the conclusion highlights the principal implications, limitations, and future research lines.

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Thesis introduction

General context and literature overview

In 2011, the German government launches a revolutionary industrial plan named *Industrie 4.0* (Kagermann et al., 2013) to increase manufacturing productivity and competitiveness through technological adoption. This phenomenon gives rise to the Fourth industrial revolution (Schwab, 2016). In a short time, Industry 4.0 spreads to other European, American and Asian countries with a series of industrial plans and public private partnerships in support of Industry 4.0 development. Some of the most known industrial plans are: Advanced Manufacturing Partnership (AMP), in the United States (The White House, 2011); Future of Manufacturing, in United Kingdom (Department for Business Energy and Industrial Strategy (BEIS) of UK, 2013); Industrie du Futur, in France (Economie.gouv.fr, 2015); "Made in China 2025", in China (State Council of the People's Republic of China, 2015); and Piano Nazionale Industria 4.0, in Italy (Ministero dello Sviluppo Economico (MISE), 2017). Among the most recognized public private partnerships there is, for example, the Industrial Internet Consortium (IIC) led by General Electric.

Industry 4.0 is based on the adoption of more than 1200 innovations (Chiarello et al., 2018), generally grouped into nine pillars (Rüßmann et al., 2015) of information and operation technologies: advanced manufacturing, virtual/augmented/diminished reality, big data, Internet of things, cloud computing, additive manufacturing, cyber security, simulation, horizontal and vertical integration. Most of these technologies already existed before 2011, but with the advent of Industry 4.0 they evolved through greater integration and interoperability enabled by Cyber Physical Systems (CPSs). CPSs allow the connection of the operations of the physical reality with computing and communication infrastructures of the virtual world (Lu, 2017). Moreover, the adoption of Industry 4.0 to different value chain phases requires a reorganization of the factory in a more integrated one, creating the so called 4.0 environment, or the smart factory (Margherita and Braccini, 2021). This new kind of factory is expected to be efficient, flexible and automated, leading to seven main kinds of performances (Dalenogare et al., 2018; Chauhan, Singh, and Luthra, 2021): production flexibility; speed of serial prototypes; greater output capacity; reduced set-up costs and fewer errors and machine downtimes; higher product quality and less rejected production; customers' improved opinion of products. This is the main reason why the term Fourth industrial revolution is used. Because, like previous industrial revolutions, Industry 4.0 leads to an economic evolution favored by a strong component of technological innovation, accompanied by profound socio-cultural and even political changes. In particular, all the industrial revolutions involve a profound and irreversible transformation that starts from the production system to involve the economic system as a whole and the entire social system.

However, management literature highlights that, to implement Industry 4.0, firms should overcome several barriers to its adoption and, to reach the above mentioned performances, firms should manage the increased complexity of Industry 4.0 systems. Literature on Industry 4.0 states that there are more than 11 kinds of barriers (Horváth and Szabó, 2019; Raj et al., 2020; Stentoft et al., 2020; Chauhan, Singh, and Luthra, 2021), depending on macro and micro levels and related both to intangible issues – such as culture, knowledge and skills – and to more tangible constraints, such as financial resources or infrastructures. Moreover, literature on complexity points out that complexity in Industry 4.0 systems may be 70% higher than in traditional systems (Mourtzis et al., 2019). In particular, the increased complexity is due to a huge amount of information exchanged among its different integrated systems, introducing new languages, new knowledge and new kind of interoperability (Ullah, 2020). This might be both an opportunity or a constraint, depending on the readiness of the firms to manage the resulting complexity. To overcome the barriers in accessing new knowledge and new concepts, governments worldwide develop industrial plans trying to create incentives for the adoption of Industry 4.0 through policies at macro level – promoting awareness on the topic and developing economic infrastructures – and at micro level – reducing the burden of investment and facilitating the development of suitable knowledge and skills.

Nonetheless – ten years after the birth of 4.0 phenomenon and despite the efforts of policy makers, managers and academics to develop its adoption – there is still a limited implementation of Industry 4.0 in firms. In particular, the adoption of one or more 4.0 technologies in the three most manufacturing countries in Europe is still weak: 20% in German automotive sector (Federal Ministry for Economic Affairs and Energy, 2020), 14% in French firms interviewed by Accenture Strategy (2020), and 17% in Italian manufacturing SMEs (Centro Studi delle Camere di Commercio Guglielmo Tagliacarne-Unioncamere, 2020). This reluctance to adopt Industry 4.0 is mainly due to the rather qualitative nature of the expected added value from Industry 4.0 (Kiel et al., 2017) and to a knowledge gap on: (i) firms' awareness on the phenomenon itself (in Italy only 26% of SMEs declares to know what Industry 4.0 is – Centro Studi delle Camere di Commercio Guglielmo Tagliacarne-Unioncamere, 2020); (ii) real data availability on economic benefits and performance (Ünal and Köhler, 2019); (iii) the understanding of how to manage several barriers and complexity issues (Chauhan, Singh, and Luthra, 2021).

Research questions and hypotheses

The research contributes to the literature on Industry 4.0 in two ways. First, it maps, classifies and measures the main Industry 4.0 related concepts: openness to Industry 4.0; performance; barriers; incentives; and complexity. Second, it tests solutions for Industry 4.0 adoption on large and fresh data in manufacturing industry, pointing out how these variables are interrelated, and looking for new success factors of Industry 4.0, to better focus policies and strategies in technological adoption.

To offer this contribution, the thesis answers the following main research question: what are, upstream, the main drivers and deterrents to the adoption of Industry 4.0 and what are, downstream, the main conditions that favor or slow down the achievement of performance? To answer this main research question, the thesis is based on a collection of three papers with distinguished aims, research questions and hypotheses, carrying out qualitative and/or quantitative approach, as summarized in figure 1. In the quantitative analysis (carried out both in the first and in the second paper), this main research question is, of course, articulated in detailed causal relationships.

The aim of the first paper is to sort out the relationship between Industry 4.0 adoption and performance. It is based on a quantitative analysis on a statistically representative sample of 1331 manufacturing local units. The analyzed variables are the independent variables BREADTH (number of 4.0 technologies adopted) and DEPTH (number of value chain phases where the technologies are adopted), measuring the openness to Industry 4.0, and the dependent variable PERFORMANCE. The following hypotheses are concerned (Hs).

H1a – Breadth helps companies obtain greater opportunities when applying the pillars of Industry 4.0 enabling technologies.

H2a – Depth helps companies obtain greater opportunities when applying the pillars of Industry 4.0 enabling technologies.

H1b – The breadth when applying pillars of Industry 4.0 enabling technologies is curvilinear, with an inverted U shape.

H2b – The depth when applying pillars of Industry 4.0 enabling technologies is curvilinear, with an inverted U shape.

H3 – Small companies obtain greater opportunities than larger ones by applying Industry 4.0 technologies.

H4 – High-tech companies obtain greater opportunities than companies in non-high-tech industries by applying Industry 4.0.

H5 – Companies that have already adopted Industry 4.0, and are inclined to further implement Industry 4.0, obtain greater opportunities.

The aim of the second paper is to deeply scout the role of barriers and incentives to Industry 4.0 adoption, through a mixed-method. First, through a qualitative analysis, it explores firms' perception on performance, barriers and incentives. Second, through a quantitative analysis, it verifies the mediation role of barriers and incentives on the above mentioned relationship on a statistically representative sample of 1732 manufacturing firms. The qualitative analysis explores the following research question.

RQ1 – Which are the main and most recurrent performance, barriers and incentives of Industry 4.0 in manufacturing firms?

To investigate the hypotheses reported below, the quantitative analysis of the second paper is based on the following variables. The independent variable is openness to Industry 4.0, measured as BREADTH of the number of 4.0 technologies adopted. The dependent variable is PERFORMANCE. The mediators are 4 categories of barriers – KNOWLEDGE, ECO-FIN, CULTURE, and SYSTEM – and INCENTIVES.

H1 – Greater openness to Industry 4.0 leads to the perception of better performance.

H2a – Greater openness to Industry 4.0 leads to the perception of higher barriers relating to knowledge issues.

H2b – Greater openness to Industry 4.0 leads to the perception of higher barriers relating to economic and financial issues.

H2c – Greater openness to Industry 4.0 leads to the perception of higher barriers relating to cultural issues.

H2d – Greater openness to Industry 4.0 leads to the perception of higher barriers relating to system conditions.

H3a – Greater perceived barriers relating to knowledge issues lead to the perception of improved performance.

H3b – Greater perceived barriers relating to economic and financial issues lead to the perception of improved performance.

H3c – Greater perceived barriers relating to cultural issues lead to the perception of improved performance.

H3d – Greater perceived barriers relating to system conditions lead to the perception of improved performance.

H4 – Greater openness to Industry 4.0 leads to a greater degree of incentives adoption.

H5 – A higher number of adopted incentives leads to the perception of improved performance.

H6a – The perception of higher barriers relating to knowledge issues leads to a greater degree of incentives adoption.

H6b – The perception of higher barriers relating to economic and financial issues leads to a greater degree of incentives adoption.

H6c – The perception of higher barriers relating to cultural issues leads to a greater degree of incentives adoption.

H6d – The perception of higher barriers relating to systems conditions leads to a greater degree of incentives adoption.

Finally, the aim of the third paper is to deepen the perception and classification of barriers and to explore the role of complexity in SMEs. Industry 4.0, in fact, increases the exchange of information not only among humans but also among humans and machines, tremendously augmenting complexity (Kumar, Suhaib, and Asjad, 2020). In doing so, the third paper carries out a qualitative analysis answering the following research questions.

RQ1 – How SMEs perceive barriers to Industry 4.0 adoption?

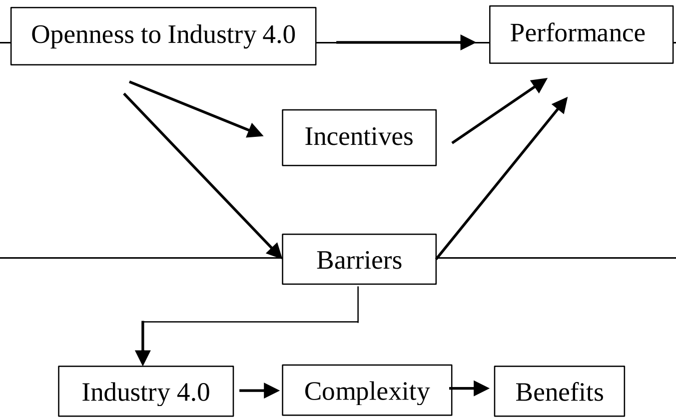
RQ2 – How SMEs perceive complexity of Industry 4.0 based systems?

Exploring the above mentioned research questions through an in depth qualitative analysis is essential due to the rather qualitative nature of the Industry 4.0 expected value added (Kiel et al., 2017). In particular, the research helps academics, managers and policy makers to really understand the driving forces and constraints of firms in Industry 4.0 adoption. Moreover, empirically verifying the listed hypotheses is vital as one of the main knowledge gap in this field, that hinder Industry 4.0 adoption, is the lack of empirical analysis on large and fresh data on the relationships between the explored variables (Ünal and Köhler, 2019; Chauhan, Singh, and Luthra, 2021).

Figure 1 – Reciprocal diagram of aims, research questions and main relationships investigated in the thesis and in each paper

Thesis main research question:

What are, upstream, the main drivers and deterrents to the adoption of Industry 4.0 and what are, downstream, the main conditions that favor or slow down the achievement of performance?

Paper	*Aim*	*Research questions (RQs) – for qualitative analysis*	*Main relationships investigated*
Paper 1	To empirically sort out the relationship between Industry 4.0 adoption and performance.	-	
Paper 2	To deeply scout the role of barriers and incentives of Industry 4.0 adoption	RQ1 – Which are the main and most recurrent performance, barriers and incentives of Industry 4.0 in manufacturing firms?	
Paper 3	To deepen the perception and classification of barriers and to explore the role of complexity in SMEs	RQ1 – How SMEs perceive barriers to Industry 4.0 adoption? RQ2 – How SMEs perceive complexity of Industry 4.0 based systems?	

Research methodology and main outputs

The research follows a mixed-method distinguished for each paper and summarized in table 1.

The first paper carries out a quantitative analysis on Secondary data from *Congiuntura Industriale in Piemonte* dataset collected by Unioncamere Piemonte (2018) on 1331 (231 adopting Industry 4.0) local manufacturing units in Piedmont's manufacturing sector (Northern Italy), with at least two employees belonging to different size classes and different product sectors. The data comes from a research agreement between Università degli Studi di Torino (Department of Management and of Scienze Economico-Sociali e Matematico-Statistiche – ESOMAS), SAA School of Management and Unioncamere Piemonte. The model is a regression analysis on: openness to Industry 4.0, measured through the independent dummy variables BREADTH and DEPTH (Vogel-Heuser and Hess, 2016); the dependent variable PERFORMANCE (sum of 6 dummies of performances); the intermediary variables SIZE (firms' dimension), HIGH (technological intensity of the sector), OPEN-ET (propensity to further adopt 4.0 technologies), measured as dummies.

The second paper carries out a quali-quantitative analysis. The qualitative analysis is based on: (i) semi-structured in-depth interviews to 9 leading figures within Industry 4.0 public-private partnerships, trade associations, applied research centers, technology transfers or trainers actively helping firms in Industry 4.0 adoption; (ii) case studies on a cross-sector sample of 11 firms combining semi-structured in-depth interviews, internal reports and web-sites. The quantitative analysis is performed on secondary data from *Congiuntura Industriale in Piemonte* dataset collected by Unioncamere Piemonte (2019) on 1732 (500 adopting Industry 4.0) local manufacturing units in Piedmont's manufacturing sector (Northern Italy), with at least two employees belonging to different size classes and different product sectors. Data comes from the same research agreement cited for the first paper. The model used is a multiple parallel-serial model, which considers the relationship between openness to Industry 4.0 (I4.0) and performance (PERFORMANCE), as driven by the direct and indirect effects of five intermediary variables related to four categories of barriers (KNOWLEDGE, ECO-FIN, CULTURE, SYSTEM) and to incentives (INCENTIVES).

The third paper is a qualitative analysis based on a focus group to 9 leading figures of public-private partnerships, trade associations, applied research centers, technology transfers or trainers actively helping firms through the Industry 4.0 transition in Italy and one semi-structured in-depth interview to one leading figure of a French organization helping firms in Industry 4.0 transition.

In doing so, the main result of the thesis is to provide a comprehensive overview, on the one hand, on the main drivers (mainly seven performances and several incentives) and constraints (fifteen barriers) to the adoption of Industry 4.0 upstream, and, on the other hand, on the main conditions that favor (such as firms' characteristics) or slow down (such as the difficulties in managing complexity) the achievement of performance downstream the adoption of Industry 4.0.

The main findings and results of the research are summarized in figure 2, highlighting the successive steps and progress from one paper to the other.

The first paper initially reconstructs a theoretical background on Industry 4.0 origins and definition, determiners and enabling technologies, and opportunities. Then, it operationalizes the concepts of openness to Industry 4.0 and performance. Finally, it empirically verifies, through a regression model on 1331 manufacturing firms, the relationship between openness to Industry 4.0 and performance. The results of the theoretical background highlight two ways to measure openness to Industry 4.0 – breadth of the number of 4.0 technologies adopted and depth of the number of value chain phases where the technologies are adopted – and six performances. The results of the empirical analysis point out a significant and positive relationship between openness to Industry 4.0 and performance, and a stronger impact for micro local units.

The second paper integrates the theoretical background of the first paper, exploring also the literature on barriers and incentives of Industry 4.0. Then, it validates and integrates the theoretical background, through semi-structured in-depth interviews to 9 participants and 11 case studies. Finally, it extends the empirical analysis of the first paper on a sample of 1732 manufacturing firms, looking at the mediation effects of barriers and incentives on the main relationship, also explored in the first paper, between openness to Industry 4.0 and performance. The new findings of the qualitative analysis of the second paper are mainly related to: (i) the identification of 1 additional performance underexplored in the first paper; (ii) the scouting of 12 barriers classified into 4 categories, related to knowledge issues, economic-financial constraints, cultural issues and system conditions; (iii) the description of the public incentives more adopted by industrial plans worldwide. The results of the quantitative analysis confirm the positive relationship between openness to Industry 4.0 and performance, and verifies a positive relationship between: (i) openness to Industry 4.0 and barriers; (ii) knowledge and economic-financial barriers and performance; (iii) openness to Industry 4.0 and incentives; (iv) incentives and performance.

The third paper deepens the analysis on SMEs, following the literature stating that SMEs have more liabilities to Industry 4.0 adoption due to limited economic, financial and human resources. In this context, the paper qualitatively expands – through a focus group to 9 participants and 1 semi-structured in depth interview – the analysis on barriers, started in the second paper, and paves the way for research on the role of complexity in Industry 4.0. The results integrate the 12 barriers found in the second paper identifying 15 barriers reclassified into 5 categories (cultural aspects, ecosystems' characteristics, firms' characteristics, human resource management, business model innovation). This new classification takes into account the distinction between macro and micro level, underestimated in the second paper but pursued by policy makers in creating the incentives.

The research contributes to the literature on Industry 4.0 mapping, classifying and measuring the main Industry 4.0 related concepts and testing solution for Industry 4.0 application on large and fresh data in manufacturing (figure 3). The qualitative results validate and integrate the literature on Industry 4.0 and open up new research lines in complexity management of Industry 4.0, that is an underexplored topic from the managerial perspective. The quantitative results test on large and fresh data the mutual relationships between the main Industry 4.0 related concepts, showing potential practical implications.

Table 1 – Reciprocal diagram for methodology and samples adopted in each paper

Paper	*Approach*	*Method and model*	*Sample*	*Data source*	*Research agreement and collaboration*
Paper 1	Quantitative	Regression analysis	Secondary data on 1331 local manufacturing units (231 adopting Industry 4.0) in Piedmont (Northern Italy).	*Congiuntura Industriale in Piemonte* dataset collected by Unioncamere Piemonte (2018).	Research agreement Università degli Studi di Torino (Management and ESOMAS Departments), SAA School of Management, and Unioncamere Piemonte.
Paper 2	Qualitative	Semi-structured in-depth interviews	9 leading figures within Industry 4.0 public-private partnerships, trade associations, applied research centers, technology transfers or trainers actively helping firms through the Industry 4.0 transition.	-	Collaboration Università degli Studi di Torino (Management Department) and CIM 4.0.
		Case studies	Cross-sector sample of 11 firms combining semi-structured in depth interviews, internal reports and web-sites.		
	Quantitative	Multiple parallel-serial model	Secondary data on 1732 local manufacturing units (500 adopting Industry 4.0) in Piedmont (Northern Italy).	*Congiuntura Industriale in Piemonte* dataset collected by Unioncamere Piemonte (2019).	Research agreement Università degli Studi di Torino (Management and ESOMAS Departments), SAA School of Management, and Unioncamere Piemonte.
Paper 3	Qualitative	Focus group and semi-structured in-depth interview	9 lading figures of public-private partnerships, trade associations, applied research centers, technology transfers or trainers actively helping firms through the Industry 4.0 transition in Italy and one in depth interview to one leading figure of a French organization helping firms in Industry 4.0 transition.	-	Collaboration Università degli Studi di Torino (Management Department), CentralSupélec (Laboratoire de Génie Industriel), OPEO and CIM 4.0.

Figure 2 - Main findings and results paper by paper

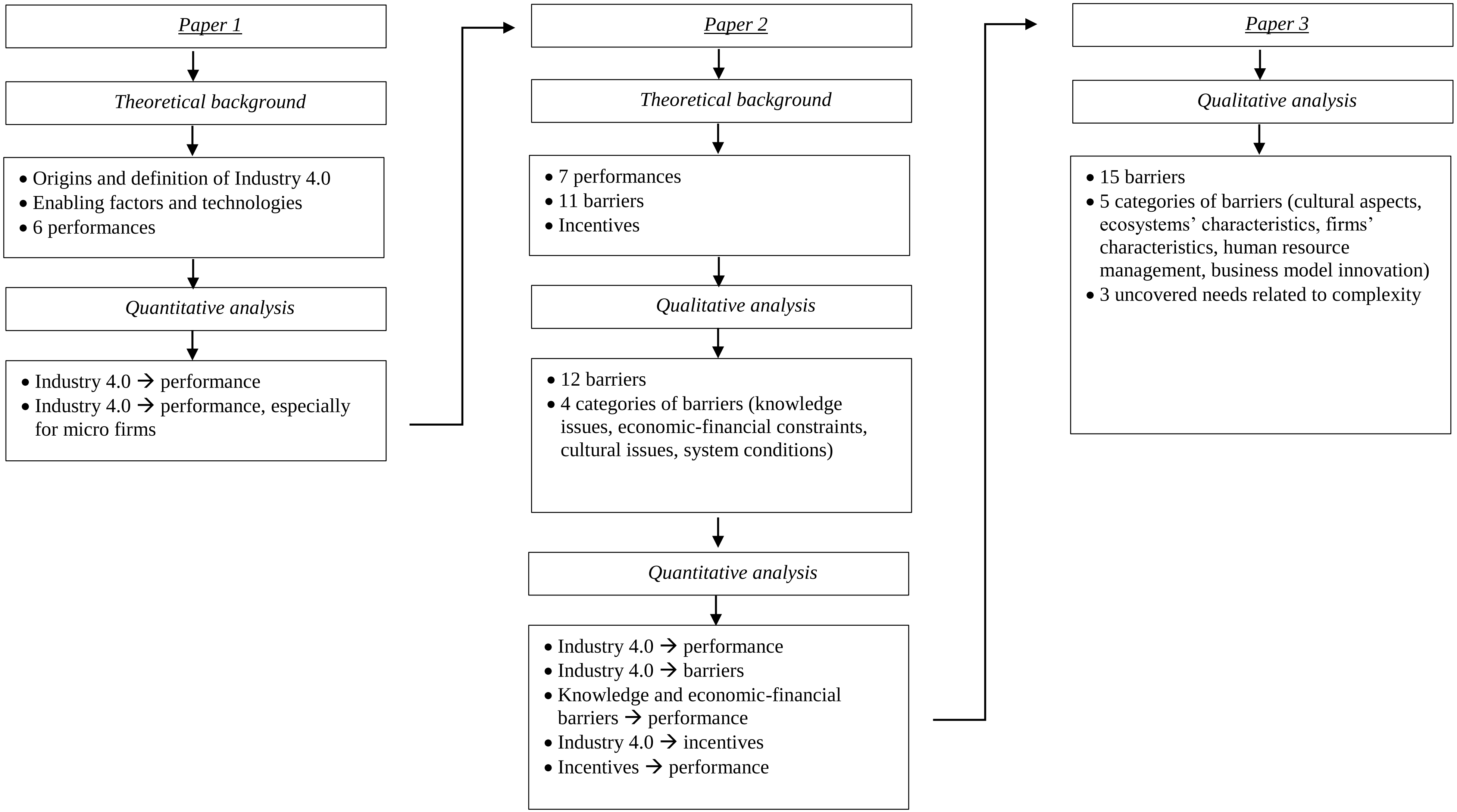
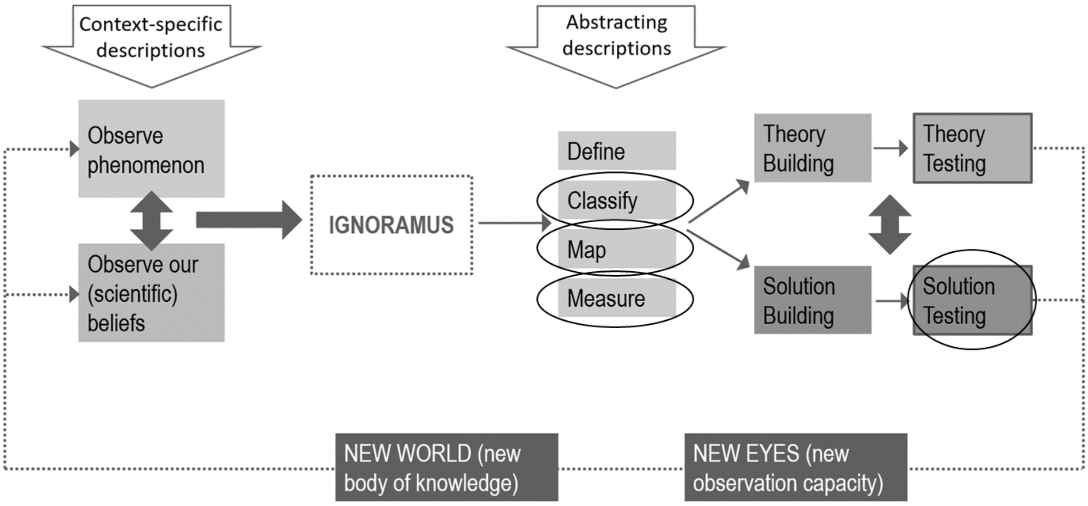


Figure 3 – Main contribution of the thesis research methodology



Source: own elaboration on a figure by Ricciardi, F. "Introduction on Scientific Method", University of Turin, PhD School in Business and Management.

As far as the practical implications are concerned, the analysis shows that more breadth and more depth of Industry 4.0 adoption lead to greater performance, depending on the firms' characteristics. This suggests to managers to adopt more 4.0 technologies to more value chain phases. Moreover, the research shows that more perceived barriers do not lead to more incentives adoption. This highlights to policy makers the main problem related to incentives, pointing out the need to improve industrial policies more tailored on real firms' constraints and to better communicate them. Finally, the study points out that Industry 4.0 increases complexity, while SMEs are not ready to manage and to profit from it. This highlights the need to develop new culture, mindset and routines in the firms to better benefit from the increased complexity of Industry 4.0.

Following these implications, the study primarily addresses innovation management scholars who want to understand from in-depth analysis and empirical data how Industry 4.0 actually works. Secondly, the study addresses complex systems engineering scholars who want to explore how Industry 4.0 increases the complexity of production systems and what are the best strategies and incentives to benefit from this revolution. Finally, the analysis addresses practitioners, managers and policy makers who want to identify the best strategies and policies to be implemented in order to obtain the best benefits from the adoption of the technologies of the Fourth industrial revolution.

Context of the research work and structure of the thesis

The research is developed through a collaboration – in the form of international thesis codirection between the Management Department of Università degli Studi di Torino and the Laboratoire de Génie Industriel of CentralSupélec, Université Paris Saclay – which allowed to enrich the study with a dual perspective of management and complex systems engineering, opening up new possibilities of analysis. Beyond the three-years doctoral fellowship supporting the research, funded by Università degli Studi di Torino, the international thesis codirection is supported by a public grant (of 5000 euros) supervised by the French National Research Agency (ANR) under the program "Investissements

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The thesis is structured as follows. Chapter 1 reports the first paper. Chapter 2 consists of the second paper. Chapter 3 is made up of the third paper. The last section outlines the conclusion, summarizing the purpose, the research questions and the hypotheses of the study, pointing out the key results and the link between results, purpose and literature, and highlighting the implications for theory and practice and the main limitations and future lines of research opened up. The order of authors in the different papers follows the Italian protocol. The candidate is the main author for all the publications. Indeed, the candidate's contribution in the first paper is mainly related to §2 Theoretical background and §3 Research hypotheses. The candidate's contribution in the second paper mainly concerns §2 Theoretical background and hypotheses development, §3.1 Methodology – qualitative analysis, §4.1 Findings – qualitative findings, §5.1 Discussion – qualitative findings. The candidate's contribution in the third paper is mainly related to §2 Theoretical background, §3 Methodology, §4 Results, § Discussion.

[1]

1. Paper 1 – Smart factory performance and Industry 4.0

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Smart factory performance and Industry 4.0

Giacomo Büchi, Monica Cugno, Rebecca Castagnoli

Highlights

- The paper builds an operationalization of the concepts of openness to Industry 4.0 and performance.
- The openness to Industry 4.0 is analyzed in terms of its breadth and depth.
- Industry 4.0 modifies local manufacturing units' performance in term of six opportunity typologies.
- Local units more open to Industry 4.0 obtain greater opportunities.
- Micro-enterprises' local manufacturing units obtain more opportunities through their openness to Industry 4.0.

Abstract

Existing literature on the Industry 4.0 concept does not empirically verify if, how, and for which types of firms, a greater openness to enabling technologies of Industry 4.0 provides further opportunities. This study analyzes the causal relationship between this degree of openness and performance, with an empirical analysis based on a sample representing local manufacturing units. Performance is measured by the extent of opportunities businesses obtain. The degree of openness is investigated using two indicators: breadth, or the number of technologies used; and depth, or the number of value chain stages involved. The regression models demonstrate that: (1) breadth and (2) depth of Industry 4.0 allow greater opportunities, and (3) micro-level local units achieve best performances. Verifying the opportunities for companies with Industry 4.0 is extremely relevant, as investments in Industry 4.0 are high in terms of costs, the acquisition of new skills, and the risks of obsolescence to enable better strategic decisions. This work also provides a scope for future analyses of this topic conducted on panel data. Despite the limited application of Industry 4.0, this study's results can encourage managers and policy-makers to implement a wider range of enabling technologies in the various stages of the value chain.

Keywords: Industry 4.0, Fourth industrial revolution, Smart factory, Innovation, Value Chain, Enabling Technologies, Openness, Breadth, Depth, Performance, Opportunities, Regression models

1.1 Introduction

The fourth Industrial Revolution—or Industry 4.0 (Kagermann, Wahlster, & Helbig, 2013a)—is changing firms' strategies, organization, business models, value and supply chains, processes, products, skills, and stakeholder relationships. Industry 4.0 has created new opportunities and vulnerabilities that must be managed and governed to positively impact both business and society.

Governments worldwide have realized the importance of this new generation of manufacturing (Reischauer, 2018) with active initiatives, including raising awareness, action plans, support, infrastructure investments, sponsorships, and tax benefits to facilitate its implementation in companies. The industrial plans in table 1 deserve particular attention.

Table 1. Main Countries' Industrial Plans

Country	*Industrial Plan*	*Reference*
Germany	High-Tech Strategy 2020	Kagermann et al. (2013b)
France	*La Nouvelle France Industrielle* (The New Industrial France)	*Conseil National de l'Industrie* (National Council of Industry; 2013)
United Kingdom	Future of Manufacturing	Foresight (2013)
United States	Advances Manufacturing Partnership	(Rafael, Jackson Shirley, & Liveris, 2014)
China	Made in China 2025	Li, 2015
Singapore	Research, Innovation and Enterprise	National Research Foundation, 2016
South Korea	Innovation in Manufacturing 3.0	Kang et al., 2016
Italy	*Impresa 4.0*	Ministero dello Sviluppo Economico, 2017

In addition to industrial plans, research programs have been launched to examine new enabling technologies designed by companies and/or private organizations, such as the Industrial Internet Consortium (Evans & Annunziata, 2012), or with public-private partnerships, such as the Factories of the Future—Horizon 2020 program (European Commission, 2016).

Industry 4.0 has rapidly grown over the last few years, accompanied by an exponential increase in literature on its many enabling technologies—and especially those pertaining to the engineering field. Despite the importance of the Industry 4.0 phenomenon, only a few economic and management studies exist, and these focus on 10 primary topics:

- The phenomenon's diffusion (Chovancová, Dorocáková, & Malacká, 2018;

Sung, 2018).

- The impact of enabling technologies on the global economy, measured through productivity, employment and unemployment, and technological and/or legal changes (Brynjolfsson & McAffee, 2014; Eichhorst et al., 2017).
- Innovation in business models (Arnold et al., 2016; Frank et al., in press; Gerlitz, 2016; Kiel et al., 2017; Laudien et al., 2016; Müller et al., 2018).
- Improving the value chain (Saucedo-Martínez et al., 2018; Kinzel, 2017).
- Redefining the supply chain (Barata et al., 2018; da Silva et al., 2018; Hoßfeld, 2017).
- Product reconfigurations (Porter & Heppelmann, 2014, 2015).
- New human resources competencies and skills (Kergroach, 2017; Krzywdzinski, 2017).
- Developing communications between people, industrial components (equipment and machinery), and products (Pan et al., 2015) and extending internal and external networks (Reynolds & Uygun, 2018; Kovács & Kot, 2016).
- Sustainability (Kiel et al., 2017; Birkel et al., 2019).
- Transforming internationalization processes (Zucchella & Strange, 2017; Chiarvesio & Romanello, 2018).
- Performance (Dalenogare et al., 2018; Lee et al., 2015).

Despite the relevance of Industry 4.0 in performance, existing works have investigated this theme through conceptual papers or case studies, and have demonstrated a positive causal relationship between the single pillars of enabling technologies and opportunities. However, literature lacks empirical studies investigating the relationship between the plurality between the pillars of Industry 4.0 enabling technologies and performance. It is necessary to consider that several pillars of Industry 4.0 enabling technologies; these can be implemented individually or through various combinations with different impacts on companies and their relationships.

Therefore, this paper aims to empirically investigate the causal relationship between the degrees of openness toward the pillars of Industry 4.0 enabling technologies and performance (Figure 1).

Figure 1. Conceptual framework

The study involves four primary steps: (1) identifying the main characteristics of the pillars of Industry 4.0 enabling technologies, and particularly their definitions and the opportunities they offer; (2) defining the research hypothesis; (3) operationalizing the concepts of openness and performance; and (4) empirically verifying the causal relationship between the degree of openness to Industry 4.0 and performance.

The analysis is conducted using a representative sample of 231 local manufacturing industry units developing the Industry 4.0 concept in Piedmont (northern Italy) in 2018 (see Section 4.1). The Piedmont units provide an excellent not only given their high added value in the manufacturing sector—24%, versus 17% in Italy overall (Istituto Nazionale di Statistica - ISTAT, 2018)—but also for its position as the first Italian region to adopt

4.0 technologies in 11.8% of its manufacturing companies, versus 8.4% in Italy (Ministero dello Sviluppo Economico, 2018).

The paper offers two original contributions to current literature:

- From a methodological perspective, it operationalizes the concept of openness and performance in Industry 4.0. Openness is measured in terms of breadth, or the number of pillars of Industry 4.0 enabling technologies implemented; and depth, or the number of stages in the value chain with these implemented technologies. Performance is measured in terms of the number of opportunities identified by the local manufacturing units.
- From an empirical perspective, the results reveal the units' openness to Industry 4.0. This study uses a set of control variables to describe these different opportunities toward openness according to the characteristics of the local units belonging to different industries.

Regarding its managerial implications, the paper indicates whether and how the pillars of Industry 4.0 enabling technologies should be implemented in companies, and identifies key points concerning companies and governance.

The remainder of this paper is structured as follows: The second section presents the theoretical background, while the third section identifies the research hypothesis. The fourth section describes the methodology, and the fifth section analyzes the research results. The conclusions are then refined with a discussion of the work's implications, limitations, and scope for future research.

1.2 Theoretical background

1.2.1 Aim and process of the literature review

The theoretical background is derived from a literature analysis on academic journals in English, identified through four criteria: the *period*, spanning January 2011 (German National Plan) to January 2019; *search terms* synonymous with Industry 4.0 or the pillars of enabling technologies; the *research domain*, or business economics; and the *research areas*, or economics, business, and management. The literature review of 249 articles identified the origins and definitions of Industry 4.0, as well as the key factors and opportunities related to the pillars of its enabling technologies.

1.2.2 Origins and definitions of Industry 4.0

Industry 4.0 is a controversial process by nature and definition given the enabling technologies that allow it to exist as well as the opportunities it brings.

The expression "fourth Industrial Revolution" was first introduced in 1988 to identify the processes of evolving inventions into innovation due to scientists on production teams (Rostow, 1988). The term was then associated to the development and application of nanotechnologies (Parthasarathi & Thilagavathi, 2011; Hung, Wang, & Chang, 2012). In 2011, this was named "Industry 4.0" after Germany's "*Industrie* 4.0" industrial plan (Kagermann, Helbig, & Wahlster, 2013b). Other countries have different names for Industry 4.0, such as the "Industrial Internet" or "Advanced Manufacturing" in the United States, "Factories of the Future" by the European Commission, and the "Future of Manufacturing" in the United Kingdom. Other such terms include the "Fourth Industrial Revolution," "Digital Factory," "Digital Manufacturing," "Smart Factory," "Interconnected Factory," "Integrated Industry," "Production 4.0," and "Human-Machine

Cooperation.”

No conceptual, operative, or universally accepted definition of Industry 4.0 has been identified thus far due to the following: First, Industry 4.0 is comprised of an estimated more than 1,200 enabling technologies (Chiarello et al., 2018). Further, its innovations rapidly become obsolete; it can be applied in a variety of domains, such as smart factories, cities, grids, health applications, homes, spaces, objects, or machines; and different disciplines have analyzed the subject, such as engineering, economics, and management, among others. Moreover, its various stakeholders—such as policymakers, managers, entrepreneurs, and academics—have diverse needs.

However, it is possible to determine certain common elements, such as automation systems, connections between the physical and virtual worlds, the recognizing of a set of enabling technologies, digitalization, the Internet, and changes in the relationships with stakeholders and in governance; these will assist in determining a definition to better encompass the phenomenon. The “Industry 4.0” expression ultimately involves adopting industrial automation systems that assist in managing the value and supply chains, and more widely manage all their related processes (Liao et al., 2017; Reischauer, 2018; Yin et al., 2017).

1.2.3 Determiners and enabling technologies

The two key factors for Industry 4.0’s success are integration and interoperability (Lu, 2017; Lasi et al., 2014; Wei et al., 2017). Integrating industrial automation systems—such as Cyber Physical System (CPS) and Cyber Physical Production System (CPPS) —results in greater and more innovative features through networking with stakeholders, both horizontally and vertically). It also helps to create connections between the cyber and physical worlds. Moreover, interoperability facilitates production processes, even without continuity, within and beyond the boundaries of a business to interconnect systems and exchange knowledge and skills.

Industry 4.0 in particular uses a series of enabling technologies that can be categorized into 10 pillars. The first nine pillars come from a study by the Boston Consulting Group (Rüßmann et al., 2015), while some authors (Wan et al., 2015; Kinsy et al., 2011) add an “others enabling technologies” category. This latter category includes a series of equally significant innovations, but with limited application domains, such as agrifood, bio-based economics, and technologies supporting the optimization of energy consumption (Maksimchuk & Pershina, 2017).

1.2.4 Opportunities of Industry 4.0

The opportunities of Industry 4.0 can be classified into six main typologies (Table 2): production flexibility, which occurs during the manufacturing of small lots; the speed of serial prototypes; greater output capacity; reduced set-up costs and fewer errors and machine downtimes; higher product quality and less rejected production; and customers’ improved opinion of products.

Table 2. Pillars of Industry 4.0 enabling technologies 4.0: Definition, opportunities, and authors

Pillars of industry 4.0 enabling technologies	*Definition*	*Opportunities*	*Authors*
① *Advanced manufacturing solutions*	This refers to the creation of interconnected and modular systems that guarantee automated industrial plans. These technologies include automatic material-moving systems and advanced robotics, the latter of which are now on the market as “cobots” (collaborative robots) or automated guided vehicles or unmanned aerial vehicles.	- *Reduces set-up costs, errors, and machine downtimes*, given the capacity to learn tasks from the operator; - *Flexibility*, given by employees’ direct participation in the most complex work and control phases and eliminating the structural and technological constraints of automatic and fixed systems; - *Higher production capacity* through the possibility of modifying the criteria, not only to evenly distribute work activities between operator and machine, but also to allow more efficient and effective work.	Chung and Swink (2009); Spanos and Voudouris (2009); Druehl et al. (2018).
② *Augmented reality*	This involves a series of devices that enriches (or lessens) human sensory perception through the access to virtual environments; this is accompanied by sensory elements, such as sound, smell, or touch. These elements can be added to mobile devices (smartphones, tablets, or PCs) or other sensors to augment vision (augmented-reality glasses), sound (earphones), or touch (gloves) to provide multimedia information.	- *Higher speed in prototyping* through the possibility of designing products and processes with augmented virtual reality; - *The reduction of set-up costs, errors and machine downtime, plus superior product quality and less production waste* due to the possibility of receiving information in real-time and providing virtual training; consequently, this improves work procedures and decision-making processes.	Coxon et al. (2016); Kim et al. (2015); Markopoulos and Hosanagar (2017).
③ *Internet of Things*	This corresponds to a set of devices and intelligent sensors that facilitate	- *Higher product evaluations from the customer* due to: a greater knowledge	Gershenfeld and Euchner (2015); Euchner (2018); Markkanen (2015);

		communication between people, products, and machines.	of customer needs and preferences with the aim of personalizing products; including customers in production, or the co-creation of value; and a greater guarantee regarding products' origin, use, and destination, which ensures the product can be effectively traced from the factory to the customer; - *The reduction of set-up costs, errors, and machine downtime, plus superior product quality and less production waste.* This is due to: a greater interconnection along the supply and distribution chains; and the ability to reveal worn or broken machinery in real-time, allowing for proactive maintenance.	Tucker et al. (2018); Porter and Heppelmann (2014, 2015); Manyika et al. (2015); Alqahtani et al. (2019); Vendrell-Herrero et al. (2017).
④	*Big data analytics*	This relates to the technologies that capture, archive, analyze, and disseminate large quantities of data derived from the products, processes, machines, and people interconnected in a company, as well as the environment around it.	- *Higher product evaluations from the customer* due to faster communications, customized products, and the capacity to profile customers and determine their relative needs; - *Flexibility* due to the possibility of demand estimations; - *Better product quality and less production waste*, which optimizes the supply chain due to warehouses' improved efficiency, distribution and sales, and limited production costs.	Lee (2015); McAffee and Brijolfsson (2012a, 2012b); Wamba et al. (2015); Bumblauskas et al. (2017); Wang et al. (2016); He et al. (2017); H. Davenport (2014); Bartosik-Purgat and Ratajczak-Mrożek (2018); H. Choi (2018); Grover et al. (2018); Lee et al. (2016).
⑤	*Cloud computing*	Cloud computing technologies facilitate the archiving and processing of large quantities of data with high performance in terms of speed, flexibility, and efficiency. Cloud computing also results in a greater number of	The opportunities and risks from using these technologies can be added to those involved in Big Data analytics and Internet of Things technologies.	Mitra et al. (2018); Nieuwenhuis et al. (2018); Mell and Grance (2011); Gottschalk and Kirn (2013); Lal and Bharadwaj (2016); Alshamaila et al. (2013); Kushida et al. (2011);

		services developed based on data for a productive system—including monitoring and control functions—to ensure quality and improve operations and production.		Vaquero et al. (2008); Aoyama and Sakai (2011); Carcary et al. (2014); Sagar et al. (2013); Chen et al. (2014).
⑥	*Cyber security*	This includes security measures designed to protect the flow of information over interconnected corporate systems.	These technologies are designed to support others by limiting the risks linked to the increasing spread of information.	Tuptuk and Hailes (2018).
⑦	*Additive manufacturing*	This additive production process allows for complex products by creating layers of materials, including such different types of materials as plastics, ceramics, metals, and resins, thus eliminating the need to assemble the material. A significant example is 3-D printing.	- *Higher speed in prototyping* due to faster times in complex design and prototyping phases; - *The reduction of set-up costs, errors, and machine downtimes plus superior product quality and less production waste* by creating small, customized production lots. This is potentially advantageous in terms of its lower production costs and waste. Further, eliminating the separation between manufacturing and assembly phases significantly reduces the lead times between orders and deliveries.	Lasi et al. (2014); Weller et al. (2015); Sasson and Johnson (2016); Laplume et al. (2016); Borger et al. (2016); Khorram Niaki and Nonino (2017); Berman (2012); Gibson et al. (2010); D'aveni (2013); Mohr and Khan (2015); Garrett (2014); Rezk et al. (2016); Petrick and Simpson (2013); Beyer (2014); Campbell et al. (2011); Attaran (2017); Reeves (2009); Wigan (2014).
⑧	*Simulation*	This involves reproducing the physical world in virtual models and allowing operators to test and optimize the settings to obtain materials, productive processes (discrete elements), and products (finished or distinct elements).	- *Higher speed in prototyping* that increases production times; - *The reduction of set-up costs, errors, and machine downtimes*.	Guzmán et al. (2012).
⑨	*Horizontal and vertical integration*	The integration offered by Industry 4.0 is characterized by two dimensions: internal versus external. The first (horizontal integration) concerns the integration and exchange of information among the different areas in the company. The second (vertical integration) concerns the company's relationships with its suppliers and customers.	- *The reduction of set-up costs, errors, and machine downtime plus superior product quality and less production waste* due to: lower costs; the ability to self-educate to identify, diagnose, and solve problems; and better connections in the incoming and out-going supply chains;	Anderl et al. (2018); Lu (2017); Xu et al. (2018).

			-*Higher production capacity* and increased productivity.	
⑩	*Other enabling technologies*	These include several technologies used for specific fields, such as the agrifood and bio-based economy, among others. This also includes the tools to determine where, when, and how energy resources are used with the aim of eliminating or reducing waste.	- *Superior product quality and less production waste* to optimize production and to decrease waste expenses.	Wan et al. (2015); Kinsy et al. (2011).

1.3 The research hypotheses

The hypotheses to be discussed in Sections 3.1 and 3.2 are taken from Industry 4.0 literature, while the hypotheses discussed in Section 3.3 are the authors' original construction.

1.3.1 Opportunities of openness to the pillars of enabling technologies

Existing literature on Industry 4.0 as identified in the theoretical background uses conceptual studies to highlight case studies and laboratory experiments and determine how the openness to individual pillars of enabling technologies provides increased opportunities (Table 1). Additionally, Vogel-Heuser and Hess (2016) demonstrate that more than one of these pillars should be applied to the various stages in the value chain to obtain greater opportunities. Therefore, it can be affirmed that openness can be measured in terms of the number of enabling technologies adopted - breadth - and/or number of stages in the value chain in which these technologies are implemented - depth (Figure 2).

Figure. 2. Operationalizing the conceptual framework

Openness to	Industry 4.0	→ Performance
- Breadth = the number of pillars of enabling technologies adopted - Depth = the number of stages in the value chain in which the pillars of enabling technologies are implemented	- Ten pillars of Industry 4.0enabling technologies	- Six macro-typologies of opportunity

Thus, two research hypotheses can be assumed:

Hypothesis 1a – Breadth helps companies obtain greater opportunities when applying the pillars of Industry 4.0 enabling technologies.

Hypothesis 2a – Depth helps companies obtain greater opportunities when applying the pillars of Industry 4.0 enabling technologies.

Management literature regarding innovation in general—and Koput's model (Koput, 1997) of innovative search and the attention-based theory of the firm in particular—practically confirms that the relationship between being open to innovation and performance is an inverted U-shaped function. Consequently, two additional research hypotheses can be assumed:

Hypothesis 1b – The breadth when applying pillars of Industry 4.0 enabling technologies is curvilinear, with an inverted U shape.

Hypothesis 2b – The depth when applying pillars of Industry 4.0 enabling technologies is curvilinear, with an inverted U shape.

1.3.2 New opportunities in production capacity

Büchi, Cugno, and Castagnoli (2018) illuminate how Industry 4.0 provides enabling technologies to help companies achieve greater opportunities following improved efficiency (Scenario I) and increased production capacity (Scenarios II and III).

Scenario I. This ranges from a production model based only on manufacturing large quantities of standardized, limited-variety products (mass production) with greater efficiency, measured in terms of higher earnings and lower costs, to models that include two other production scenarios.

Scenario II. This involves manufacturing products to satisfy each individual customer's needs, with production efficiency near mass production but in limited numbers (mass customization; Fogliatto, da Silvera, & Borenstein, 2012; Tseng, Jiao, & Wang, 2010).

Scenario III. Products are manufactured to acquire purchasing experience regarding individual customers' tastes based on their preferences and production volumes, compared to Scenarios I and II (mass personalization; Tseng, Jiao, & Wang, 2010; Chellappa & Sin, 2005).

Mass customization and mass personalization facilitate variety in the product range, which spans the many of a kind to one of a kind varieties. This can then be altered over time in response to the growing demand for variety, which consequently results in a further decrease in average unit costs.

Anderson (2004, 2006) defines this method as a "long tail strategy," which guarantees companies will profit by selling smaller volumes of customized products that are difficult to find in the market, rather than only selling large volumes of mass-produced products (Brynjolfsson, Hu, & Smith, 2010). Similar situations have arisen from manufacturing small (niche) lots due to additive manufacturing (Shapeways, 2015), which can offer on-demand products through 3-D printing.

The current study maintains that unlike larger businesses, smaller firms' mass-production model deters them from obtaining economies of scale and networking, but the latter should obtain greater benefits by adopting enabling technologies. This is because they can adapt their production capacity—even temporarily—to emerging market needs, the time to market, and efficiency and productivity quality standards.

Therefore, the following can be assumed:

Hypothesis 3 – Small companies obtain greater opportunities than larger ones by applying Industry 4.0 technologies.

1.3.3 The importance of innovation

Given what has been discussed thus far in Section 3, the authors derive the following original hypotheses by positing that the causal relationship between openness and performance might be influenced by the degree of innovation. Innovation can occur as a part of a high-tech industry and to the propensity of companies to further innovate in Industry 4.0.

Therefore, the following hypotheses can be assumed:

Hypothesis 4 – High-tech companies obtain greater opportunities than companies in non-high-tech industries by applying Industry 4.0.

Hypothesis 5 – Companies that have already adopted Industry 4.0, and are inclined to further implement Industry 4.0, obtain greater opportunities.

1.4 Methodology

1.4.1 Sample

This paper analyzes the secondary data from the *Congiuntura Industriale in Piemonte* dataset collected by the *Unioncamere Piemonte* (2018) – Annex I. The survey data refers to the year 2018, and is obtained from a representative sample of 1,331 local units in

Piedmont's manufacturing sector (northern Italy), with at least two employees belonging to different size classes and different product sectors. This region case is particularly noteworthy, as it is highly committed to manufacturing (ISTAT, 2018) with a high degree of innovation within Industry 4.0 (*Ministero dello Sviluppo Economico,* 2018). This large-scale industrial survey aims to provide data for an analysis of the manufacturing sector's performance, with a specific theme concentrating on Industry 4.0. The survey's implementation and validation is managed by *Unioncamere Piemonte*. The questionnaire was administered by e-mail to the managers of local manufacturing units between January and April 2018.

The questionnaire contains the local manufacturing units' demographic characteristics, the number of employees, and the sector to which they belong; the thematic section dedicated to Industry 4.0 is composed of five main questions regarding the following areas:

1. *The Adoption of Industry 4.0* (dummy).
2. *Adopted technologies:* a list of the 10 pillars of Industry 4.0 enabling technologies (advanced manufacturing, augmented reality, the Internet of Things, Big Data, cloud computing, cyber security, additive manufacturing, simulations, horizontal and vertical integration, and others). Each local unit can adopt one or more of these pillars.
3. *Stages of the value chain*: a list of the phases of the value chain in which each pillar is employed, including production, research and development, warehouse logistics, purchasing, sales, and administration.
4. *Future investments*: the willingness to further invest in Industry 4.0 (dummy).
5. *Perceived opportunities*: a list of opportunities gained by adopting Industry 4.0, as identified in the theoretical background, including: less time from prototype to production, greater productivity through shorter set-up times, the reduction of errors and machine downtimes, better quality and less waste, and greater product competitiveness due to greater product functionality. The "other opportunities" category was ultimately added after validating the theoretical framework through in-depth interviews with managers.

1.4.2 Econometric measures and model

This research aims to empirically investigate the relationship between the degree of openness to the 10 pillars of Industry 4.0 enabling technologies. This is accomplished through independent variables (*BREADTH* and *DEPTH*) and a dependent variable (*P*, or performance). These concepts are adopted from Vogel-Heuser and Hess' (2016) work and applied to an empirical analysis. Further, different linear and non-linear regression models contain a set of control variables.

Dependent variables

The performance variable (*P*) sums the six opportunity variables (Table 1), each of which is a dummy variable coded as zero and one to indicate no opportunities and perceived opportunities, respectively. The six dummies were then summed to obtain an indicator of use, which evaluates the depth of opportunities, ranging from zero (few opportunities to use Industry 4.0) to one (many opportunities).

Independent and control variables

The level of openness towards Industry 4.0 is assessed through the *BREADTH* and *DEPTH* variables identified in Industry 4.0 literature (Vogel-Heuser & Hess, 2016).

The *BREADTH* variable is comprised of a combination of the 10 pillars of Industry

4.0 enabling technologies. Each variable is a dummy variable, coded as zero to indicate these were not implemented, while one indicates these were implemented. The 10 dummies were then summed to obtain an indicator of Industry 4.0 implementation, ranging from one (only one pillar has been adopted) to 10 (all pillars have been implemented). Although the variable is a relatively simple construct, it has a high degree of internal consistency, with a Cronbach's alpha coefficient of 0.8.

The *DEPTH* variable acts as a measure for companies to use Industry 4.0 pillars intensely throughout the value chain; *DEPTH* is comprised of the same 10 pillars as in the previous case, but each of these pillars in this case is a dummy variable coded as zero if Industry 4.0 methods are not used or rarely used in the value chain, and one if they are used frequently. Again, the 10 dummies were then summed to obtain an indicator of use, ranging from and including zero when few pillars have been implemented, to 10 when pillars are frequently used. Although the variable is a relatively simple construct, it has a high degree of internal consistency, with a Cronbach's alpha coefficient of 0.8.

The model uses the following control variables.

- Four *SIZE* variables based on the number of employees (dummy): micro-sized [2 to 10], small [10 to 50], medium [50 to 250], and large [250+].
- The *HIGH* variable measures the influence of industries with higher technological content, including the chemical, petroleum, and plastic materials; electronics; mechanical; and transportation industries (dummy).
- The *OPEN-ET* variable considers if the local units are inclined to further implement Industry 4.0 (dummy).

1.5 Results and Discussion

1.5.1 Descriptive analysis

The representative sample is comprised of 1,331 local units varying in size and belonging to different industries (Table 3); however, only 15% of the sample has implemented Industry 4.0. Moreover, only 231 local units have adopted one or more pillars of Industry 4.0 enabling technologies in one or more stages of the value chain. On average, 2.7 pillars have been adopted (breadth), and they have been introduced in 0.8 stages in the value chain (depth).

The figure 3 demonstrates that the openness, breadth, and depth of the pillars are more likely to occur:

- in industries with more frequently used technologies, such as the chemical and oil, plastic material manufacturing, and mechanical engineering and transport industries; and
- in medium-sized and large local units.

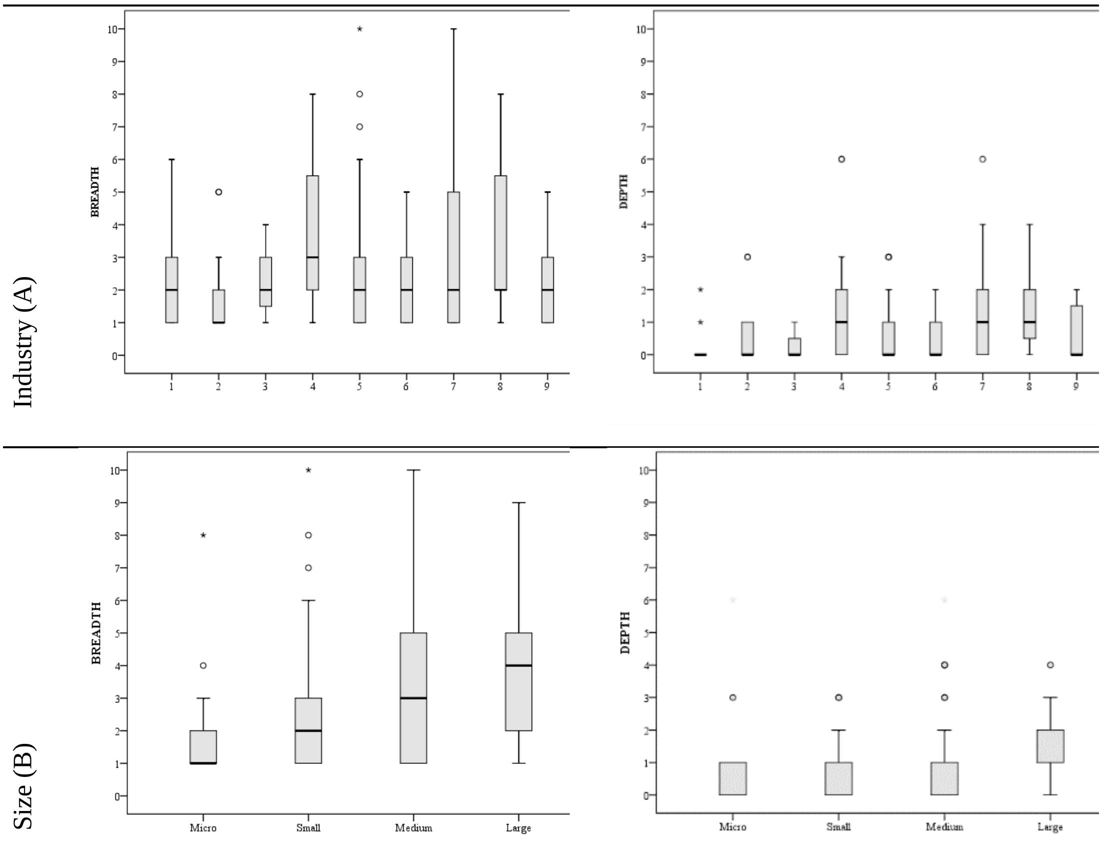
The graphs also indicate differentiated situations within the same industry and class size, which highlights an incredibly varied phenomenon according to the local unit surveyed.

Table 3. The primary indicators of openness to Industry 4.0 by industry and size

Variable	*N. LU*	*% LU Industry*	*LU Industry 4.0 (n = 231)*

			4.0	*Breadth mean*	*Depth mean*
Industry	1. Food	164	7.9	2.6	0.2
	2. Fabrics, clothing, and footwear	180	11.7	1.8	0.6
	3. Wood and furniture	59	5.1	2.3	0.3
	4. Chemical, petroleum, and plastic materials	121	23.1	3.5	1.3
	5. Metals	294	15.3	2.5	0.5
	6. Electronics	102	17.6	2.2	0.5
	7. Mechanical	208	23.6	3.1	1.1
	8. Transport	61	19.7	3.4	1.5
	9. Other manufacturing sectors	142	8.4	2.2	0.6
Size	Micro [2–10]	422	5.0	1.8	0.7
	Small [10–50]	631	13.6	2.2	0.5
	Medium [50–250]	224	32.6	3.2	1
	Large [250+]	54	38.9	4.3	1.5
Total		1331	–	–	–
Average		–	15.1	2.7	0.8

Figure 3 – Breadth and depth by industry and size (n = 231)



1.5.2 Confirmatory analysis

Table 4 displays the regression analysis results, coefficients, standard errors, statistics χ^2, and p-values. The three columns indicate the regression models adopted with the different variables. The first model is comprised of a linear regression analysis that considers only the effect of the independent variables (*BREADTH* and *DEPTH*) on the dependent variable (*P*). The second model is a linear regression that considers the Model 1 variables as well as the effects of the control variables. These variables concern the size class (*SIZE*), the degree of technology implemented in its industry (*HIGH*) and the local units' openness to further implementing Industry 4.0 (*OPEN-ET*). The third model is obtained by inserting two variables—$BREADTH^2$ and $DEPTH^2$—to evaluate the relationship's non-linear effects.

The three models confirm Hypotheses 1 and 2, as they report significant coefficients for *BREADTH* and *DEPTH* that are greater than zero. Thus, it has been demonstrated that greater breadth (Hypothesis 1a) and greater depth (Hypothesis 2a) in applying Industry 4.0 result in greater opportunities for local units. However, this is only partially true for Hypothesis 3, as the coefficient in the different size classes is only significant and greater than one for micro-level local units. Therefore, these units obtain greater opportunities than large local units by applying pillars of Industry 4.0 enabling technologies.

In summary, Hypotheses 1b and 2b cannot be confirmed or rejected due to the insignificance of $BREADTH^2$ and $DEPTH^2$. As the results also reject Hypotheses 4 and 5, it can be observed that the degree of innovation does not influence performance.

Table 4. Linear and non-linear regression models

Model	*Coeff.* (1)	*S.E.*	*P-value*	*Coeff.* (2)	*S.E.*	*P-value*	*Coeff.* (3)	*S.E.*	*P-value*
BREADTH	.372	.034	***	0.124	0.035	**	0.345	0.101	**
DEPTH	.175	.081	*	0.192	0.064	*	0.267	0.131	*
SIZE - micro				1.001	0.207	***	0.839	0.217	***
SIZE - small				0.866	0.120	***	0.647	0.143	**
SIZE - medium				0.766	0.149	***	0.563	0.169	*
HIGH				0.236	0.123	*	0.281	0.128	*
OPEN-ET				0.375	0.126	*	0.153	0.124	
$BREADTH^2$							-0.28	0.012	
$DEPTH^2$							-0.21	0.029	
Number/obs.		231		231			231		
F	162.672		***		97.746	. ***	79.629		***

*, **, and *** indicate that the coefficients are statistically significant at the < 5%, < 1%, and < 1 ‰ levels, respectively.

The analysis also tested the variable inflation factor (VIF) among the independent variables, resulting in a VIF less than 1.6; among the control variables, the VIF is less than 3.6.

1.5.3 Discussions

Analyzing the representative sample of Piedmont's local manufacturing units reveals a causal relationship between their openness to Industry 4.0 and performance. Further, the descriptive analysis' results make it possible to verify how Industry 4.0 is an emerging phenomenon in Piedmont. Of all the local manufacturing units surveyed, 15% have pursued adoption, measured in terms of the application of at least one pillar of 4.0-enabling technologies. This figure parallels other European areas, and primarily France at 15% to 17% (Boston Consulting Group - BCG, 2018), and it is higher than the average Italian region, or 8% (Ministry of Economic Development, 2018). The Piedmont local manufacturing units' adoption of Industry 4.0 still highlights a gap with Germany's national average, or a 25% adoption rate (BCG, 2018). This gap could be partially attributed to a delay in the nations' implementation of an Industry 4.0 national plan, which occurred in September 2016 in Italy (Ministry of Economic Development, 2016), compared to 2011 in Germany (Kagerman et al., 2011). Nevertheless, Piedmont is an important case study because the Italian region is ranked first in adopting Industry 4.0 as well as in its long tradition in the manufacturing sector.

The data on the degree of openness to Industry 4.0 also confirms what was highlighted in Sauter's (2016) conceptual study: a strong differentiation depending on the individual economic sector and the size of the manufacturing company. Moreover, local units in high-tech sectors—such as the chemical, petroleum, and plastic materials; metals; electronics; mechanical; and transportation industries—exhibited a higher degree of openness in terms of both breadth and depth.

The confirmatory analysis, conducted through different regression models, verifies a positive relationship between the openness to enabling Industry 4.0 technologies and performance. This empirically confirms what was stated in Vogel-Heuser and Hess' (2016) work.

1.6 Conclusion

The paper analyzes the causal relationship between the openness to Industry 4.0 and performance. The work is conducted through a confirmatory analysis of the hypotheses based in literature and by constructing and testing new hypotheses. The empirical research is based on a sample of local manufacturing units.

The paper's originality involves: a) identifying the opportunities to gain technologies enabling Industry 4.0; b) operationalizing the openness to Industry 4.0 into two concepts—its *breadth* and *depth*—as well as the concept of performance; and c) verifying the literature used for the hypotheses. Therefore, this empirical analysis reflects what has been mentioned in the Introduction regarding this paper's dual contributions.

From a methodological perspective, this work also operationalizes the concepts of openness and performance in Industry 4.0. Empirically, the results indicate the opportunities of openness toward Industry 4.0. The work uses a set of control variables to describe the different opportunities according to the characteristics of the local units belonging to different industries.

The paper theorizes that more open local units—with openness based on the number of enabling technologies or on their application in different stages of the value chain—are more likely to obtain greater opportunities in terms of flexibility, speed, increased production capacity, decreased errors and costs, and an improved product quality and ability to meet customer needs.

The study also confirms that openness leads to better opportunities in the manufacturing industry, while smaller local units are likely to obtain greater opportunities. This is partially justified in Industry 4.0 literature in connection with works examining the internationalization process (Ahokangas et al., 2014; Hmood & Ai-Madi, 2013), small and medium-sized enterprises (Hosseini et al., 2019), and start-ups (Mets & Kelli, 2011). Additionally, other authors posit a link exists between the greater benefits obtained by smaller companies and the possibility to overcome a lack of economies of scale due to mass customization (Fogliatto et al., 2012) and personalization (Tseng, Jiao, & Wang, 2010; Chellappa & Sin, 2005).

Current results do not clarify whether breaking points exist, after which openness in terms of breadth and depth can negatively influence innovative performance. Finally, the study rejects the hypotheses that innovative industries and the propensity to innovate might influence performance.

Implications

Despite any political and institutional agendas to develop Industry 4.0 in businesses, the analysis indicates this is a recent phenomenon and has been seldom implemented by businesses, not only in Italy, but also in the first countries to launch such innovation processes. Moreover, it is estimated that only a quarter of German companies have invested in Industry 4.0 (Rüßmann et al., 2015).

As mentioned in the introduction, the paper identifies some managerial implications, indicating whether and how the pillars of enabling technologies should be implemented in companies and identifying key points concerning companies and governance.

The research results first suggest that entrepreneurs should adopt Industry 4.0 in their companies to obtain greater performance. Second, policy-makers should promote mixed incentives that could encourage companies to adopt more enabling technologies in more stages of the value chain.

Finally, the results concerning the emphasis on opportunities to micro manufacturing local units, could allow to forecast that social and institutional environment promoting policies towards cross fertilization between small enterprises and big companies, as well as universities, will be very important in the near future for Piedmont. It is encouraging that regional and local institutions are already moving in this direction.

Limitations and future research

Innovation research has potentially high costs and commitments to hiring personnel with specific knowledge, competencies, and skills to define the potential of various technologies, customers, and markets without becoming obsolete through innovation. Subsequently, such investments can only be assessed in the long-term. Therefore, the obtained results deserve further confirmatory studies of panel data that assesses the benefits obtained over longer periods of time.

Noteworthy developments could also be obtained regarding the aspects that cannot be investigated using the current database. The most promising lines of research have been identified by applying a regression model that considers different dependent variables to measure the impact of applying Industry 4.0 on companies' results, such as their turnover percentages, improved production capacity, increased employee numbers, lower costs, and/or greater profits.

1.7 Appendix to paper 1

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1.7.2 Declaration of Interest Statement

None.

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2. Paper 2 – Openness to Industry 4.0 and performance: The impact of barriers and incentives

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Openness to Industry 4.0 and performance: The impact of barriers and incentives

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Highlights

- We operationalize the concepts of barriers and incentives to Industry 4.0 adoption.
- Greater openness to Industry 4.0 leads to the perception of higher barriers.
- Greater knowledge, economic, and financial barriers stimulate improved performance.
- Greater openness to Industry 4.0 drives the adoption of incentives.
- Greater perceived economic and financial barriers do not induce firms to adopt more incentives.

Abstract

The impact of barriers and incentives on the relationship between openness to Industry 4.0 and performance have so far received little scholarly attention. As a result, this paper explores this relationship by employing a mixed methods approach. A qualitative analysis using in-depth interviews and multiple case studies identifies prominent barriers and incentives, whilst a quantitative analysis on a representative sample of 500 local manufacturing units in Piedmont (a region of Northern Italy) is undertaken via an OLS regression-based path analysis. The results of the parallel-serial multiple mediation model show that: (1) greater openness to Industry 4.0 is related to better performance; (2) greater openness to Industry 4.0 leads to a higher perception of barriers; (3) greater knowledge-related and economic and financial barriers improve performance, abstracting from the adoption of incentives; and (4) greater openness to Industry 4.0 drives the adoption of incentives. However, perceived economic and financial barriers are found not to drive firms to adopt more incentives. The study contributes to the Industry 4.0 literature by identifying previously unidentified strengths and weaknesses to barriers and incentives,

and highlights the necessity of policies that reflect real firms' needs.

Keywords: Industry 4.0, Openness, Performance, Barriers, Incentives, Mediators

2.1 Introduction

In announcing its High-Tech Strategy 2020 Action Plan, the German Government formally started promoting changes in firms that can boost the competitiveness of manufacturers (Kagermann, Helbig, & Wahlster, 2013). Academics, managers, and policymakers agree that the adoption of cyber-physical systems and Industry 4.0 technologies in smart factories allows for flexible production, improves supply chains, and leads to more efficient business management, with significant technological, economic, and social impacts (Horváth & Szabó, 2019; Bag, Gupta, & Kumar, 2021). However, this opportunity comes in the context of prominent threats to the future of manufacturing: rapid changes in environmental conditions, changing customer expectations, reduced product lifecycles, and competition between countries.

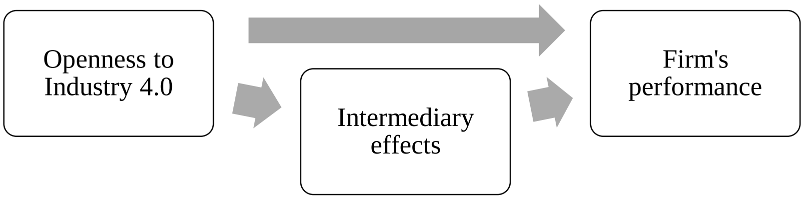
The majority of previous research (conventions, conferences, and publications) focuses on the analysis of the technological challenges posed the Fourth Industrial Revolution or Industry 4.0 (Oesterreich & Teuteberg, 2016; Pfeiffer, 2017; Frank, Dalenogare, & Ayala, 2019; Oztemel & Gursev, 2020; Marcucci, Antomarioni, Ciarapica, & Bevilacqua, 2021), and largely ignores the strategic and operational management of firms' performance. In addition, studies have mainly explored the topic through conceptual papers and case studies, thereby identifying a positive relationship between Industry 4.0 adoption and firms' performance but ensuring that empirical research remains in a state of infancy. Only a few authors have carried out confirmatory research on the phenomenon (e.g., Dalenogare, Benitez, Ayala, & Frank, 2018, Horváth & Szabó, 2019; Büchi, Cugno, & Castagnoli, 2020a).

Several authors have noted that the implementation of Industry 4.0 is a complex process and that different firms face a different series of barriers (Kiel, Müller, Arnold, & Voigt, 2017b; Dalenogare et al., 2018; Stock, Obenaus, Kunz, & Kohl, 2018; Agostini & Filippini, 2019; Birkel, Veile, Müller Hartmann, & Voigt, 2019; Horváth & Szabó, 2019; Raj, Dwivedi, Sharma, & de Sousa Jabbour, 2020; Ivanov & Dolgui, 2020; Müller, Buliga, &Voigt, 2020), with each barrier causing different impacts on Industry 4.0 adoption and performance. Therefore, it is important to understand these differing effects of the barriers that hinder the adoption of Industry 4.0 technologies as they become increasingly commonplace within firms across the world (Dalenogare et al., 2018).

To overcome these barriers, several industrial plans and public-private partnerships (e.g., *Industrial Internet Consortium* and *Factories of the Future*) have been launched to support Industry 4.0 advancement. However, thus far, individual barriers and incentives have been considered separately and without any consistent framework, meaning that little is known about their interdependencies (Kiel et al., 2017b). Therefore, there is a need to identify barriers, incentives, and relationships that could support the development of mitigation strategies, which could themselves induce a smoother adoption of Industry 4.0 technologies (Kamble, Gunasekaran, & Sharma, 2018).

In addition, it is not yet clear, at least from an empirical perspective, to what extent different barriers, different incentives, and firms' characteristics impact the relationship between openness to Industry 4.0 and firm performance. Therefore, despite the benefits that Industry 4.0 technologies provide to firms, there is substantial progress that needs to be made (Dalenogare et al., 2018; Frank et al., 2019). This paper serves to develop this research stream by empirically analyzing the effects of intermediary factors (barriers and incentives) on the causal relationship between openness to Industry 4.0 and firms' performance using qualitative and quantitative analysis (Figure 1).

Figure 1. Conceptual framework



The paper identifies performance, barriers, and incentives based on a theoretical background integrated with semi-structured interviews and case studies. The study operationalizes the concept of openness to Industry 4.0 and firms' performance according to the structure formulated by Büchi, Cugno, and Castagnoli (2020a):

- Openness to Industry 4.0 is measured in terms of the absolute number of Industry 4.0 technologies adopted; and
- Firms' performance is measured in terms of the absolute number of opportunities perceived by firms when adopting Industry 4.0 technologies.

The study is split into five phases: (1) the identification of intermediary factors; (2) the integration and validation of the theoretical background for Industry 4.0 performance; (3) the definition of research hypotheses; (4) the operationalization of intermediary factors; and (5) empirical tests of the causal relationship between openness to Industry 4.0 and firms' performance considering the various intermediary effects.

The analysis is carried out on a representative sample of 500 manufacturing units in Piedmont (a region of Northern Italy) which implemented one or more Industry 4.0 technologies in 2019. This sample is chosen because of the relevance of the Italian manufacturing sector which, with a turnover of around 900€ billion, is the second largest in Europe, after Germany. Piedmont also has high levels of value added compared to the average for Italy – 24% for Piedmont against 17% for Italy (ISTAT, 2018) – and has a high degree of Industry 4.0 technology implementation in manufacturing compared to the Italian average – 28.9% in Piedmont against 8.4% in Italy (MISE, 2018).

This paper is relevant for four reasons. First, it proposes a more inclusive theoretical approach that takes into consideration barriers and incentives as complements of the relationship between Industry 4.0 and firms' performance. Second, the methodology operationalizes the concepts of barriers and incentives to Industry 4.0. Third, the study empirically identifies the operational dynamics linking openness to Industry 4.0 and performance through an articulated set of intermediary effects. Fourth, the results provide practical advice to entrepreneurs and managers about the barriers and incentives that may hinder or support the implementation of Industry 4.0.

The paper is structured as follows. Section 2 defines and examines Industry 4.0, the concepts of openness and performance, and the factors that influence the studied relationship, as well as stating the research hypotheses. Section 3 describes the methodology of the qualitative analysis that integrates and validates the theoretical background and a quantitative analysis that tests the hypotheses. Section 4 reports the main results and Section 5 discusses these results. Section 6 highlights the most promising theoretical and practical implications, identifies limitations, and proposes avenues for future research.

2.2 Theoretical background and hypothesis development

This theoretical background develops the concepts of Industry 4.0, openness to Industry 4.0, performance, barriers, and incentives, and identifies research hypotheses.

The theoretical background is constructed using the following databases: Web of Science (WoS), Scopus, and EBSCO. WoS and Scopus are the most authoritative international sources for academic work in the social sciences (Vieira & Gomes, 2009), guaranteeing an optimal balance between: (1) coverage of existing works; (2) convenience in retrieving papers; and (3) the standardization of information in the database. EBSCO is added to integrate the results, since the EBSCO Information Service is a leading provider of research databases.

Analysis of the English-language literature was undertaken by selecting research that met four criteria.

- *Period*: From January 2011 – the introduction of the German National Plan – to October 2020
- *Keywords*: 17 phrases associated with Industry 4.0 (“Industry 4.0” OR “4th industrial revolution” OR “Fourth industrial revolution” OR “Factor* of the Future” OR “Future of Manufacturing” OR “Digital Factor*” OR “Digital Manufacturing” OR “Smart Factor*” OR “Interconnected Factor*” OR “Integrated Industr*” OR “Production* 4.0” OR “Human-Machine-Cooperation*” OR “Industrial Internet” OR “Cyber-physical System*” OR “CPS” OR “Cyber-physical production system*” OR “CPPS”), 5 words or phrases associated with performance (“performance*” OR “opportunit*” OR “benefit*” OR “advantage*” OR “driving force*”), 5 words associated with barriers (“barrier*” OR “obstacle*” OR “disadvantage*” OR “risk**” OR “challenge*”) and 2 words associated with incentives (“incentives” OR “measures”).
- *Search string*: Used 17 phrases associated with Industry 4.0 AND 5 words or phrases associated with performance AND 5 words associated with barriers AND2 words associated with incentives.
- *Research areas*: A literature review of 316 economic, business, and management papers identified Industry 4.0 definitions and the operationalization of openness to Industry 4.0, performance, barriers, and incentives

The main studies referenced are described in Table 1.

Table 1. Summary of the main studies referenced

Authors' names and year	*Approach*	*Methodology*	*Units of analysis*	*Identified performance*	*Identified barriers*
Agostini and Filippini (2019)	Quantitative	Cluster analysis	1,000 Italian manufacturing firms	Improved productivity of human resources	None
Birkel, Veile, Müller, Hartmann, and Voigt (2019)	Qualitative	Literature review and 14 in-depth interviews with experts	German manufacturing firms	None	Economic, social, and environmental risks
Büchi, Cugno, and Castagnoli (2020a)	Quantitative	Survey	231 local manufacturing units in Northern Italy	Production flexibility, which occurs during the manufacturing of small lots; the speed of serial prototypes; greater output capacity; lower set-up costs, fewer errors and reduced machine downtimes; higher product quality and fewer rejected products; improved customer opinion of products	None
Calabrese, Ghiron, and Tiburzi (2020)	Qualitative	39 in-depth interviews	Manufacturing sector	Cost reduction; production time reduction; production line flexibility; productivity; profitability; competitiveness; output quality	Difficulties in employee reorganization; resistance to factory reorganization; large investments; different communications standards among machines of different vendors; vulnerability to cyberattacks; regionally limited infrastructure; flaws in the legal/regulatory framework

Dalenogare, Benitez, Ayala, and Frank (2018)	Quantitative	Regression analysis	2,225 manufacturing firms in Brazil	Improved production customization; improvement in product quality; reduction of operational costs; increased productivity; reduction of product launch timeframes; improved sustainability; increased processes; visualization and control; reduced worker satisfaction	None
Horváth and Szabo (2019)	Qualitative	Semi-structured interviews	26 Hungarian manufacturing companies	Growing competition; increased innovation capacity and productivity; expectations of customers; energy-saving efforts and improved sustainability; support for management; opportunity for business model innovation	Human resources and work circumstances; shortage of financial resources; standardization problems; concerns about cybersecurity and data ownership; technological integration; difficulties in coordinating across organizational units; lack of planning skills and activities; organizational resistance
Kiel, Arnold, and Voigt (2017a)	Qualitative	Semi-structured interviews with experts and analysis of firms' documents	76 manufacturing companies	Increased flexibility; optimized decision making; customization; highly profitable business models; improved work-life balance	None
Kiel, Müller, Arnold, and Voigt (2017b)	Qualitative	In-depth interviews with experts	Manufacturing firms	None	Lack of a skilled workforce, conflicts between workers due to changing working environments; shortage of financial resources; data security; lack of skilled internal human resources; new investments that aggravate the strong demand for internal financial resources; lack of clear standards; organizational resistance

Müller, Buliga and Voigt (2018)	Qualitative	In-depth interviews	68 automotive supply, mechanical engineering, electrical engineering, and ICT firms	Increased services; improved customer experience; business model innovation	Particularly costly process due to the level of investment required and the purchase and/or transformation of machinery; need for new skills and organizational and management transformation; lack of skilled internal human resources; new investments that aggravate the strong demand for internal financial resources; lack of clear standards
Müller, Buliga, and Voigt (2020)	Qualitative	Structural equation model	221 German industrial enterprises	Increasing the efficiency of transactions; chances to develop novel business model designs	None
Raj, Dwivedi, Sharma, and de Sousa Jabbour (2020)	Qualitative	Comprehensive literature review and discussions with industry experts; grey decision-making trial and evaluation laboratory (DEMATEL) approach	Manufacturing sector	None	Large investment into Industry 4.0; lack of clarity regarding economic benefits; challenges in value chain integration; in-branch security risks; low maturity level of desired technologies; inequality; disruption of existing jobs; lack of standards, regulations, and forms of certification; lack of infrastructure; lack of digital skills; challenges in ensuring data quality; lack of internal digital culture and training; resistance to change; ineffective change management; lack of an associated digital strategy; resource scarcity
Stentoft, Adsbøll, Wickstrøm, Philipsen, and Haug (2020)	Quantitative	Mixed methods	190 medium-sized Danish manufacturing firms	Reduced costs; improved time-to-market; improved response to customer requirements	Lack of standards; few financial resources; few human resources; lack of understanding of the strategic importance of Industry 4.0; focus on operation at the expense of developing the company (ambidexterity); lack of data protection (cybersecurity); lack of a qualified workforce; lack of knowledge about Industry 4.0; required education of employees; lack of employee readiness; lack of understanding of the interplay between technology and human beings

2.2.1 Industry 4.0

The neologism "Industry 4.0" is composed of a first part that reflects the historical basis of manufacturing and a second part – "4.0" – that refers to the fourth phase of the industrialization process (Kagermann et al., 2013).

The development of Industry 4.0 follows the enormous increases in productivity that stemmed from mechanized production plants driven by water and steam energy (mechanization) in the second half of the 18th century, the division of labor and the advent of mass production using electricity (electrification) at the beginning of the 20th century, and the computerization of industrial production by programmable logic controllers (digitalization) in the early 1970s (Shrouf, Ordieres, & Miragliotta, 2014; Wolter et al., 2015; Ghobakhloo, 2018).

The central technological axis of Industry 4.0 is the communication, intermediation, and relationship environment (environment 4.0) realized through cyber-physical systems (CPSs) and/or cyber-physical production systems (CPPSs). Environment 4.0 employs human resources for creative and problem-solving activities, and guarantees its functionality through two key factors: integration and interoperability (Lu, 2017). Integration enables innovative functionalities through network connections between products (primary, intermediate, and final), people (B2C customers and employees), locations (including remote locations), means of production (machines, workpieces, and modules), and partners (suppliers, strategic affiliates, and B2B customers) (Schneider, 2018). Network connections increase productivity through collaboration at the micro- (i.e., people and machines), meso- (i.e., systems and suppliers) and macro- (i.e., enterprises and companies) levels (Korambath et al., 2014; Büchi, Cugno, & Castagnoli, 2020b). Communication between different stakeholders within the organizational structure and along the value chain facilitates the connection of physical and virtual operations. Interoperability allows for the realization of seamless production both within and beyond the firms' boundaries, through interconnections between production systems and exchanges of knowledge and skills between production structures and across firms.

2.2.2 Openness to Industry 4.0

Industry 4.0 is implemented through a novel combination of established and new technologies. The type and level of Industry 4.0 technologies' performance depend on their means of application and function, as well as on the departments in which they are utilized. Previous studies identify a wide range of Industry 4.0 technologies: Italian industrial plan identifies 39 (*Impresa 4.0*, MISE, 2017), the French industrial plan identifies 47 (*La Nouvelle France Industrielle*, Le Conseil National de l'Industrie, 2013), while other works have identified over 1,200 technologies (Chiarello, Trivelli, Bonaccorsi, & Fantoni, 2018). Some studies (e.g., Rüßmann et al., 2015) classify the portfolio of enabling technologies into nine pillars: advanced manufacturing, augmented reality, the internet of things, big data analytics, cloud computing, cyber security, additive manufacturing, simulation, and horizontal and vertical integration. Kinsy et al. (2011) and Wan, Cai, and Zho (2015) add the additional category of *other 4.0 technologies*, which includes a number of equally significant innovations, but with often limited domains of application, such as agri-food, bio-based economics, and technologies supporting the optimization of energy consumption (Maksimchuk & Pershina, 2017).

Industry 4.0 introduced the 10 R processes of advanced production, namely refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover (Bag et al., 2021).

Conceptual studies, case studies, or laboratory experiments on Industry 4.0 have shown that openness to individual pillars of Industry 4.0 technologies offers more opportunities. Vogel-Heuser and Hess (2016) and Büchi, Cugno, and Castagnoli (2020a) empirically show that multiple pillars should be applied at various stages of the value chain in order to produce more opportunities. Therefore, there is evidence to suggest that openness to Industry 4.0 should be measured in terms of the number of technologies adopted (i.e., breadth of use), such that this informs our analytical approach.

2.2.3 Performance

The literature on Industry 4.0 performance demonstrates how openness to Industry 4.0 technologies in one or more phases of the value chain allows firms to improve performance (Vogel-Heuser & Hess, 2016; Büchi, Cugno, & Castagnoli, 2020a). This performance improvement identified by the literature can be classified into 7 categories (labeled here as ‘P’ categories), which are reported in Table 1.

P1 Production flexibility

Industry 4.0 has been identified as a major determinant for improving production flexibility (Ahuett-Garza & Kurfess, 2018; Cavalcante, Frazzon, Forcellini, & Ivanov, 2019; Dubey, Gunasekaran, Childe, Wamba, Roubaud, & Foropon, 2019; Frank et al., 2019) through virtualization, decentralization, and network creation (Fragapane, Ivanov, Peron, Sgarbossa, & Strandhagen, 2020).

Additionally, production flexibility can be reached through combinations of mass customization and mass personalization, which necessitate the production of a variety of products. Mass customization involves the creation of products at limited volumes that meet individual customers’ needs with a level of efficiency close to that of mass production (Fogliatto, da Silvera, & Borenstein, 2012), whilst mass personalization is the production of products and purchasing experiences at limited volumes according to individual consumers’ preferences (Chellappa & Sin, 2005; Tseng, Jiao, & Wang, 2010).

P2 Speed of serial prototypes

Industry 4.0 allows for the evaluation of the functionality and performance of core and component products and processes through the creation of virtual models. These “digital twins” provide the possibility of examining the performance of products or factories in different contexts and reduce the length of the product and production development process in industrial contexts that are both highly competitive and time-to-market oriented (Lasi, Fettke, Kemper, Feld, & Hoffmann, 2014; Bauer, Hämmerle, Schlund, & Vocke, 2015; Fatorachian & Kazemi, 2020; Moeuf et al., 2020).

P3 Greater output capacity

Many of the Industry 4.0 technologies applied to production systems allow for small batch production and production flexibility, thus improving production volumes (Calabrese, Ghiron, & Tiburzi, 2020) by 45–55% (McKinsey, 2019). The lower costs of Industry 4.0 technologies allow creating production environments characterized by higher productivity and greater flexibility along with cost containment (Fragapane et al., 2020). Thanks to the 4.0 environment it is possible to enable efficient mass production, thereby offering increases in overall production levels by combining mass customization and mass personalization. The combination of these scenarios allows companies to operate a long tail strategy (Anderson, 2004, 2006), which guarantees higher profits through the production of smaller volumes of customized products which are difficult to find on the market using large volumes of mass-produced products (Brynjolfsson, Hu, & Smith, 2010).

P4 Reduced set-up costs, fewer errors, and shorter machine downtimes

Industry 4.0 reduces costs, errors, and downtimes through the real-time monitoring of operating conditions for key resources, highlighting efficient downtimes, and communicating these to operators through user-friendly devices (i.e., tablets, smartphones, or smartwatches). This monitoring allows for immediate intervention and the speedy restoration of peak operating conditions (Georgakopoulos, Jayaraman, Fazia, Villari, & Ranjan, 2016). Industry 4.0 allows for the development of predictive maintenance models, based on collected data and subsequent analysis, that offer a means of comparing operational or performance values (i.e., efficiency or compliance) and reduce machine downtime (Hughes, Dwivedi, Rana, Williams, & Raghavan, 2020). These activities reduce maintenance costs by supporting production management through the supply of information. Firms can therefore employ Industry 4.0 methods to increase supply volumes, achieve significant cost savings, and ensure micro-level performance improvements (Kiel et al., 2017b; Calabrese et al., 2020; Fatorachian & Kazemi, 2020; Stentoft et al., 2020).

P5 Higher product quality and fewer rejected products

Industry 4.0 allows for the production of higher quality goods (Porter & Heppelmann, 2014, 2015; Stentoft et al., 2020) and the reduction of waste (Paritala, Manchikatla, & Yarlagadda, 2017), while significant improvements can also be achieved in energy efficiency (Lins & Oliveira, 2017; Szalavetz, 2019). The literature notes that Industry 4.0 can support the achievement of environmentally sustainable manufacturing with the development of green products, manufacturing processes, and supply chain management structures (de Sousa Jabbour, Jabbour, Foropon, & Godinho Filho, 2018; Müller, Buliga, & Voigt, 2018; Birkel et al., 2019).

P6 Customers' improved opinion of products

Industry 4.0 technologies allow firms to develop or increase their comparative advantage over their competitors as the demand for products that are adapted to consumers' expectations and needs increases (Adolph, Tisch, & Metternich, 2014; Karre, Hammer, Kleindienst, & Ramsauer, 2017; Stentoft et al., 2020). Industry 4.0 also raises the degree of customer involvement in products (Kagermann et al., 2013; Ustundag & Cevikcan, 2017), such that Müller, Buliga and Voigt (2018) note that Industry 4.0 affects three elements of manufacturing: value creation, value capture, and value offer.

P7 Improved productivity of human resources

Djuric, Urbanic, and Rickli (2016) highlight that the implementation of Industry 4.0 enables the greater productivity of human resources due to the raised efficiency of work and the improvement of working conditions through the replacement of humans performing dangerous activities. The increased productivity of human resources can derive from improved skills, greater organizational and collaborative capacity across different areas of the firm, and an ability to learn from each other (Agostini & Filippini, 2019).

Based on the theoretical background, the primary research hypothesis is developed as follows:

H1: Greater openness to Industry 4.0 leads to greater perceived performance.

This is the primary hypothesis, on which all the other hypotheses depend. As such, if this hypothesis is not verified, the study cannot be conducted.

2.2.4 Barriers

Previous studies highlight several barriers that can hinder the effective implementation of Industry 4.0 technologies. The barriers presented in the literature are separated into 11 types (labeled here as 'B' categories).

B1. Inadequate information on the potential offered by Industry 4.0 technologies

Koch, Kuge, Geissbauer, and Schrauf (2014) and Basl's (2017) studies highlight the number of firms that have not implemented Industry 4.0 and do not intend to even produce studies on the economic feasibility of Industry 4.0 technologies due to a lack of information on the potential benefits or drawbacks of its application. In addition, Müller, Buliga and Voigt (2018) empirical analysis of a sample of German entrepreneurs shows that implementation of Industry 4.0 technologies is a particularly costly process due to the level of investment required to purchase or transform machinery, the need to acquire new skills, and the necessary organizational and management transformation. Koch et al. (2014), Müller, Buliga and Voigt (2018), and Birkel et al. (2019) also show that Industry 4.0 technologies require significant investments which have uncertain amortization schedules and uncertain future uses. Furthermore, Kache and Seuring (2017) state that, in addition to economic investments, major changes in human resource capabilities and processes and technologies at the corporate and local levels are required. Similar results are highlighted by Masood and Sonntag (2020).

B2. Insufficient knowhow within companies

Industry 4.0 changes will ensure that creative and communicative workers become more valuable to companies (Erol, Jäger, Hold, Ott, & Sihn, 2016) since the challenges that Industry 4.0 poses require continuous innovation and learning, which is dependent upon the capabilities of key personnel (Shamim, Cang, Yu, & Li, 2016). Additionally, creativity and innovativeness might be useful in fulfilling customers' requirements (Sriram & Vinodh, 2020). However, such knowledge and skills are not always available to firms (Calabrese et al., 2020). Industry 4.0 adoption requires new skills and knowledge (Ras, Wild, Stahl, & Baudet, 2017, Wei, Song, & Wang, 2017) and a highly skilled workforce that is capable of managing the interaction between processes and information flows, and cooperating to solve problems (Balasingham, 2016; Erol et al., 2016). Therefore, one of the main challenges for Industry 4.0 implementation is the lack of skilled internal human resources (Adolph et al., 2014; Karre et al., 2017; Kiel et al., 2017a; Müller & Voigt, 2017). Moreover, the foremost requirement for initiating Industry 4.0 consists of cross-functional collaborations through the interconnection of all elements in the value chain network (Ras et al., 2017; Ghadge, Kara, Moradlou, & Goswami, 2020). The literature also shows that the employees with different skill levels are important for improving performance (Okorie, Subramoniam, Charnley, Patsavellas, Widdifield, & Salonitis, 2020; WEF, 2020).

B3. Few skills in the labor market

Liboni et al. (2019) note that a major barrier to Industry 4.0 adoption is the lack of a skilled workforce in the labor market (Kumar, Singh, & Kumar, 2021). SMEs, in particular, are seen to lack the skills that would enable the efficient exploitation of Industry 4.0 technologies (Moeuf et al., 2020). This acts both as a barrier to the development of Industry 4.0 and as a problem in the short to long term given the professional profiles formed in educational institutions at various levels (Baygin, Yetis, Karakose, & Akin, 2016; Benešová & Tupa, 2017; Motyl, Baronio, Uberti, Speranza, & Filippi, 2017). It is therefore imperative that companies train employees in order to transition to Industry 4.0 production methods (Kagermann et al., 2013). The skills most in demand are: information and data literacy; communication and collaboration, digital content creation, safety and security, and problem solving (Flores, Xun Xu, & Lu, 2019).

B4. Insufficient financial resources within the firm

Industry 4.0 requires a significant investment (Kumar, Singh, & Dwivedi, 2020) with an uncertain return (Müller, Buliga, & Voigt, 2018) as the rapid evolution of technologies makes these investments risky (Kagermann et al., 2013; Schneider, 2018). Birkel et al. (2019) also highlight the long and uncertain amortization and the high investment required in personnel. This is most noticeable in SMEs where managers tend to favor major investments (Calabrese et al., 2020). Additionally, financial constraints are a significant challenge to adopting Industry 4.0 in terms of the development of an advanced modern infrastructure and sustainable process innovations (Ghadge et al., 2020).

B5. Scarcity of external financing

Kagermann et al. (2013), Müller, Buliga and Voigt (2018), Schneider (2018), Birkel et al. (2019), and Calabrese et al. (2020) note that the lack of internal coverage for financial resources ensures that firms often experience difficulties in accessing external capital, which further aggravates other issues.

B6. Insufficient infrastructure

Industry 4.0 uses a combination of CPS-enabling technologies that, through the internet of things – a global network infrastructure composed of many connected elements of sensory, communication, networking, and information processing technologies (Tan & Wang, 2010), enables the creation of virtual networks that support operations in smart factories (Oesterreich & Teuteberg, 2016; Peruzzini, Grandi, & Pellicciari, 2017; Xu, Xu, & Li, 2018). In order to achieve corporate interconnectivity between suppliers and customers within the value chain and along the supply chain, firms need access to economic infrastructure (primarily broadband internet connections) that enable the various elements – products, devices, people, places, means of production, and partners – to communicate with each other instantaneously. The existence of ICT infrastructure is therefore a prerequisite for Industry 4.0 data transmission and systems integration (Erol, Schumacher, & Sihn, 2016). Consequently, having inadequate economic infrastructure poses a serious risk to the competitiveness of firms (Birkel et al., 2019).

B7. Legal uncertainties

The transformation of production centers into smart factories is a long and difficult process, made more complicated by issues relating to legal uncertainties over liability for, and ownership of, personal data and the protection of intellectual property (Birkel et al., 2019). In addition, at the international scale, Industry 4.0 opportunities come with possible vulnerabilities due to differing regulations across countries (Wu & Feng-Kwei, 2015). There remains a need for legislation governing cross-border intra- and inter-firm cooperation and trade, health, safety at work, and working hours (Kiel et al., 2017b; Birkel et al., 2019). Furthermore, security breaches via the sharing of information between partners are a particular concern (Koch et al., 2014).

B8. Difficulties in developing partnerships with universities and research centers

Collaborative strategies for implementing R&D are crucial to the success of any firm. However, as the literature highlights, organizations encounter problems in R&D activities on Industry 4.0 technologies because of difficulties establishing or strengthening partnerships with universities and research centers (Mittal, Khan, Romero, & Wuest, 2018). Such bilateral and multilateral partnerships can help firms (and SMEs especially) to access new opportunities (Müller, Buliga, & Voigt, 2018). However, connecting with multiple partners involves barriers to coordination that require the creation of value networks which enable the development of a profitable and sustainable ecosystem that outputs mutually produced value (Dellermann, Fliaster, & Kolloch, 2017; Ghanbari, Laya, Alonso-Zarate, & Markendahl, 2017). In addition, it is important to create partnerships between firms to acquire new external knowledge and to better develop Industry 4.0 technologies (Müller et al., 2020).

B9. Lack of clear standards

The lack of clear standards (Kovaitė, Šūmakaris, & Stankevičienė, 2020) hinders intra- and inter-firm collaboration and Industry 4.0 technology implementation. Specifically, Industry 4.0 technology adoption can be limited by: low levels of technological integration, particularly within the internet of things (Müller & Voigt, 2017); inadequate security in data transmission, both between organizations and within organizations (Cimini, Pinto, Pezzotta, & Gaiardelli, 2017; Kiel et al., 2017a); and the limited reliability and stability of machine-to-machine communications (Varghese & Tandur, 2014; Sung, 2018). Further, the variety of data types and sources, the different standards used across the several partners in a supply chain, and unstandardized interfaces represent challenges to information sharing under Industry 4.0 (Müller, Veile, & Voigt, 2020). Finally, the lack of trust impedes cross-company information sharing and collaboration in particular in SMEs (Müller et al., 2018).

B10. Organizational resistance

Another primary obstacle to Industry 4.0 adoption is cultural and technical acceptance by human resources (Birkel et al., 2019; Horváth & Szabó, 2019, Theorin, Bengtsson, Provost, Lieder, Johnsson, Lundholm, & Lennartson, 2017). An internal culture of embracing technological advancement must be nurtured throughout the organization to ensure teams are ready to adopt new technologies (Raj et al., 2020).

However, many managers and workers remain unwilling to change their production strategies and tasks (Raj et al., 2020), and in many cases there is a real resistance to new technologies (Haddud, de Souza, Khare, & Lee, 2017). Specifically, this could be because some technologies generate vast amounts of personal data on spending behavior, financial management, domestic habits, and health information, and employees often fear that Industry 4.0 technologies can increase the degree of surveillance over their work (Moeuf et al., 2020).

B11. The firm's sector of operation does not need Industry 4.0 investment

Whilst Industry 4.0 technology adoption offers many concrete advantages in terms of lower costs and higher revenues, these require a considerable amount of resources for implementation (Büchi, Cugno, & Castagnoli, 2018) and the reorganization of the entire business operation (Raj et al., 2020). Indeed, many firms have not introduced Industry 4.0 technologies and do not intend to produce feasibility studies due to a lack of information about the benefits or drawbacks (Koch et al., 2014; Basl, 2017; Müller, Buliga, & Voigt, 2018), perhaps signifying a belief that the entire sector does not need Industry 4.0 (Birkel et al., 2019; Horváth & Szabó, 2019; Müller et al., 2020; Stentoft et al., 2020).

The theoretical background shows there are 11 barriers to Industry 4.0. These perceived barriers are primarily centered around knowledge issues, economic or financial issues, cultural issues, or system conditions. Hence, the following research hypotheses are posited:

H2a: Greater openness toward Industry 4.0 leads to higher perceived barriers related to knowledge issues.

H2b: Greater openness toward Industry 4.0 leads to higher perceived barriers related to economic or financial issues.

H2c: Greater openness toward Industry 4.0 leads to higher perceived barriers related to cultural issues.

H2d: Greater openness toward Industry 4.0 leads to higher perceived barriers related to system conditions.

Additionally, Dalenogare et al. (2018) show that the different types of barriers have different effects on performance. Therefore, the following hypotheses are proposed:

H3a: Greater perceived barriers related to knowledge issues lead to the perception of improved performance.

H3b: Greater perceived barriers related to economic and financial issues lead to the perception of improved performance.

H3c: Greater perceived barriers related to cultural issues lead to the perception of improved performance.

H3d: Greater perceived barriers related to system conditions lead to the perception of improved performance.

2.2.5 Incentives

The transformational wave caused by the German Government's *High-Tech Strategy 2020 Action Plan* led many countries to implement industrial plans that improved firms' competitiveness and productivity on the manufacturing sector (Kagermann et al., 2011). At around the same time, the United States launched the *Advanced Manufacturing Partnership* (Rafael, Shirley, & Liveris, 2014), which was followed by France's *Nouvelle France Industrielle* (Le Conseil National de l'Industrie, 2013) and the United Kingdom's *Future of Manufacturing* (Foresight, 2013). Asian countries' initiatives were then introduced, with China's *Made in China 2025* initiative (Wübbeke, Meissner, Zenglein, Ives, & Conrad, 2015), Singapore's *Research Innovation Enterprise 2020 Plan* (National Research Foundation, 2016), and South Korea's *Innovation in Manufacturing 3.0* (Kang et al., 2016). Lastly, Italy launched its *Piano Industria 4.0* (MISE, 2017) and Brazil introduced its plan *Industrial Inovação, Manufatura Avançada e o Futuro da Indústria* (ABDI, 2017). More recently, many more initiatives aiming to spread the Industry 4.0 concept and promote Industry 4.0 technology adoption by local firms have been launched in both developed and developing countries. Alongside these industrial plans, research programs [e.g., *Factory of the Future* (European Commission, 2016)] and public-private partnerships [e.g., *Industrial Internet Consortium* (Evans & Annunziata, 2012)] have also been launched.

Although different in terms of the types of actions and investments undertaken, these government-developed plans are shaped by the needs of industries in their respective countries and reflect local economic conditions, current infrastructure, firm characteristics, and social and cultural norms. Nevertheless, it is possible to identify common characteristics of these industrial plans, including tendencies to undertake awareness-raising activities, create economic infrastructure, deliver training programs, and promote partnership development. Equally, actions specifically addressing businesses are commonly present, including incentives for investment in technology (hyper-amortization and super-amortization) and for the development of intangible resources and training facilities (e.g., tax relief for activities considered essential to the development of the firm), the provision of financial resources, and support for the development of "made in" initiatives. Jain and Ajmera (2020) state that government facilities are major enablers of Industry 4.0 adoption. Furthermore, a study by MISE (2018) shows that greater openness to Industry 4.0 leads firms to adopt more incentives. We thus propose the following research hypothesis:

H4: Greater openness toward Industry 4.0 positively affects the extent of incentive adoption.

Additionally, industrial plans show that governments worldwide have implemented a number of incentive programs to improve the perceived performance of Industry 4.0 technologies (Kagermann et al., 2013; MISE, 2018). Therefore, we propose the following research hypothesis:

H5: The adoption of incentives leads to the perception of improved performance.

The literature (e.g., Frank et al., 2016; MISE, 2018) also highlights how different business plans exploit several incentives to reduce the perceived extent of barriers. This study thus proposes that the degree to which barriers are perceived affects the use of incentives; however, since the types of barriers vary, it is conceivable they have different effects on the incentive uptake degree. As such, we propose the following research hypotheses:

H6a: The perception of higher barriers related to knowledge issues leads to a greater degree of incentive adoption.

H6b: The perception of higher barriers related to economic and financial issues leads to a greater degree of incentive adoption.

H6c: The perception of higher barriers related to cultural issues leads to a greater degree of incentive adoption.

H6d: The perception of higher barriers related to system conditions leads to a greater degree of incentive adoption.

2.2.6 Research hypotheses model

Based on the described theoretical background and the research hypotheses posited in the previous sections, we develop a model that investigates the relationship between the openness to Industry 4.0 and performance with different mediators (Figure 2).

2.3 Methodology

As shown in Figure 3, the paper uses a mixed-methods methodological approach combining elements of qualitative and quantitative research methods. This approach presents an excellent opportunity to advance the literature by providing a deeper understanding of a complex phenomenon. It also allows to address an exploratory and a confirmatory issue within the same study, along with a better methodological triangulation (Venkatesh, Brown, & Bala, 2013).

Figure 3 shows an overview of the steps used in this study. The theoretical background allows us to identify the concept of openness toward Industry 4.0, performance, barriers, and incentives. The first step – qualitative analysis – allows to validate and integrate the theoretical background, through semi-structured in-depth interviews with academics, entrepreneurs, and policymakers possessing solid experience in Industry 4.0, as well as multiple case studies. The second step – quantitative analysis – allows to test research hypotheses, the paper uses survey data from a sample of manufacturing units. The following sub-sections present the methods used in more detail.

Figure 2. Research hypotheses model

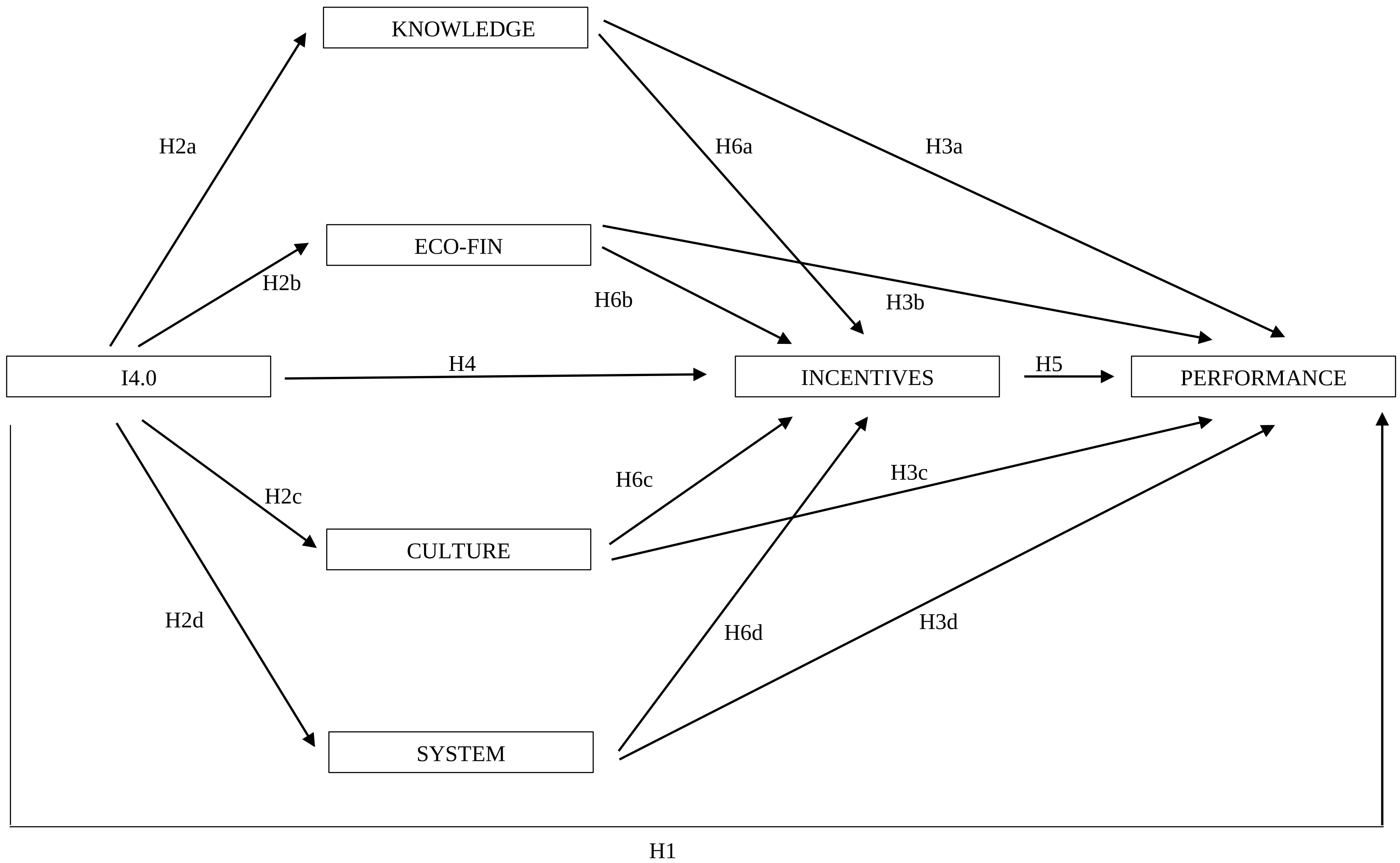
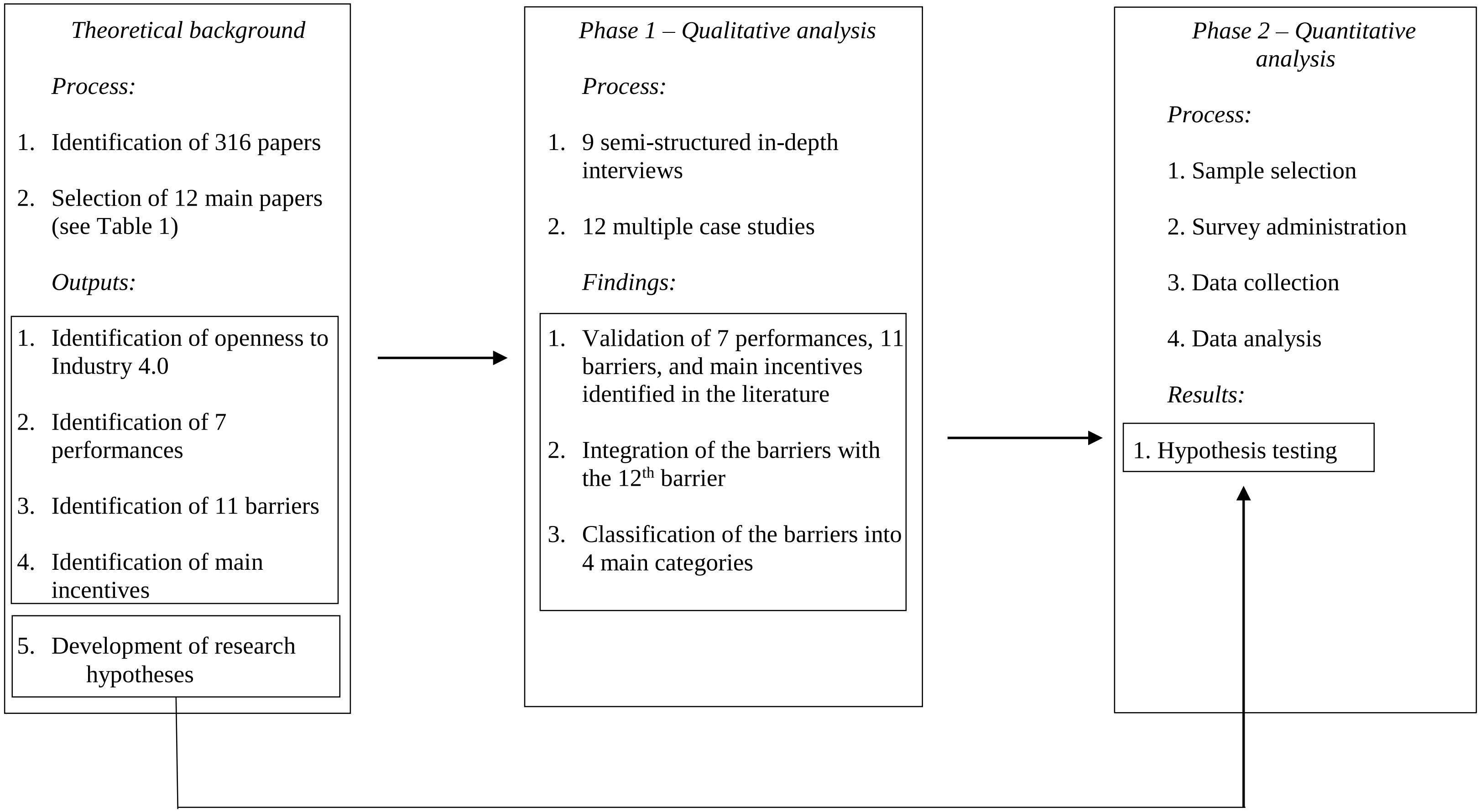


Figure 3. Methodological steps



2.3.1 Qualitative analysis

Kamble et al. (2018), Raj et al. (2020), and Stentoft et al. (2020) highlight that the performance of businesses after adopting Industry 4.0 technologies and the barriers to adoption remain largely unexplored. This gap shows the need to validate and integrate the theoretical background using our approach.

2.3.1.1 Semi-structured in-depth interviews

Semi-structured in-depth interviews with experts allow for data to be collected systemically while also ensuring that new and unexpected information can be included (Cannel & Khan, 1968; Yin, 2009). The participants in these semi-structured interviews are leading figures within Industry 4.0 public-private partnerships, trade associations, applied research centers, technology transfers or trainers actively helping firms through the Industry 4.0 transition (Table 2). These institutions are either located in or collaborate with relevant actors located in Piedmont (Northern Italy).

Table 2. Profiles of interviewed experts

Interviewed experts (E)	*Institutional association*	*Region*
E1	SME association	Piedmont, Northern Italy
E2	Technological organization	Piedmont, Northern Italy
E3	Technological organization	Piedmont, Northern Italy
E4	SME association	Piedmont, Northern Italy
E5	Local administration	Piedmont, Northern Italy
E6	Foundation	Piedmont, Northern Italy
E7	Technological organization	Abruzzo, Central Italy
E8	Competence center	Piedmont, Northern Italy
E9	Consultant in research center	Piedmont, Northern Italy

The semi-structured in-depth interviews were carried out with the representatives (i.e., presidents, CEOs, managers, consultants) of organizations promoting business development in the manufacturing sector. The involved organizations facilitate networks between business, research, finance, and training at the regional and interregional levels for the growth and economic and industrial development of the sector. Among the involved experts there are organizations representing and providing financial support to firms (E1, E5, E8 in Table 1); organizations creating relationships with research centers (E2, E3, E6 in Table 1); organizations creating networks for innovation (E4 in Table 1); organizations developing the sector's supply chain (E7 in Table 1); and research centers developing innovation 4.0 and providing strategic support to businesses (E9 in Table 1). The firms include more than 400,000 SMEs, while the other organizations provide support to more than 400 enterprises. All the organizations involved—in parallel with the development of business relationships, research, and finance—directly or indirectly carry out training in 4.0 upskilling and reskilling.

The interviews took place in January 2019 via Skype, lasted for 60 minutes each, and were recorded and transcribed. The authors carried out the interviews, following a semi-structured guide informed by the themes arising from the literature review. Some questions that were typically included are reported in Table 3.

Table 3. Semi-structured interview guide for institutions

1. Please provide a description of your institution (size, field, kinds of firms with which you collaborate)
2. Please describe the current degree of Industry 4.0 technology adoption by firms with which you work
3. In your opinion, what is the relevance of the following 10 new digital 4.0 technologies?
4. In your opinion, what are the main Industry 4.0 opportunities for firms?
5. In your opinion, what are the main barriers to Industry 4.0 technology implementation faced by firms?
6. In your opinion, what are the main incentives to Industry 4.0 technology adoption for firms?

The study adopts an interpretive methodology to identify themes emerging from the data in three phases. First, the interview transcripts are compared, the experiences of the interviewees are analyzed, and primary themes are identified. Second, a categorical aggregation is carried out and emerging patterns are identified. Third, the data are revisited to search for relationships between the literature review results and the different concepts emerging from the semi-structured interviews (§5.1).

Respondents have been anonymized to ensure confidentiality and increase result reliability.

2.3.1.2 Multiple case studies

The multiple case studies consist of in-depth semi-structured interviews on a cross-sector sample of firms (Table 4).

The multiple case studies consider 12 firms belonging to manufacturing sector, distinguished by their technology levels: low technology, medium-low technology, medium-high technology, and high technology industry. For each sector, there are three analyzed firms. The interviewed firms have been mainly conducted with SMEs and, in most cases, implementing Industry 4.0 through the application of CPS and specific 4.0 technologies. In a few cases only one technology is implemented. However, in most cases, the technologies are adopted in the production and design phases and, in one case, they are adopted in all the value chain phases. Most firms adopt Industry 4.0 for internal use, while a few companies produce 4.0 technologies for the market. In the majority of cases, the respondents are the firms' owners.

These semi-structured interviews are combined with additional materials, such as internal reports and web-sites (Eisenhardt & Graebner, 2007).

Firms are selected for inclusion in this sample following the Eurostat (2018) classification of manufacturing industries into categories based on R&D intensities (i.e., low-technology, medium-low-technology, medium-high-technology, and high-technology industries). The sampling criteria are based on an expectation that the more technology intensive the industries are, the more they are ready to use (or indeed are more likely to already use) Industry 4.0 technologies (Dachs, Kinkel, & Jäger, 2019).

The multiple cases studies were analyzed by interviews held in January 2019 via Skype. These lasted for 120 minutes and were recorded and transcribed. The authors carried out the multiple case studies following a semi-structured guide informed by the themes arising from the literature review. The typical questions included are displayed in Table 5.

Table 4. Profiles of the multiple case studies participants

Multiple case study (CS) participants	*CS1*	*CS2*	*CS3*	*CS4*	*CS5*	*CS6*	*CS7*	*CS8*	*CS9*	*CS10*	*CS11*	*CS12*
Industry	Low-technology industry	Low-technology industry	Low-technology industry	Medium-low-technology industry	Medium-low-technology industry	Medium-low-technology industry	Medium-high-technology industry	Medium-high-technology industry	Medium-high technology industry	High-technology industry	High-technology industry	High-technology industry
Size	Small	SME	Startup	Medium	Large	Medium	Medium	Medium	Medium	Small	Large	Small
Industry 4.0 technology adopted	CPS; cloud; internet of things; cyber security	Advanced manufacturing	CPS	CPS; cloud; internet of things; cyber security	CPS; cloud; internet of things; cyber security	Cobots	Virtual reality; augmented reality	Virtual reality; augmented reality	CPS	Additive manufacturing	All Industry 4.0 technologies	Advanced manufacturing
Current/potential application areas of Industry 4.0 technologies	Production	Production	Distribution	Production and distribution	Production and distribution	Production	Design and marketing	Design and marketing	Production	Production	All areas	Production
User or producer of Industry 4.0 technologies	User and producer	User	User	User and producer	User and producer	User	User	User	User	User	User and producer	User
Informant	Owner	Owner	Founder	Owner	Owner	Owner	Owner	Owner	Owner	Founder	Innovation	Owner

Table 5. Semi-structured in-depth interview guide for the multiple case studies

1. Please provide a description of your firm (size, age, products, markets, production methods, suppliers, customers)
2. Please describe your firm's degree of Industry 4.0 adoption
3. What is the relevance of the following 10 new digital 4.0 technologies for your firm and which of the technologies do you currently use?
4. What are the main opportunities presented by Industry 4.0?
5. What are the main barriers encountered to implementing Industry 4.0 technologies?
6. What are the incentives for adopting Industry 4.0 technologies?

At this point, this study adopts (for the interviews) an interpretive methodology to identify the themes emerging from the data in three phases. First, the interviews transcripts are compared, the experiences of the interviewees from the multiple case studies analyzed, and the primary themes identified. Second, a categorical aggregation is carried out and emerging patterns are identified. Finally, the data are revisited to identify relationships between the literature review results and the different concepts emerging from the semi-structured interviews.

The design of the multiple case studies adheres to the recommendations of Eisenhardt (1989), Voss, Tsikriktsis, and Frohlich (2002), and Yin (2009) regarding construct validity, internal and external validity, and reliability. Construct validity is achieved by choosing measurement standards that capture the primary features of the constructs under examination (Eisenhardt, 1989) – that is, the performance, barriers, and incentives identified through the literature review (Kiel et al., 2017a). The reconstruction of analyzed papers, both in terms of quality and quantity, guarantees analytical and procedural rigor (Strozzi, Colicchia, Creazza, & Noè, 2017; Fatorachian & Kazemi, 2018). External validity – that is, the generalizability of the results (Voss, Tsikriktsis, & Frohlich, 2002) – is reached by carrying out nine interviews on a heterogeneous sample of firms, since conducting multiple interviews improves the validity and utility of results (Eisenhardt & Graebner, 2007; Yin, 2009). Internal validity – that is, the ability of the evidence to support the presence of causal relationships (Edmondson & Mcmanus, 2007; Yin, 2009) – is attained through the semi-structured interviews with managers familiar with the implementation of Industry 4.0 technologies in their firms. Further, in the process of the multiple case studies, the respondents have been granted anonymity.

The size of the qualitative sample is selected based on two factors. The first one is that the extant qualitative studies on the topic have adopted similar sample sizes (Horváth & Szabó, 2019; Moeuf et al., 2020). The second one is determined on the basis of theoretical saturation (Denzin & Lincoln, 1994).

2.3.2. Quantitative analysis

The quantitative analysis tests the relationship between openness to Industry 4.0 and performance, as driven by barriers and incentives. The following sections present the sample and measures used, the selected variables, and the parallel-serial multiple mediation model.

2.3.2.1 Sampling and measurement

The hypotheses are tested using a publicly available secondary dataset entitled *Congiuntura Industriale in Piemonte*, for which data is collected every year by

Unioncamere Piemonte (2019)[2] – Annex I. The data for the year 2019 are obtained from a representative sample of 1,732 local manufacturing units in Piedmont (Northern Italy) which have at least two employees working in prominent economic sectors of the manufacturing industry: food; textiles, clothing, and footwear; wood and furniture; chemicals, petroleum, and plastics; metals; electronics and mechanical goods; transport; or other manufacturing industries) across different size classes (micro, small, medium, and large enterprises)

Before sharing the data file, *Unioncamere Piemonte* deleted cases with missing data and validated the dataset. Not all units in the dataset adopted Industry 4.0; However, in this study, only local units that adopted one or more Industry 4.0-enabling technologies were analyzed. This produced a sample of 500 local manufacturing units (28.9% of the original 1,732 local units). This percentage is above the national average of Italian firms in the industrial and service sectors, for which the equivalent percentage figure recorded in 2017 was 8.4%, and above the sample of large 'Made in Italy' companies (which had an annual turnover of over 1,000,000€) in Northern Italy, which recorded 19% (MISE, 2018). This region is particularly noteworthy, as it is highly committed to manufacturing (ISTAT, 2018), with a high degree of innovation as part of Industry 4.0 (*MISE*, 2018).

This large-scale industrial survey provides data for analysis of the manufacturing sector's performance and dedicates a specific section to Industry 4.0. The survey, which was conducted by e-mail with the input of the managers of local manufacturing units between January and April 2019, was implemented and validated by *Unioncamere Piemonte*.

The survey contains information on local manufacturing units' demographic characteristics, their number of employees, and their sector of operation. The thematic section dedicated to Industry 4.0 is composed of seven main questions relating to the following focuses.

1. Industry 4.0 adoption (dummy coding).
2. Industry 4.0 technologies adopted out of a list of 10 pillars (advanced manufacturing, augmented reality, the internet of things, big data, cloud computing, cyber security, additive manufacturing, simulations, horizontal and vertical integration, and *other technologies*). Each local unit can adopt one or more of these pillars.
3. Stages of the value chain from a list of the six phases of the value chain in which each pillar can be employed (production, R&D, warehouse logistics, purchasing, sales, and administration).
4. Future investments (i.e., the willingness to invest in Industry 4.0 over the next three years) (dummy coding).
5. (5) Perceived opportunities from a list of seven opportunities associated with the adoption of Industry 4.0, as identified in the theoretical background (reduced time from prototype to production, greater productivity through shorter set-up times, the reduction of errors and machine downtimes, better quality and less waste, greater product competitiveness due to greater product functionality, improved human resources productivity). The *other opportunities* category was added after the validation of the theoretical framework through in-depth interviews with experts.

[2] Unioncamere Piemonte is the regional chamber of commerce, industry, crafts, and agriculture union for the Piedmont region (Northern Italy). The chamber system is made up of about 500,000 firms from a variety of economic sectors. In total, they represent more than 1,500,000 employees

6. (6) Perceived barriers from a list of twelfth barriers that hinder the adoption of Industry 4.0 technologies, as identified in the theoretical background (little information on the potential offered by Industry 4.0 technologies, insufficient knowhow or lack of internal skills, few skills available in the labor market, insufficient financial resources within the firm, a lack of external financing, insufficient broadband connections, legal uncertainties, problems in relationships with universities and research centers, a lack of clear standards, organizational resistance, the firm's business sector not being seen to need investment in Industry 4.0, a lack of information on public facilities to support investment in Industry 4.0 technologies). The *lack of information on public facilities to support investment in Industry 4.0 technologies* and *other barriers* categories were added after the validation of the theoretical framework through in-depth interviews with experts.
7. (7) Business plan incentives from a list of nine incentives (MISE, 2017) that firms can use to adopt and/or implement Industry 4.0 technologies (super-amortization, hyper-amortization, contributions for the purchase of capital goods, guarantee funds, R&D tax credits, a "Made in Italy" extraordinary plan, training tax credit 4.0, intangible capital funds, and *other measures*). Each firm can activate one or more incentives without the need to participate in tenders.

2.3.2.2 Variable selection

The paper empirically analyzes the relationship between the degree of openness to the ten pillars of Industry 4.0 and firms' performance, as driven by perceived barriers and incentives. Openness is reflected by the independent variable I4.0, which is based on the empirical analysis of Büchi, Cugno, and Castagnoli (2020a), and the dependent variable is PERFORMANCE.

Dependent variables

The performance variable (PERFORMANCE) sums the seven opportunity variables listed in Section 2.3, where each is a dummy variable coded as 1 to indicate perceived opportunities or 0 otherwise. The seven dummies are then summed to obtain an indicator of the breadth of opportunities, ranging from 0 – indicating that no opportunities are perceived to derive from the adoption of Industry 4.0 technologies – to 7, where opportunities are seen to derive from all aspects.

Independent variables

The level of openness to Industry 4.0 is assessed by the breadth of 4.0 technologies identified in the Industry 4.0 literature (Vogel-Heuser & Hess, 2016; Büchi, Cugno, & Castagnoli, 2020a).

The value of I4.0 is the sum of the ten pillars of Industry 4.0 technologies, where each is a dummy variable, coded as 1 if the technology is implemented and 0 otherwise. The ten dummies are then summed to obtain an indicator of Industry 4.0 implementation, ranging from 1 – if only one pillar has been adopted – to 10, if all pillars have been implemented. Although the variable is a relatively simple construct, it has a high degree of internal consistency, producing a Cronbach's alpha coefficient of 0.8.

Intermediary variables

The Industry 4.0 literature (see Section 2.4) shows that there are distinct types of barriers (i.e., those relating to knowledge, economic and financial issues, cultural issues, and system conditions) that can hinder the adoption of Industry 4.0, and several incentives that promote adoption. Reflecting this, we employ four barrier types: KNOWLEDGE, ECO-FIN, CULTURE, and SYSTEM.

The KNOWLEDGE variable is made up of two barriers: insufficient knowhow within companies and few skills in the labor market. Each variable is a dummy variable, coded as 1 if the barrier is perceived, and 0 otherwise. The two dummies are then summed to obtain a knowledge barrier indicator ranging from 0, if no knowledge barriers are perceived, to 2, if both knowledge barriers are perceived. Although the variable is a relatively simple construct, it has a high degree of internal consistency, producing a Cronbach's alpha coefficient of 0.7.

The ECO-FIN variable is made up of two barriers: insufficient financial resources within the firm and scarcity of external financing. Each variable is a dummy variable, coded as 1 if the barrier is perceived, and 0 otherwise. The two dummies are then summed to obtain an indicator of economic and financial barriers, ranging from 0, if no economic and financial barriers are perceived, to 2, if both economic and financial barriers are perceived. Although the variable is a relatively simple construct, it has a high degree of internal consistency, producing a Cronbach's alpha coefficient of 0.9.

The CULTURE variable is made up of three barriers (little information on the potential offered by Industry 4.0 technologies, a perception that the business sector of operation does not need investment in Industry 4.0, and organizational resistance). Each variable is a dummy variable, coded as 1 if the barrier is not perceived, and 0 otherwise. The four dummies are then summed to obtain an indicator of cultural barriers, ranging from 0, if no cultural barriers are perceived, to 4, if all cultural barriers are perceived. Although the variable is a relatively simple construct, it has a high degree of internal consistency, producing a Cronbach's alpha coefficient of 0.7.

The SYSTEM variable is made up of four barriers: legal uncertainties, insufficient economic infrastructure, difficulties developing partnerships with universities and research centers, and a lack of clear standards). Each variable is a dummy variable, coded as 1 if the barrier is perceived, and 0 otherwise. The four dummies are then summed to obtain an indicator of system condition barriers, ranging from 0, if no system condition barriers are perceived, to 4, if all system condition barriers are perceived. Although the variable is a relatively simple construct, it has a high degree of internal consistency, producing a Cronbach's alpha coefficient of 0.7.

The INCENTIVES variable is a combination of ten incentives. Each variable is a dummy variable, coded as 1 if the incentive is utilized, and 0 otherwise. The ten dummies are then summed to obtain an indicator of incentives, ranging from 1, if only one incentive is used, to 10, if all incentives are used. Although the variable is a relatively simple construct, it has a high degree of internal consistency, producing a Cronbach's alpha coefficient of 0.7.

2.3.2.3 Parallel-serial multiple mediation model

The hypotheses developed in Section 2.6 are evaluated through an OLS regression-based path analysis using the parallel-serial multiple mediation model – a method that has recently become more popular with researchers (Moyer-Guse, Chung, & Jain, 2011; Krieger, Katz, Kam, & Roberto, 2012; Valdesolo & Graham, 2014; Richard & Purnell, 2017). The sample size is slightly above the average for parallel-serial multiple mediation model studies (Krieger, Katz, Kam, & Roberto, 2012; Moyer-Guse, Chung, & Jain, 2011; Richard & Purnell, 2017; Valdesolo & Graham, 2014), which supports the reliability of the obtained results.

The research hypotheses propose the existence of a relationship between openness to

Industry 4.0 (I4.0) and performance (PERFORMANCE) affected by five intermediary factors – four concerning the different types of barriers (KNOWLEDGE, ECO-FIN, CULTURE, and SYSTEM) and one concerning incentives (INCENTIVES). The model blends serial and parallel mediation processes, where parallel mediation considers the four types of barriers that influence the serial intermediary incentives.

Estimation is undertaken via an OLS regression-based path analysis, conducted using a PROCESS macro v.3.5 for SPSS (Hayes, 2020). The direct and indirect effects of I4.0 are estimated using six equations: one for each of the five mediators and one for performance. The model was tested using the bootstrapping method on samples of 5,000 units.

2.4 Findings and Results

2.4.1. Qualitative findings

The results of the qualitative analysis are reported below, following the same division into four main topics used in the theoretical background section: openness to Industry 4.0, performance, barriers, and incentives. The analysis of the text of the semi-structured in-depth interviews with experts and the respondents of the multiple case studies allowed us to identify the recurring keywords and phrases and identify main categories. These results are summarized in Table 6 and the main concepts are then developed in the following sections.

Table 6. Qualitative findings

Topic	*Categories*	*Recurring keywords/phrases*
Openness toward Industry 4.0	Breadth of 4.0 technology adoption	- Types of technologies - Combination of different technologies
Performance	P1 – Production flexibility	- Mass customization - Mass personalization - Real-time answer to market changes - Adaptability to market requirements - Satisfaction of customers' needs - Increased variety
	P2 – Speed of serial prototypes	- Reduced time in the design phase due to simulation - Reduced waste of material due to additive manufacturing
	P3 – Greater output capacity	- Use of different production models in varying combinations: mass production + mass customization + mass personalization - Higher full capacity
	P4 – Reduced set-up costs, fewer errors, and shorter machine downtimes	- Optimization - Waste reduction due to virtual reality and simulation - Increased scale and scope economies - Predictive maintenance - Increased resistance to production failures - Reduced lead time - Faster time to market - Energy saving
	P5 – Higher product quality and fewer rejected products	- Energy efficiency - Sustainability - Circular economy
	P6 – Customers' improved opinion of products	- Co-design - Co-creation - Tailored products - Interconnected products through Internet of Things
	P7 – Improved productivity of human resources	- Work-life balance - Smart working - Work flexibility - Improved ergonomics of working devices - Increased internal and external communication

		- Training courses through virtual/augmented reality - Greater inclusiveness
Barriers	C1 – Knowledge	- Insufficient knowhow within companies (B2) - Few skills in the labor market (B3) - Little information on public facilities to support investments in Industry 4.0 (B12)
	C2 – Eco-fin	- Insufficient financial resources within the firm (B4) - Scarcity of external financing (B5)
	C3 – Culture	- Inadequate information on the potential offered by Industry 4.0 technologies (B1) - Perception that the business sector of operation does not require investment in Industry 4.0 (B11) - Organizational resistance (B10)
	C4 – System	- Legal uncertainties (B7) - Insufficient economic infrastructure (B6) - Difficulties developing partnerships with universities and research centers (B8) - Lack of clear standards (B9)
Incentives	Breadth of incentives adoption	- Investment in technology - Development of intangible resources and training facilities - Provision of financial resources - Support for the development of “made in” initiatives

2.4.1.1 Openness toward Industry 4.0

The experts identified strong growth in the adoption of Industry 4.0 by firms. Similar observations were made by the respondents to the case studies.

As far as operation technologies are concerned, the highest growth is linked to additive manufacturing, followed by advanced manufacturing, which have been mainly implemented through the use of collaborative robots. Regarding information technologies, industrial analytics and cloud computing are the most developed technologies.

The results of the interviews and case studies show that the concept of openness toward Industry 4.0 is linked to the breadth of the adopted 4.0 technologies, considering that both the type of technology (e.g., advanced manufacturing, augmented reality) and the combinations between technologies are relevant. Therefore, the theoretical background of the openness toward Industry 4.0 has been validated by the qualitative analysis.

2.4.1.2 Performance

The experts and respondents observed that firms pay particular attention to their performance related to production flexibility and greater output capacity. Concerning this aspect, the experts of the organizations representing firms (E1, E5, and E8) pointed out that the performance that allows them to respond in a timely manner to demand imbalances and the execution of customized products are perceived as more important than others. In particular, this perception is that of SMEs, in that without 4.0 solutions there would be difficulties in modifying volumes and product variety quickly and with low costs. In case studies as well, the entrepreneurs, CEOs, and startup founders emphasized above all the importance of the performance indicators related to flexibility, production capacity, and better product perception by customers. For example, interviewee CS11 affirmed that: "Since we have adopted Industry 4.0, we have achieved a clear improvement in production capacity thanks to the support of 3D printing in mass production. The latter has been particularly useful in responding to our customers' requests for customized production."

According to expert E8: "Industry 4.0 makes possible to remotely manage relations with customers [...], to empower supply chains, new forms of conviviality for the promotion of products and spaces for the valorization of firms, partly supporting the crisis of distrust in Made in Italy products." A similar answer was given by interviewee CS7: "Since we have created our products with augmented reality, our customers are more satisfied and also help us to develop products for other customers […]."

Expert E9 pointed out that: "Entrepreneurs ask us for technologies that allow to reduce maintenance costs, to increase the volumes produced, and to achieve significant cost savings […] in order to improve the economies of scale, scope and networking."

All experts and entrepreneurs agree that a fundamental role is played by the 4.0 skills that can facilitate the implementation of Industry 4.0. For instance, expert E6 stated that: "Participants in our lessons, once they have joined the company, empower the learning ability to the other members thanks to a greater capacity for collaboration and exchange on the skills and abilities learned."

Furthermore, the experts emphasized the importance of simulation in prototyping. In this regard, expert E7 reported: "Since manufacturing companies have adopted simulation technologies, the speed of prototyping has largely increased, while production waste have been reduced." This statement also underscores the relevance of Industry 4.0 in reducing production waste, alongside the ability to control energy consumption. Expert E9 also highlighted this last point: “[...] In particular, the Internet of Things allows greater control over energy consumption and intervening in real time limiting waste.”

The recurring keywords/phrases in the interviews show that most experts and respondents perceive all seven performance categories identified in the theoretical background section. Therefore, the theoretical background of performance has been validated by the qualitative analysis.

Additionally, in most cases, the performance types are jointly perceived as combinations of several performances. The experts thus recommend to measure the perception of performance in terms of breadth, that is, as a perception of one or more performances.

2.4.1.3 Barriers

The experts and respondents highlighted that there are four main barriers, namely those related to knowledge issues, economic-financial resources, cultural aspects, and system conditions.

The knowledge issues seem stronger for highly innovative sectors (e.g., automotive, aerospace). In this regard, expert E9 stated: “Firms describe accurately their problems [...] and they know that 4.0 technologies can help them [...]. However, it is necessary not only to adopt technologies but also to provide them with strategic support for the new management of the firms.”

Additionally, expert E1 highlighted: “The use of the term Industry 4.0 is not clear. In particular, small firms often confuse individual 4.0 technologies with the opportunities that arise from the realization of a 4.0 environment.” The experts also pointed out that these technologies can only be implemented through the interconnection of smart factory, which that requires ad hoc infrastructure. However, they considered that most SMEs adopt a limited number of technologies and do not often create an integrated 4.0 environment. For example, respondent E8 stated: “Applying Industry 4.0 is not only buying new technologies, but it is the result of a total reconfiguration of the company,” while respondent CS10 explained: “The application of 4.0 technologies is complicated and requires a long procedure.”

The experts also identified problems related to a lack of knowledge on the opportunities of Industry 4.0. The difficulties also concern the acquisition of skills, knowledge, and abilities through the internal training of human capital and the use of suitable professional profiles in the labor market. As reported by expert E9, “Industry 4.0 changes the competencies of both white collars and blue collars. The latter, in particular, often have less specific knowledge and technical skills in routine tasks, while increasing the digital skills that allow them more control over more production phases, more machines, and more functions”.

Furthermore, experts E3 and E6 agreed that: “Employees must have a specialization on their specific tasks, but at the same time, they must have transversal knowledge so that they can collaborate in teams and be more adaptable to the various tasks [...]. The development of this competence can only be partially covered by reskilling.” Expert E2 added that: “The most required skills in the labor market are related to hard and soft digital skills, security, and problem solving activities.” In this regard the respondent CS11 adds that: “Since our firm has become smart, we are having problems identifying qualified Industry 4.0 workforce,” and respondent CS4 emphasized: “The employees were incredulous […] and displays and iPad could support them in the quality control of products. However, understanding this change was not easy. […] The tasks were very different from the previous ones."

The experts pointed out that investing in Industry 4.0 requires substantial capital that is not always available to firms and might be difficult to access externally. Concerning this aspect, expert E1 stated: "In addition to the difficulties linked to the shortage of human resources, there has been a serious liquidity crisis in Italian firms." Expert E4 and E5 agreed and stressed that: "[As organizations] in this direction, we have realized several vouchers and activities in favor of the acquisition of connectivity and training of human resources." CS10 added: "The customer couldn't believe it: A small 3D printer had made his dreams come true! […] However, the result was not easy if we think that we started with few resources (financial)."

The nine experts all agreed that the main barriers to Industry 4.0 are related to the lack of transformation of organizational processes and cultural resistance. This resistance is partly due to the presence of smaller family businesses that put the interests of the family before those of the business in Italy. The various interviewees agreed that entrepreneurs are inclined to question to status quo: "It has always been done so… why we should change?" Expert E1 insisted that: "The greatest difficulty for entrepreneurs is the transformation of a 4.0 behavior, that is, the willingness to promote behaviors that develop new ways of doing business and transform business models."

In some cases, entrepreneurs were even convinced that the industry to which their firms belong to does not need to adopt Industry 4.0. These problems are well highlighted by expert E4: "When I contact firms, many entrepreneurs answer me: [...] among the many troubles, why should I take care of Industry 4.0? Making them understand the opportunities of Industry 4.0 is not easy [...]." Expert E4 also pointed out that: "It is not only a problem of culture, but also of fear that the changes undertaken will not bring good profit. Very often those in charge of the firm answer me that their sector does not require technological investment. […]."

Expert E5 emphasized that: "The application of Industry 4.0 can only be implemented through an interconnection of the enterprise with the supply and distribution chain and therefore requires a strong use of technical infrastructure for the transmission of information and legislation that covers the new digital transformations and promotes the implementation of international cooperation." Expert E3 also pointed out this problem and emphasized further difficulties: "At present, many entrepreneurs complain about a lack of unambiguous standards."

Based on the opinions of the experts and interviewees, the implementation of Industry 4.0 in enterprises must be accompanied by the creation of partnerships and networks between enterprises for the development of innovation ecosystems. Expert E7, in fact, reported: "The creation of long supply chains and the aggregation of firms through a bottom-up approach is necessary to better respond to different market needs." Additionally, the experts generally underlined the relevance of collaboration and exchanges with universities and research centers, stating, for example: "For a company, creating alliances with research centers and universities becomes fundamental" (E7). Respondent CS1 also reported: "When we wanted to implement Industry 4.0 we didn't know where to start. [...] Then we found out, thanks to our representative organizations, who could help us." Respondent CS11 stated: "If we do not have the internal capabilities to understand which 4.0 technologies to apply, our employees know which research centers to contact and which external consultants can help us identifying the right incentives (industrial plan measures)." Raising this issue, one expert noted: "Entrepreneurs come to us to find solutions to their problems […] and are surprised that there are already places dedicated to the development and implementation of 4.0 solutions" (E1).

In conclusion, all experts validate the importance of all barriers identified in the theoretical background section. The qualitative analysis also identifies an additional barrier perceived by most participants but not identified in the literature. This barrier was thus added to the 11 barriers presented in the theoretical background section and classified as B12 – little information on public facilities to support investments in Industry 4.0. B12 reinforces the perception of cultural barriers, which, according to the participants, present sizeable problems.

Additionally, the qualitative analysis results lead to the classification of barriers into the four categories—knowledge issues, economic and financial issues, cultural issues, and system conditions (see Table 6). The barriers considered most influential were cultural, namely B1 (inadequate information on the potential offered by 4.0 technologies), B10 (organizational resistance), B11 (perception that the business sector of operation does not need investment in Industry 4.0) and B12 (little information on public facilities to support investments in Industry 4.0), and economic and financial, that is, B4 (insufficient financial resources within the company) and B5 (scarcity of external financing).

The several categories of barriers (related to knowledge issues, economic-financial aspects, cultural concerns, and system conditions) are perceived in most cases as a sum of several barriers belonging to the same category. This is why the experts recommended to measure the perception of barriers in terms of breadth for each category.

2.4.1.4 Incentives

The experts and respondents state that different firms have a varied degree of knowledge on industrial plans. All companies are generally aware that the business plan allows them to support the development of Industry 4.0. However, when asked to go into detail about the firms' incentives, they show a heterogeneous knowledge of government incentives. Larger firms and newborn firms have a deep knowledge of industrial plan incentives.

By contrast, the experts and respondents implied that SMEs have a superficial knowledge of government incentives. For instance, expert E4 stated: "[…] The biggest problem is that firms do not know the existence of certain incentives and/or do not know how to access them."

Both experts and respondents agreed that the application of incentives under the Italian Industrial Plan (Impresa 4.0) can facilitate the adoption of Industry 4.0 and identified that the most used incentives are those related to the amortization of investments in technologies and to human capital training. Therefore, the qualitative analysis allows to validate the theoretical background on incentives as well.

Furthermore, in most cases, several incentives are adopted as combinations. Therefore, experts recommend to measure the adoption of incentives in terms of breadth.

2.4.2 Quantitative results

The results of the multiple parallel-serial model, which considers the relationship between openness to Industry 4.0 (I4.0) and performance (PERFORMANCE), as driven by the direct and indirect effects of five intermediary variables, is shown in Tables 7 and 8.

The first four mediators, linked to the nature of the barriers, do not condition themselves causally – parallel mediations – but their paths condition the incentives – serial mediation.

The model has seven specific indirect effects, four of which pass through only one mediator (a1b1; a2b2; a3b3, and a4b4), and three pass through two mediators (a1d41b4; a2d42b4; and a3d43b4). The sum of these effects produces the total indirect effect. The direct effect of I4.0 is c′ and the sum of the direct and indirect effects is the total effect of I4.0 on PERFORMANCE. In this model, the total effect can also be estimated by regressing PERFORMANCE onto I4.0 without any mediators included in the model.

Table 7. Direct effect

Effect	*SE*	*t*	*p*	*LLCI*	*ULCI*
.1478	.0255	5.7884	<.0001	.0976	.1979

Table 8. Indirect effects

	Effect	*BootSE*	*BootLLCI*	*BootULCI*
TOTAL	.3670	.0125	.0144	.0641
Ind1 I40→KNOWLEDGE→PERFORMANCE	.0113	.0053	.0027	.0234
Ind2 I40→ECO-FIN→ PERFORMANCE	.0069	.0046	.0002	.0179
Ind3 I40→CULTURE→PERFORMANCE	.0023	.0026	-.0019	.0065
Ind4 I40→SYSTEM→PERFORMANCE	.0036	.0062	-.0078	.0168
Ind5 I40→INCENTIVES→PERFORMANCE	.0131	.0070	.0002	.0279
Ind6 I40→KNOWLEDGE→INCENTIVES→PERFORMANCE	.0013	.0011	-.0005	.0038
Ind7 I40→ECO-FIN →INCENTIVES →PERFORMANCE	-.0014	.0009	-.0036	-.0001
Ind8 I40→CULTURE→INCENTIVES→PERFORMANCE	-.0005	.0006	-0017	.0005
Ind9 I40→SYSTEM→INCENTIVES→PERFORMANCE	.0001	.0015	-.0029	.0031

Table 7 shows a significant effect, whilst Table 8 shows that the indirect effects on perceived barriers are in some cases very weak. This suggests that some barriers and incentives might also be independent from openness to Industry 4.0. The results relating to our hypotheses are provided below.

Figure 4 presents the results of the hypotheses testing and Table 9 provides an overview of the hypotheses supported or those not supported and those accepted or rejected. In total, out of the 15 hypotheses, only hypothesis H6b is rejected and H3c, H3d, H6a, H6c, and H6d are not supported.

H1 proposes that greater openness to Industry 4.0 leads to the perception of better performance. The empirical results show a positive and significant relationship between these two factors ($ß = 0.148$, $t = 5.788$, $p < 0.001$). Hence, H1 is accepted.

H2a states that greater openness to Industry 4.0 leads to the perception of higher barriers relating to knowledge issues. The results indicate a positive and significant relationship between these variables ($ß = 0.051$, $t = 3.533$, $p < 0.001$), which provides evidence to accept H2a.

H2b proposes that greater openness to Industry 4.0 leads to the perception of higher barriers relating to economic and financial issues. The empirical results indicate a significant and positive relationship between these factors (ß = 0.031, t = 2.338, $p < 0.01$), thus accepting H2b.

H2c states that greater openness to Industry 4.0 leads to the perception of higher barriers relating to cultural issues. The results show a positive and significant relationship (ß = 0.031, t = 1.761, $p < 0.1$), thereby providing evidence to accept H2c.

H2d proposes that greater openness to Industry 4.0 leads to the perception of higher barriers relating to system conditions. The results show a positive and significant relationship (ß = 0.075, t = 5.555, $p < 0.001$). Hence, is find evidence to accept H2d.

H3a proposes that greater perceived barriers relating to knowledge issues lead to the perception of improved performance. In this case, the empirical results do not indicate a significant relationship (ß = 0.224, t = 2.910, $p < 0.1$). Hence, H3a is accepted.

H3b states that greater perceived barriers relating to economic and financial issues lead to the perception of improved performance. The empirical results show a positive and significant relationship (ß = 0.223, t = 2.670, $p < 0.1$). Therefore, evidence is found to accept H3b.

H3c affirms that greater perceived barriers relating to cultural issues lead to the perception of improved performance. The empirical results indicate no significant relationship (ß = 0.073, t = 1.174, $p > 0.1$); Therefore, H3c is not supported.

H3d proposes that greater perceived barriers relating to system conditions lead to the perception of improved performance. The empirical results indicate no significant relationship (ß = 0.048, t = 0.599, $p > 0.1$). Hence, H3d is not supported.

H4 proposes that greater openness to Industry 4.0 leads to a greater degree of incentives adoption. The empirical analysis shows a positive and significant relationship (ß = 0.075, t = 2.273, $p < 0.1$), providing evidence to accept H4.

H5 states that a higher number of adopted incentives leads to the perception of improved performance. The empirical analysis shows a positive and significant relationship (ß = 0.175, t = 5.057, $p < 0.1$). Therefore, evidence is found to accept H5.

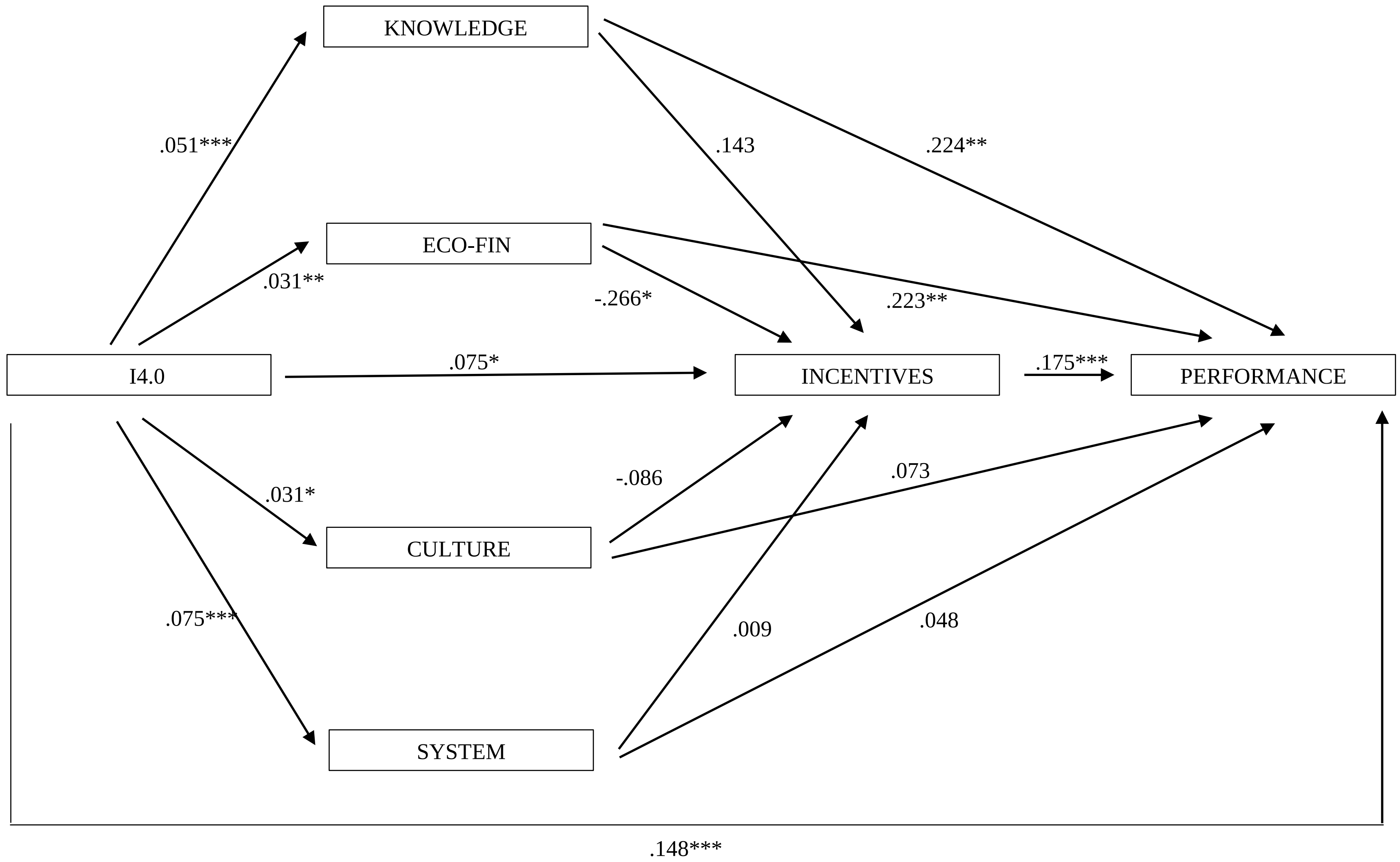
H6a considers the perception of higher barriers relating to knowledge issues to lead to a greater degree of incentives adoption. In this case, the empirical results do not indicate the presence of a significant relationship (ß = 0.143, t = 1.432, $p > 0.1$). Therefore, H6a is not supported.

H6b states that the perception of higher barriers relating to economic and financial issues leads to a greater degree of incentives adoption. The empirical analysis shows a negative and significant relationship (ß = -0.266, t = -2.461, $p < 0.1$). Hence, H6b is rejected.

H6c proposes that the perception of higher barriers relating to cultural issues leads to a greater degree of incentives adoption. The empirical results indicate no significant relationship (ß = -0.086, t = -1.070, $p > 0.1$); Therefore, H6c is not supported.

H6d states that the perception of higher barriers relating to system conditions leads to a greater degree of incentives adoption. The empirical results indicate no significant relationship (ß = 0.009, t = 0.086, $p > 0.1$). Thus, *H6d* is not supported.

Figure 4. Results



*, **, and *** indicate that the coefficients are statistically significant at the <5%, <1%, and <1% levels, respectively

Table 9. Hypothesis testing results

H	*Short description*	*Outcome*	*Accepted or rejected*	*Impact*
H1	I40 → Performance	Supported	Accepted	A greater openness toward Industry 4.0 corresponds to a higher perceived performance
H2a	I40 → Knowledge	Supported	Accepted	A greater openness toward Industry 4.0 corresponds to more perceived knowledge barriers
H2b	I40 → Eco-fin	Supported	Accepted	A greater openness toward Industry 4.0 corresponds to perceived economic-financial barriers
H2c	I40 → Culture	Supported	Accepted	A greater openness toward Industry 4.0 corresponds to higher perceived cultural barriers
H2d	I40 → System	Supported	Accepted	A greater openness to Industry 4.0 corresponds to higher perceived system barriers
H3a	Knowledge → Performance	Supported	Accepted	A higher perception of knowledge barriers corresponds to higher perceived performance
H3b	Eco-fin → Performance	Supported	Accepted	A higher perception of economic-financial barriers corresponds to higher perceived performance
H3c	Culture → Performance	Not supported	-	-
H3d	System → Performance	Not supported	-	-
H4	I40 → Incentives	Supported	Accepted	A greater openness toward Industry 4.0

				corresponds to higher incentives adoption
H5	Incentives → performance	Supported	Accepted	A higher incentive adoption corresponds to higher perceived performances
H6a	Knowledge → Incentives	Not supported	-	-
H6b	Eco-fin → Incentives	Supported	Rejected	A higher perception of economic-financial barriers does not correspond to a higher incentive adoption
H6c	Culture → Incentives	Not supported	-	-
H6d	System → Incentives	Not supported	-	-

2.5 Discussion

2.5.1 Discussion of qualitative findings

From the analysis of the answers of the experts and interviewees, some reflections confirm and/or apply the management literature.

Larger firms and those belonging to the high-tech sectors are more used to adopt Industry 4.0. The results confirm the empirical results of Dachs et al. (2019). The increased propensity to use enabling technologies by younger firms can be explained by the presence of young employees, with a high propensity for innovation 4.0 and/or with specific digital skills.

The performance factors related to greater production flexibility and greater output capacity clarify that Industry 4.0 allows to combine mass production, mass customization, and mass personalization. This opportunity—combined with the reduction of costs—favors companies with economies of scale, relevant scope, and networking. These results confirm those theoretically highlighted by Büchi et al. (2018).

Human resources 4.0 allows a better implementation of Industry 4.0 in firms. This result is in line with the literature (i.e., Moeuf et al., 2020). The results also show that, if 4.0 resources are available, they can create an environment that stimulates the productivity of the entire organization.

However, there is still a lack of proper recognition of both the term Industry 4.0 and the related opportunities. Additionally, the adopted 4.0 technologies are still limited. This confirms the theoretical results of Vogel-Hesuer and Hess (2016). The results also highlight that the implementation of these technologies takes place in several phases of the supply chain. This confirms the empirical study of Büchi et al. (2020a).

The implementation of Industry 4.0 requires large investments that firms do not always have available internally and are not easy to access externally. This confirms the literature as well. From the results of this study, it emerges that the barriers considered most influential are the cultural ones related to: *B1 (inadequate information on the potential offered by 4.0 technologies)*, *B10 (organizational resistance*) and *B11 (perception that* *the business' sector of operation does not need investment in Industry 4.0).* To these barriers already identified in the literature, the qualitative analysis conducted identifies an additional one: B12 (*little information on public facilities to support investments in Industry 4.0).*

The implementation of Industry 4.0 must also be accompanied by the creation of partnerships and networks between firms for the development of innovation ecosystems. However, this aspect is little highlighted in the literature, which only highlights the difficulty of alliances with research centers, without considering an ecosystem and supply chain approach.

The most used incentives are related to taxation, such as the amortization of investments in 4.0 technologies and human capital training. Few studies showed how incentives can support the implementation of Industry 4.0, despite Jain and Ajmera (2020) stating that government facilities are one of the major enablers of Industry 4.0 adoption.

2.5.2 Discussion of quantitative results

Using a representative sample of Piedmont's local manufacturing units, the results firstly produce a positive and significant relationship between openness to Industry 4.0 and performance – H1 (ß = 0.148***) – which shadows those found by Büchi, Cugno, and Castagnoli (2020a) and conceptually proposed by Vogel-Heuser and Hess (2016).

The positive relationship between openness to Industry 4.0 and incentives adoption is verified (H4). This result is in line with previous observations by Frank et al. (2016) and MISE (2018). However, the study should point out that the level of significance is rather weak, such that this evidence is open to question.

A positive relationship between openness to Industry 4.0 and four types of perceived barriers is found (H2a, H2b, H2c, and H2d). This result conforms with studies conducted by Birkel et al. (2019), Raj et al. (2020), and Stentoft et al. (2020). However, the paper should again note that the significance levels of some of these results are relatively weak, suggesting that this evidence remains open to interpretation.

It is possible to identify further results based on both the perception of barriers and incentives adoption. In this section, the paper considers some of the most noteworthy results.

In analyzing the results, the following elements are considered separately:

- the effects of perceived barriers on performance deriving from incentives (H3a, H3b, H3c, and H3d); and
- the effects of perceived barriers on performance deriving from the effect of perceived barriers on incentives.

The first set of relationships exhibits a positive and significant effect on performance from perceived barriers relating to knowledge (H3a, ß = 0.224*) and economic and financial issues (H3b, ß = 0.223*). However, there is no significant effect of the perception of cultural and systemic barriers on performance. The following provides an interpretation of these results.

It seems plausible that knowledgeable managers able to perceive barriers (according to the literature this idea is linked to the openness to Industry 4.0, but from our results this knowledge may be also independent from the openness to Industry 4.0) related to knowledge and economic and financial aspects are associated with firms that are able to produce better performance independently of incentives effects. This evidence is not statistically significant as far as perceived cultural and systemic barriers are concerned. In other words, firms that are able to perceive barriers that the firm itself is able to affect, are also able to perform better. In this circumstance, experts and interviewees highlight a greater relevance placed on knowledge-related barriers and economic and financial barriers.

The positive relationship between incentives adoption and performance is found to be statistically significant (H5, ß = 0.175*), according with the findings of the literature (Frank et al., 2016; MISE, 2018), which states that the more incentives firms adopt, the better their performance. This therefore reflects the aims that governments have in establishing industrial plans based around Industry 4.0 in order to promote productivity and competition (Dalenogare et al., 2018).

It is now possible to consider the effects of perceived barriers on performance as impacted by the extent of perceived barriers on incentives. Starting from the idea that the perception of barriers is a proxy of management's intelligence, our results indicate that the perception of barriers does not lead to the adoption of incentives. The only apparent exception to this is for economic and financial barriers, which produce a significant and negative relationship (H6b, ß = -0.266*). This result suggests that the perception of economic and financial barriers limits the adoption of incentives because incentives are considered large enough to overcome barriers. Nevertheless, as noted previously, the effects of adopted incentives on performance are positive and statistically significant.

It can therefore be inferred that incentives are not specially designed to counter the types of barriers perceived by firms or, potentially, that firms cannot identify concrete benefits from incentives. In fact, the empirical results show that firms which adopt more incentives perform better, thereby shadowing the trend found in interviews, following which it was necessary to add B12 (*little information on public facilities to support investments in Industry 4.0*) to the other barriers previously identified.

2.6 Conclusion

The implementation of Industry 4.0 is a primary focus for economies across the world in order to improve the competitiveness and productivity of the manufacturing industry.

This paper, through a theoretical background analysis, identifies seven performances, 11 barriers, and the main existing government incentives through a mixed-method divided into two phases. The first phase, the qualitative analysis, consists of nine semi-structured in-depth interviews with experts and 11 multiple case studies. Despite the small size of the sample, the results reached theoretical saturation. The qualitative analysis integrates and validates the theoretical background, identifying a twelfth barrier. The qualitative analysis also highlights that the 12 barriers can be reclassified into four macro-categories linked to knowledge issues, economic-financial resources, cultural aspects, and system conditions.

The second phase, the quantitative analysis, explores the role of the performance, barriers and incentives identified in the previous phase. The questionnaire was developed to include the residual category of "other" in terms of performance, barriers, and incentives to assess whether entrepreneurs perceive further elements. The analysis of the quantitative results (absolute frequency = 0) allows verifying there are no additional elements to those already identified during the qualitative analysis.

The quantitative analysis confirms the hypotheses of the literature on a sample of 500 local manufacturing units and empirically verifies the relationships between openness to Industry 4.0 and performance influenced by perceived barriers to and incentives for

Industry 4.0 adoption. The quantitative analysis adopts a parallel-serial multiple regression model. This technique identifies the direct and indirect effects of openness to Industry 4.0 using six equations – one for each of the five mediators and one for performance. The model is also assessed using the bootstrapping method on samples of 5,000 units.

The results confirm that openness to Industry 4.0 provides opportunities to the manufacturing sector. However, this relation is affected by a set of intermediate influences, as explained below.

Openness selects firms that are able to perceive a wide variety of barriers. Following the direct effect of the perception of barriers on performance (via the intermediate effect of incentives), it is possible to find a positive and significant relationship between the perception of internal managerial variable and performance. This suggests that the perception of such barriers impacts performance independently of incentive adoption.

Furthermore, in general, barriers do not lead to the adoption of incentives, suggesting that incentives are perceived as relating to the barriers themselves. This is consistent with the finding that economic and financial barriers are seen as impediments to the adoption of incentives because incentives are not large enough to outweigh these barriers.

2.6.1 Theoretical contribution

The paper originally contributes to the managerial literature on Industry 4.0 in three ways: (a) by identifying the concepts of openness to Industry 4.0, performance, barriers, and incentives; (b) by operationalizing the concepts of openness to Industry 4.0, performance, barriers, and incentives; and (c) by verifying the literature on which the hypotheses of this study are based.

Additionally, the paper presents novel data in a research area that hitherto lacks empirical data on the barriers and incentives to Industry 4.0 adoption among firms.

The results verify that the higher the openness toward Industry 4.0, the higher the perceived performance. However, firms have difficulties in adopting Industry 4.0 because of different barriers, which are not all equally important for all firms. Finally, the results show that firms use incentives to overcome barriers, but not all barriers lead to incentive adoption.

2.6.2 Practical implications

The results presented in this paper also have implications on policy and management approaches.

First, the results suggest that entrepreneurs should adopt Industry 4.0 technologies in order to improve performance despite the perception of barriers, as the barriers identified in the theoretical background and confirmed by interviews and case studies may serve as guides for managers, as the review comprehensively covers the possible barriers relating to implementing Industry 4.0 technologies.

Secondly, since the results suggest that some managers prefer to overcome barriers without making use of incentives, it appears that some incentives are either not easy to use or not tailored to firms' needs. A remarkable example of this is the perception of economic and financial barriers, which even discourage firms from adopting incentives.

Third, the results suggest that governments should continue to create programs that promote the transition towards Industry 4.0 technologies in order to help firms overcome barriers such as *B7 (legal uncertainties)* and *B9 (lack of clear standards).* More specifically, however, the results suggest that policymakers should promote incentives that recognize firms' needs and adopt more efficient bureaucratic processes in order to help firms overcome perceived barriers to adopting incentives.

2.6.3 Limitations and future research

One limitation of the research relates to the subjective nature of two of the considered variables: perceived performance and perceived barriers. More accurate results could be obtained by analyzing quantitative data in terms of the changes in costs and revenues.

Some results lead to unexpected outcomes that deserve further investigation, such as the negative relationships between perceived economic and financial barriers and incentives; the positive effect of knowledge and perceived economic and financial barriers on performance.

Furthermore, the study focuses on barriers and incentives. However, to help firms further improve their performance, future research could analyze different driving forces behind Industry 4.0 implementation and different types of incentives to determine if they respond differently to different barrier types.

Although this study considers a representative sample of 1,732 firms, the still limited adoption of Industry 4.0 reduced the reference population to 500 firms. Studies on larger samples could evaluate how variables such as enterprise size, sector, propensity toward technological openness, and the different human resources can influence the relationship.

Finally, it may be of interest to further develop this research idea using samples from other countries to compare the results across countries and/or across different geographic areas.

2.7 Appendix to paper 2

2.7.1 References

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2.7.3 Declaration of competing interests

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3. Paper 3 – Managing Complexity in Industry 4.0 Based Systems: A Qualitative Analysis[3]

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Abstract

Modelling a System is a challenging task, especially if integration and interoperability between branches, machines, products and people are almost overarching as in Industry 4.0. However, engineering and managerial literature little analyze SMEs' readiness to handle barriers and complexity in Industry 4.0 based systems. The paper analyzes the perceived barriers faced by manufacturing SMEs adopting Industry 4.0 and the ways to manage complexity in Industry 4.0 based systems. The research is carry out through a focus group and an in-depth interview with selected organizations in Italy and France. The expected findings are that: (1) there are five macro-categories of barriers related to cultural aspects, ecosystems role, firms' characteristics, human resource management, business model innovation; (2) there are two main unsatisfied needs that limit the benefits of Industry 4.0 adoption. The theoretical contribution of the paper is to open up future research lines both in managerial and engineering literature to identify solutions to these barriers and unsatisfied needs. The paper suggests to managers and policy makers some interesting cues to maximize Industry 4.0 opportunities.

Keywords: Industry 4.0, Barriers, Complex systems, SMEs, Manufacturing.

3. 1 Introduction

Since 2011, the Fourth Industrial Revolution or Industry 4.0 (Kagermann et al., 2013) is tremendously changing the world inside and outside firms (Schwab, 2016). Despite the visible impacts of Industry 4.0 on firms, societies and complex systems in general, there is no clear nor unique definition of this neologism. However, focusing on firms, some scholars define Industry 4.0 as an integrated, adapted, optimized, service-oriented, and interoperable manufacturing process which is correlate with algorithms, big data, and high technologies (Lu, 2017).

Scholars have analyzed Industry 4.0 from diverse perspectives identifying that it enables companies to achieve: greater competitiveness and productivity (Xu, Xu & Li, 2018); better value chain (Saucedo-Martínez et al, 2018; Kinzel, 2017) and supply chain efficiency (Barz et al., 2019; Rosin et al., 2020; Merino et al., 2020); improved business activities (Schneider, 2018); highest performance (Dalenogare et al., 2018). In particular, some studies show that the more technologies 4.0 adopted, the more benefits obtained (Büchi, Cugno & Castagnoli, 2020; Vogel-Heuser & Hess, 2016) through economies of

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scale, scope and networking (Büchi, Cugno & Castagnoli, 2018). Last but not least is the role of Industry 4.0 on firms' sustainability favoring the circular economy (Machado, Winroth & Da Silva, 2020; Kiel et al., 2017).

As can be seen, the impact of Industry 4.0 on firms is analyzed by several studies, however, some key elements related to its adoption remain uncovered. At present, there are few studies investigating the barriers perceived by firms in Industry 4.0 adoption (Horváth & Szabó, 2019; Moeuf et al., 2020; Raj, Dwivedi, Sharma, and de Sousa Jabbour, 2020; Stentoft, Adsbøll, Wickstrøm, Philipsen, and Haug, 2020). Moreover, the existing literature is still in an early phase and presents a knowledge gap on how firms deal with complexity in Industry 4.0 based systems.

The paper is part of these two research stream and investigates how small and medium-sized enterprises (SMEs) perceive barriers to Industry 4.0 adoption (Stenoft et al., 2020; Moeuf et al., 2020) and manage the complexity of Industry 4.0 based systems. The research is carried out through a qualitative analysis divided into three phases. The first phase reconstructs the theoretical background through a literature review of the main barriers perceived by SMEs. The second phase validates and integrates the results of the theoretical background through a focus group with experts having a wide experience on the phenomenon. The third phase compares the results obtained through a semi-structured in-depth interview with an expert on the subject, and investigates how SMEs manage complexity in Industry 4.0 based systems.

Focus groups and interviews are carried out with leading figures of public-private partnerships in Industry 4.0, trade associations, centers and/or poles dealing with applied research, technology transfer and training active in accompanying manufacturing SMEs in the transition 4.0 in Italy and France.

The analysis focuses on the manufacturing sector because Industry 4.0, although it is a cross-sector phenomenon, initially started within the manufacturing sector (Kagermann et al., 2013). The later expansion to other industries is also reflected in the evolution of the Italian industrial plan name, first referring to Industry 4.0 (MISE, 2017), then to Enterprise 4.0 (MISE, 2017) and finally to Transition 4.0 (MISE, 2020).

The analysis is carried out cross countries on the two European countries competing for second place in Europe, after Germany, for the total value of manufacture. From 2017, in fact, France is second (with 889.4 billion euros) and Italy is third (with 883.7 billion euros), Eurostat, (2017). The cross countries analysis is carry out to identify whether two countries – having similar manufacturing rate and not so different socio-economic conditions and firms' characteristics – have similar barriers to Industry 4.0 adoption and similar solutions to manage Industry 4.0 complexity.

The article offers an original contribution identifying the barriers to Industry 4.0 adoption and finding how SMEs manage complexity in Industry 4.0 based systems.

The research identifies SMEs' perceived barriers and key points concerning corporate governance and suggests proposals for improvement for industrial policy actions in support to Industry 4.0.

The paper is structured as follows: the second section identifies the barriers that may hinder the Industry 4.0 adoption; the third section illustrates the methodology adopted; the fourth section reports the main results; the fifth section discusses the results focusing on SMEs readiness to Industry 4.0 adoption; the conclusion describes the main limitations, highlights the implications and suggests future research lines.

3.2 Theoretical background

The theoretical background comes from an analysis of the literature carried out on Web of Science (WoS) database, selecting English language academic journals and applying three search criteria: period (from January 2011 – introduction of the German National Industrial Plan – to June 2020); research terms (Industry 4.0 synonyms and barriers synonyms); research areas (economic, business and management). The literature review allows the identification of several barriers able to hinder Industry 4.0 adoption classified into 11 types.

The first barrier identified concerns Few information on the potential offered by technologies 4.0 (Basl, 2017). The conceptual literature show that many companies do not intend to develop research on the economic feasibility of technologies 4.0 because of the limited information on the potential offered. Similar results are highlighted by an empirical survey on German companies (Müller, Buliga & Voigt, 2018) which highlights how entrepreneurs estimate Industry 4.0 as a high investment process due to the change of machinery, the formation of new skills and the transformation of business activity.

The second perceived barrier concerns Insufficient know-how within companies. The literature on Industry 4.0 seems to agree that companies need new knowledge and skills to manage new technologies (Wei, Song, & Wang, 2017; Karre et al., 2017; Kiel, Arnold & Voigt, 2017; Kiel et al., 2017).

The third barrier identified in the literature is related to Few skills on the labor market (Liboni et al., 2019) also referring to the types of profiles formed by educational institutions at various levels (Baygin et al., 2016; Motyl et al., 2017; Benešová & Tupa, 2017).

The fourth perceived barrier concerns Insufficient financial resources within the company (Kiel, Arnold & Voigt, 2017; Kiel et al., 2017).

The fifth barrier identifies that the shortcomings in financial resources may affect a Scarcity of external financing further worsening the situation of the previous barrier.

The sixth perceived barrier is Insufficient economic infrastructures. Industry 4.0 is enabled through the Internet of things that requires the need for several economic infrastructures, primarily broadband connection, which allow communication between connected elements based on sensory, communication, networking and information processing technologies.

The seventh perceived barrier concerns the Legal uncertainties that the company may encounter following the adoption of Industry 4.0. This barrier is related to the responsibility of the company's data, trade restrictions, intellectual property protection and differences between the regulations of different countries.

The eighth barrier concerns Difficulties in alliances with universities, polytechnics and research centers. This barrier is due to the high need for research and development and for new knowledge to adopt and manage technologies 4.0 (Mittal et al., 2018).

The ninth perceived barrier is linked to Lack of unambiguous standards. This barrier is due to a low security of data transmission in both inter and intra-organizational relationships (Kiel, Arnold & Voigt, 2017; Kiel et al., 2017) and to limited reliability and stability of machine-to-machine communications (Sung, 2018).

The tenth perceived barrier is Organizational resistance linked to the degree of flexibility of human resources towards innovation (Automation Alley, 2017; Kiel et al., 2017; Vey et al., 2017; Von Leipzig et al., 2017; Bauer et al., 2015; Horváth & Szabó, 2019).

The eleventh barrier concerns the perception that The business sector to which the firm belongs does not need investment in Industry 4.0. This barrier is due to the high investments required by Industry 4.0 and the uncertain return on investment (Horváth & Szabó, 2019).

In addition to these barriers, many scholars (Lu, 2017; Piccarozzi, Aquilani, & Gatti, 2018) identify an additional barrier upstream of all the others: Lack of unambiguous definition of Industry 4.0. This barrier is also aggravated by: the presence of several Industry 4.0 synonyms – Industrial Internet, Advanced Manufacturing, Factories of the Future, Future of Manufacturing, Digital Factory, Digital Manufacturing, Smart Factory, Interconnected Factory, Integrated Industry, Production 4.0 and Human-Machine Cooperation (Büchi, Cugno, & Castagnoli, 2020) – used in a confused way; the number of enabling technologies involved – Chiarello et al., 2018 estimate that there are more than 1200 enabling technologies 4.0 – and their rapid obsolescence and high turnover.

These barriers are of different relevance depending on the size of the company and are generally higher in smaller companies (Stentoft et al., 2020).

3.3 Methodology

The paper follows a qualitative approach. In particular, the research is made by a focus group and a semi-structured in-depth interview.

First, the theoretical background has been implemented by focus group with practitioners with a solid experience in SMEs' Industry 4.0 adoption.

Second, a semi-structured in-depth interview with an expert on SME's Industry 4.0 adoption allows a structured data collection ensuring that new and unexpected information can be included (Yin, 2009; Cannel & Khan, 1968) such as the ones linked to managing complexity in Industry 4.0 based systems.

The qualitative approach is chosen because of the high degree of subjectivity of the phenomenon. This subjectivity is due to the fact that barriers are not only measurable barriers such as economic or infrastructural ones, but are also barriers related to knowledge of the revolution, of its opportunities and incentives and to innovative propensity of entrepreneurs, managers and employees. In addition, empirically grounded research on Industry 4.0 is still scares (Stentoft et al., 2020), which is why qualitative focus group and interview serve to explain the results from the literature review in five main empirical categories. Specifically, explanatory qualitative studies help to understand 'which', 'how' and 'why' certain relationships emerge (Yin 2009). Finally, the use of qualitative interviews is due to a gap in extant literature about the relevance and practice of Industry 4.0 technologies among SMEs (Barratt, Choi, and Li 2011).

3.3.1 Focus group

The focus group is addressed to experts in manufacturing SMEs technological adoption allowing to obtain the most complete, objective and broad spectrum view of the phenomenon under analysis. In order to ensure the desired intra-group heterogeneity, participants are selected among different experts with a broad background of collaboration with many SMEs in the manufacturing sector. The manufacturing industry represent a preferential one since Industry 4.0 – although it is a phenomenon transversal to all economic sectors – was born within manufacturing enterprises (Kagermann, 2013).

The focus group participants are leading figures of public-private partnerships in

Industry 4.0, trade associations, centers and/or poles dealing with applied research, technology transfer and training active in accompanying companies in the 4.0 transition (Table 1).

Tab. 1. Profile of focus group participants

Participants	*Occupation*	*Region*
A.C.	SMEs' association	Italy (Piedmont, Northern Italy)
P.D.	Technological pole	Italy (Piedmont, Northern Italy)
C.F.	Technological pole	Italy (Piedmont, Northern Italy)
V.I.	SMEs' association	Italy (Piedmont, Northern Italy)
N.M.	Local administration	Italy (Piedmont, Northern Italy)
L.M.	Foundation	Italy (Piedmont, Northern Italy)
R.T.	Technological pole	Italy (Abruzzo, Central Italy)
E.P.	Competence center	Italy (Piedmont, Northern Italy)
L.Mi.	Consulting	Italy (Piedmont, Northern Italy)

An email is sent to the participants to describe the focus group procedure and to distribute an information sheet and a written waiver form. The information sheet includes basic information on qualitative research procedure, methodology (e.g. number of participants and inclusion criteria), organization and logistics (e.g. setting and duration) and content to be discussed.

In total 9 experienced Industry 4.0 professionals from 8 different institutions participate. The profession of the participants concerns the accompaniment – from an engineering-technological, economic-managerial and bureaucratic-administrative point of view – of Italian SMEs towards Industry 4.0.

All participants take part in a 180-minute guided session in a virtual classroom organized through the Zoom platform. The online solution is the only one possible during the Covid-19 emergency in Italy. However, respondents are extremely focused on the process and on the topic. The focus group is recorded and transcribed.

The whole process is deliberately unstructured to enhance spontaneous interventions. The role of the moderator is to facilitate every representation of the phenomenon and to increase the generation of ideas among the participants, favoring a process of social sharing of personal opinions, without interruptions, judgements or signs of approval in order to favor maximum fluidity. At the end of the session, the moderator devotes time to summarize and share the results obtained in order to allow participants to verify the information collected.

The information emerged during the focus group are recorded and transcribed. In order to explore and summarize the information provided by the participants, a content analysis is carried out. The content analysis is widely used in qualitative research to develop objective inferences on a specific topic of interest through the analysis of any type of communication, in this case the textual material resulting from the transcription of the focus group. Following Yin (2013) the analytical framework includes three phases: (1) analysis of the transcription of each participant's observations; (2) identification of common recurring themes; (3) analysis of shared themes. The analysis is performed by the authors independently through open coding. The first author performs the first phase of coding. The second phase is carried out by all authors. The recurrent concepts identified covering the same areas are condensed into key concepts. The selected key concepts are highlighted for similarities and differences and are then grouped to produce reference areas and sub-categories. Inter-observer consensus is ensured throughout the whole process. A sample of the generated material is checked by all authors for consistency and coding accuracy. Table 2 provides an example of how the coding is performed.

3.3.2 Semi-structured in-depth interview

The semi-structured in-depth interview is carry out with a practitioner working in a company that helps SMEs and enterprises in the transition to 4.0 in France. The in-depth interview is made in addition to the focus groups to compare the Italian and French reality, to investigate latent and unforeseen aspects and to start research on how SMEs manage complexity in Industry 4.0 based systems.

The interview take place online in July 2020 via Skype. The online solution is adopted as the only one possible during the Covid-19 emergence in Europe. However, the interviewee is really focused on the process and on the topic too. In-depth interview lasts 60 min and is recorded and transcribed. The authors carry out the interview administrating a semi-structured guide derived from the themes arising from the literature review. Typical questions included are:

Section 1 – Main advantages encountered by SMEs adopting Industry 4.0

Section 2 – Main barriers faced by SMEs adopting Industry 4.0

Section 3 – Approach used by SMEs adopting and implementing Industry 4.0

Section 4 – Modes and tools helping SMEs in managing complexity in Industry 4.0 based systems.

Section 5 – Further information to validate familiarity and reliability of the interviewee on the topic.

The study adopts an interpretive methodology to identify themes emerging from the analysis of the data. The interview transcript is compared to the results of the focus group. First, the experience of the interviewee is analyzed and the emerging themes are identified. Second, a categorical aggregation is carried out and emerging patterns are identified. Third, the data are revisited to search for relationships between the literature review results, the focus group results and the different concepts emerged in the in-depth interview.

Tab. 2. Example of barriers coding

Number of barrier	*Areas of barriers highlighted by participants*	*Dimensions identified in literature*	*Illustrative coding examples*
1	-	Few information on the potential offered by technologies 4.0	-
2	Lack of managers/employees 4.0 within the company	Insufficient know-how within companies	"Once you buy a machine, you need someone to take care of it, an innovation explorer dedicated to Industry 4.0" (A.C.)
3	Generational polarization; lack of young entrepreneurs; generational turnover	Few skills on the labor market	"There is a lack of generational turnover in SMEs" (E.P.)
4	Insufficient financial resources	Insufficient financial resources within the company	"Small and micro enterprises do not have sufficient resources to invest alone in Industry 4.0" (L.M.)
5	Lack of ecosystem support and facilities in the early stages of development	Scarcity of external financing	"Piedmont does not assist companies in the first periods of innovation, unlike neighboring regions such as Lombardy or Emilia Romagna" (P.D.)
6	Digital retrofitting, revamping problems, digital infrastructure limits	Insufficient economic infrastructures	"One of the issues related to the adoption of Industry 4.0 is the revamping and digital retrofitting of machinery" (E.P.)
7	Bureaucratic complexity	Legal uncertainties	"The Italian National Plan for Industry 4.0 is highly complex with regard to the certification of investments made" (L.M.)
8	-	Difficulties in alliances with universities, polytechnics and research centers	-
9	-	Lack of unambiguous standards	-
10	Cultural problem, lack of approach 4.0, difficulty in innovative business models	Organizational resistance	"The most difficult change for traditional companies is to review their business model from a servitization perspective" (P.D.)
11	Perception of need, psychological aspects	The business sector to which the firm belongs does not need investment in Industry 4.0	"The automation process is more experienced by large companies. SMEs perceive this need less and do not know how to deal with it" (R.T.)
12	Shortage of information on public facilities to support investment in technologies 4.0.	-	"It is not true that SMEs have little information on Industry 4.0, they have confused information about it" (V.I.)

3.4. Findings

3.4.1 Focus group findings

During the focus group, participants agree that the techniques used allows them to reflect profitably on their professional experience in Industry 4.0 and positively enriches the discussion.

The focus group with experts confirms the relevance of barriers emerged from the theoretical background, except for the first barrier - Few information on the potential offered by technologies 4.0 – the eighth barrier – Difficulties in relations with research centers – and the ninth barrier – Lack of univocal standards. These barriers are not mentioned by the focus group participants. One possible motivation lies in the fact that the participants in the focus group are professionals who belong to or collaborate with research centers, universities and technology poles. This may create a bias in the perception of these three barriers.

The theoretical background of the barriers is implemented by the twelfth barrier: Few information on public facilities to support investments in Industry 4.0. Moreover, it emerges that firms gives a different degree of importance to perceived barriers according to their nature related to (Table 3): cultural aspects; ecosystem characteristics; firms' characteristics; human resource management (HRM); business model innovation.

In particular, from the coding of the information obtained, 5 categories and 17 sub-categories emerge regarding the barriers that SMEs encounter adopting Industry 4.0.

Tab. 3. Main barriers to the adoption of Industry 4.0 in Italian SMEs

Categories	*Sub-categories*
Cultural aspects	Scarce attitude to innovation Inhomogeneity of the Industry 4.0 definition Complexity related to the certification of the use of incentives of the National Plan Lack of an approach 4.0 Lack of cultural support from institutions Relevance of psychological aspects in the perception of the need for innovation
Ecosystems' characteristics	Lack of networks between firms and institutions Lack of an integrated supply chain approach Little support from the institutions in the early stages of development Infrastructural limits Traditional dependence of the SMEs on large companies or groups
Firms' characteristics	SMEs' dimensional problems
	Problems of SMEs' location in poorly communicating geographical areas
HRM	Generational Polarization Absence of professionals dedicated to Industry 4.0 within companies
Business model innovation	Relative novelty of the servitization phenomenon

Each of the barriers listed in Table 3 is considered relevant by all participants with unanimous agreement without hesitation, doubt or perplexity. The work of the moderator is to reconstruct which of the barriers identified is most important according to the participants.

Cultural aspects

The participants - unlike the authors' expectations, focused on the strong relevance of economic and infrastructural barriers - place more emphasis on cultural issues in the adoption of Industry 4.0.

Cultural aspects are an upstream problem of the barriers to the implementation of Industry 4.0 and concern first of all a defining problem. The presence of different synonyms of Industry 4.0 – Fourth Industrial Revolution, Internet or Advanced Manufacturing (US), Factories of the Future (European Commission), Future of Manufacturing (UK), Digital Factory, Digital Manufacturing, Smart Factory, Interconnected Factory, Integrated Industry, Production 4.0, Human-Machine-Cooperation – does not facilitate the determination of the research domain boundaries. In addition, Industry 4.0 is often wrongly linked only to the adoption of enabling technologies without a long-term vision and without an approach 4.0 to redefine the working environment at 360 degrees. With reference to the defining issues, the authors highlight that the focus group participants themselves often use the term digitalization as a synonym for Industry 4.0 although the two terms are not synonymous, but rather the evolution of each other.

Further elements related to cultural problems are related to the propensity of entrepreneurs and employees to innovate, the lack of institutional support in this direction and the difficulty in taking advantage of tax benefits.

Ecosystems' characteristics

Among the main barriers emerge the limits of the ecosystem in which Italian SMEs are located. In particular, the participants in the focus group insist on the lack of an integrated supply chain approach 4.0. "This approach should be based on the development of business networks through technologies 4.0". (A. C.), "It should consider a long supply chain going beyond the traditional concept of an industrial supply chain and basing itself on collaboration between companies and organizational innovation that breaks up traditional supply chains" (C. F.).

However, the concept of collaboration also leads to differing opinions. In particular, it is stressed that "We should not only talk about collaborations, but about innovation chains, where the focal point is emulation and confrontation between entrepreneurs" (L.M.). From the terms used by the several participants regarding the concept of network or supply chain, it can be seen that the defining problem – far from being just a conceptual problem – remains not only among entrepreneurs but also among experts in the sector on some specific issues. It is therefore necessary to develop studies in this area to guide effective and efficient public policies and entrepreneurial strategies for the development of Industry 4.0.

Other concepts related to ecosystem concurs with the lack of support from institutions in the early stages of development, infrastructural limits for the proper functioning of technologies 4.0 and the traditional dependence of SMEs on large firms that have made smaller companies less innovative and more passive. In this last element, the theme of the supply chain emerges again as a determinant which should help SMEs to innovate following the model imposed by larger companies.

Firms' characteristics

Among the characteristics of firms, first of all, the dimensional problems of SMEs emerge, exacerbated by the discontinuous location in the territory which limits exchanges between firms. It should be noted that the concept of collaboration and supply chain previously emerged returns in this case as well.

Finally emerges a "Problem of rigidity of the organizational structures of SMEs, structured as if they were large firms, which slows down innovation processes and especially bottom-up initiatives that could be favored by the freedom of initiative of the new generations more accustomed to digital" (E. P.).

Human resource management

A topic linked to the one emerged in the previous point of the organizational rigidity of SMEs, is the generational polarization. This element, together with the absence of professional figures dedicated to Industry 4.0 within the firms, or rather as external consultants of several companies, is seen as a serious lack by the participants in the focus group. The "Need for an Industry 4.0 manager or employee or an Innovation explorer helping the company and its employees to integrate machinery into production activities and maximize its benefits" (A. C.) is suggested almost unanimously. In addition, the focus group shows the need for employees to have T-shape knowledge in the company, i.e. having a main specialization on a subject but, at the same time, being able to have transversal knowledge so as to be able to collaborate as a team and to be a human resource more adaptable to the various tasks. For this reason, a re-skilling training activity is necessary.

Business model innovation

The last point highlighted by the participants concerns the low capacity of business model innovation. In this regard, it emerges that the servitization business model is a phenomenon that is difficult to establish in Europe, unlike what happened in the United States. "Many companies, in fact, find difficulties to reconvert offering more services" (N. M.) because "Reviewing the business model is one of the activities that most profoundly modify a company and therefore lead to greater inertia" (C. F.).

3.4.2 Semi-structured in-depth interview findings

The in-depth interview is carried out with a dual purpose. The first is to compare the results of the focus group. The second is to extend the results of the focus group by bringing out information more specifically focused on how to manage complexity in Industry 4.0 based systems.

As far as the first aspect is concerned, the interview to an expert in SMEs' Industry 4.0 adoption in France confirms the primary role of the cultural factor highlighted by the focus group participants. In particular, the interviewee points out that the main problem of SMEs' reluctance to adopt Industry 4.0 is related to the low propensity of entrepreneurs to a high degree of technological and automation dependence and to a low knowledge and understanding of technologies 4.0. This reticence is also highlighted by the name of the French industrial plan for the development of Industry 4.0 (Ministère de l'Economie de l'Industrie et du Numérique, 2016). In fact, the interviewee pointed out how the term Industrie du Future was preferred to the expression 4.0 in order to avoid overemphasizing the technological aspect.

In addition, the interviewee agrees with the participants in the focus group concerning the problem of the geographical dispersion of enterprises. To this problem, the interviewee adds the problem of dispersed teams from which it emerges the need to encourage forms of collaboration and exchange of data within the same enterprise even before the supply chain level.

As far as the second aspect is concerned, the interviewee starts from the two main needs that SMEs have in managing the complexity in Industry 4.0 based systems that are currently unsatisfied in most SMEs: Need to use data in real time; Need for collaboration between employees.

In this regard, the interviewee points out that Industry 4.0 allows to obtain and store large amounts of data. However, the systems traditionally used by firms for the internal management – ESM or the more advanced ERPs – do not allow the real-time use of these data due to system rigidities. This rigidity also hinders real-time communication and information exchange between employees.

The Need for collaboration among employees also emerges in the focus group. In particular, the need for employees in the company to possess T-shape knowledge, i.e. having a main specialization on a subject but, at the same time, being able to have transversal knowledge in order to work together as a team and be a human resource more adaptable to the various tasks.

In response to this need for collaboration, a re-skilling training activity is proposed in the focus group. The interviewee recommends to develop the re-skilling by enhancing the use of apps for the real-time exchange of information.

These two limitations of SMEs mean that the adoption of Industry 4.0 does not bring the expected benefits by limiting the propensity of companies to adopt it due to problems upstream of Industry 4.0 itself.

3.5 Discussion

The results identify 11 barriers through the literature review and an additional barrier through the qualitative analysis. Further, the results of focus group and interview to expert in Industry 4.0 adoption of manufacturing SMEs show five main categories of barriers and two main uncovered needs that hinder SMEs' readiness to adopt Industry 4.0.

These results could be analyzed in relationships with SMEs’ readiness to Industry 4.0 adoption. In particular, the qualitative analysis shows a relatively low degree of Industry 4.0 readiness and concrete use among the sample of Italian and French SMEs. This is in line with an empirical analysis by Stentoft, Rajkumar, and Madsen (2017) showing that large companies have a significantly higher Industry 4.0 readiness than SMEs, which can be explained by larger companies having a relatively higher availability of resources to exploit the technologies.

However, the results show that this scarce readiness to Industry 4.0 adoption might be related to two different barriers leading to two opposite consequences.

From one side, the paper’s results show that this scarce readiness in SMEs’ Industry 4.0 adoption is highly dependent on the first category of barriers emerged from the analysis: Cultural aspects. SMEs, in fact, show some weakness related to: difficulties to define Industry 4.0; scarce innovative attitude; lack of approach 4.0 to transform firms into smart factories; psychological resistance to the perception of the needs for innovation. Hence the results show a clear lack of awareness of the technologies and of Industry 4.0 as an overall concept. These results support the findings by Issa, Hatiboglu, Bildstein, & Bauernhansl (2018) who found that SMEs in general struggle with such technologies.

From the other side, the results show that the current stage of Industry 4.0 application is highly linked to ecosystem conditions and to an integrated supply chain approach. This open-up the possibility that the current degree of Industry 4.0 adoption of SMEs might mature in the coming years as more practical applications developed by larger companies or innovative SMEs enable a wider application of such innovations in SMEs. This is in line with Stentoft et al. (2020).

Despite these qualitative results show a positive relationship between barriers in Industry 4.0 adoption, needs in complexity management and Industry 4.0 readiness, the literature demonstrates that, in some cases, barriers seemingly do not make the SMEs less Industry 4.0 ready. In fact, some studies (Büchi, Cugno, & Castagnoli, forthcoming) empirically verify that certain categories of barriers do not appear to influence the adoption of the technologies. One explanation may be that companies that engage in Industry 4.0 initiatives and report of high barriers are simply more aware of such barriers compared to companies with less focus on Industry 4.0 (Stentoft et al., 2020). For these reason, it should be suggested that firms and policymakers focus on the drivers instead of on the barriers in order to improve Industry 4.0 readiness and effective implementation looking at the opportunities rather than focusing on the constraints (Stentoft et al., 2020).

3.6 Conclusion

The paper analyzes, through a qualitative approach, the Italian and French manufacturing SMEs' readiness to adopt and implement Industry 4.0 and to manage complexity in Industry 4.0 based systems. Industry 4.0, in fact, was born in manufacturing firms – even if it reached a rapid expansion in all the industries – and Italy and France are the European countries that reached the higher manufacturing turnover following Germany (Eurostat, 2017), the country where Industry 4.0 concept was born (Kagermann et al., 2013).

The research is carried out through a focus group and a semi-structured in-depth interview with practitioners belonging to public-private partnerships in the field of Industry 4.0, trade associations, centers and/or clusters involved in applied research, technology transfer and training active in accompanying enterprises in the transition 4.0.

In particular, the research focuses on SMEs knowledge, adoption and implementation approach of Industry 4.0, main barriers faced by SMEs during these processes, awareness and usage of models and tools to manage complex systems in Industry 4.0.

The main results are that from one side SMEs face five main barriers – related to cultural aspects, ecosystem role, firms' characteristics, HRM and business model innovation – where the most intense barrier is the cultural one. From the other side SMEs has two main unsatisfied needs – the need to use real-time data and the need for real-time communication – which hinder the achievement of the potential benefits of Industry 4.0.

3.6.1 Theoretical contribution and managerial implications

The results presented have several research contributions and provide implications for policy and management.

The research contributes to the literature with an interdisciplinary approach in two main fields integrating Industry 4.0 management literature with engineering tools to manage system complexity. The key contributions of the paper are as follows. First, it identifies the barriers to implement Industry 4.0 in the manufacturing industry in the context of developed economies. Second, it classifies the 11 types of barriers into 5 main categories. This classification allows to identify the degree of influence of each barrier and provides better decoding of uncertainty and vagueness in the responses of experts. Second, the paper explores the solution used by firms in managing Industry 4.0 based system complexity identifying two main uncovered needs that may prevent firms from fully benefiting from the Industry 4.0 revolution.

The results might suggest relevant managerial implications concerning how to solve the goal 8 of the UN Sustainable Development Goals on decent work and economic growth through a better understanding of how to reach performance and efficiency in Industry 4.0 based systems. In particular, the results help firms to formulate appropriate strategies to achieve a higher degree of success in implementation of Industry 4.0. The results reveal that managers and policy makers should consider to: enhance culture of managers and employees in favor of innovation; improve ecosystems in support of technological adoption; support SMEs which generally have less resources than big companies; develop HRM encouraging generational exchange; stimulate business model innovation.

3.6.2 Limitations and future research lines

The research is still in an early phase. For this reason, findings are proposed as suggestions for future research lines to expand and quantitatively verify it and to guide effective and efficient public policies and business strategies for Industry 4.0 development.

In particular, some limitations and concerns arise from this study. First, the analysis is based on a limited number of experts (10) and on a limited number of countries (2). For a generalization of the research findings, more responses from multiple industries should be collected and analyzed. Second, some additional quantitative techniques should be applied to enable a comparison within the results. Furthermore, some additional barriers remain uncovered in the current studies. For example, quoting verbatim from a speech by the proponent of the Italian Institute for Artificial Intelligence (I3A): “One of the biggest challenges of Industry 4.0 is the ethical issue of the role, the scope and the impact of these technologies that are not neutral nor uncontrollable by human being”. Hence, the research should be enriched widening the sample of expert and broadening the professional background of the interviewees in order to have a more complete and detailed view of barriers and solutions to Industry 4.0. Finally, the paper investigated barriers to Industry 4.0 implementation and solutions in complexity management. To help overcome these barriers and to improve these solutions, future research could analyze different enabling factors and drivers for Industry 4.0 implementation.

3.7 Appendix to paper 3

3.7.1 References

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Thesis conclusion

The research focuses on the effects of Industry 4.0 adoption in manufacturing firms. In particular, the thesis aims to answer the following research question: what are, upstream, the main drivers and deterrents to the adoption of Industry 4.0 and what are, downstream, the main conditions that favor or slow down the achievement of performance? To shed light on how firms perceive and manage driving forces and constraints of Industry 4.0, the thesis is based on a collection of three articles, respectively exploring the role of performance, barriers, incentives and complexity in Industry 4.0 based systems. The first paper investigates whether a positive relationship between openness to Industry 4.0 and performance exists and if this relationship has an inverted U-shape form and/or if it is influenced by firms' characteristics. The second paper explores whether the relationship between openness to Industry 4.0 and performance is mediated by barriers and incentives. The third paper focuses on how SMEs perceive and manage barriers and complexity in Industry 4.0.

The results of the first paper verify a positive relationship between openness to Industry 4.0 and performance, showing that both greater breadth (measured as number of 4.0 technologies adopted) and greater depth (measured as number of value chain phases where the technologies are adopted) of Industry 4.0 allow higher performance (measured through 6 performances). Moreover, the first paper verifies that micro-level local units achieve higher performances. The qualitative findings of the second paper validate the literature on performance and incentives of Industry 4.0, and integrate the literature on barriers, identifying 12 barriers classified into 4 categories (related to knowledge issues, economic-financial aspects, cultural issues and system conditions). The quantitative results of the second paper empirically verify a positive relationship between: (i) openness to Industry 4.0 and the four categories of barriers; (ii) knowledge and economic-financial barriers and performance; (iii) openness to Industry 4.0 and incentives; (iv) incentives and performance. The findings of the third paper: (i) further integrate the analysis on the barriers, identifying three additional barriers and reclassifying the 15 barriers into 5 categories, to take into account the relevant distinction between macro and micro level also made by worldwide industrial plans in defining the incentives; (ii) identify two main problems related to the increased complexity of Industry 4.0 for SMEs. These problems are the following: (i) Industry 4.0 allows to obtain and store large amounts of data, while the systems traditionally used by firms for the internal management – ESMs or the more advanced ERPs – do not allow the real-time use of these data, due to system rigidities; (ii) Industry 4.0 allows to extensively collaborate even outside the firms' boundaries, while SMEs have structural communication problems due to over-specialized skills and geographic dispersion. Both the findings of the qualitative analysis and the results of the quantitative analysis directly help to answer the aim and research question of the thesis and the sub aims, research questions and hypotheses formulated in the three papers.

Theoretical contribution and practical implications

As far as the theoretical contribution is concerned, the research has four main strengths, which allows to enrich literature both on management and on complex systems engineering. First, the study, through the quantitative analysis carried out in the first and in the second paper, confirms the literature on Industry 4.0 and performance, showing that the more Industry 4.0 adoption, the more performance perceived by manufacturing firms (Dalenogare et al., 2018). Moreover, it integrates the above mentioned literature, testing the relationship in an emerged country instead of in an emerging one (Dalenogare et al., 2018). Besides, the study enriches the research stream on Industry 4.0 and performance, by investigating the topic from a broader perspective than focusing only on the performance related to supply chain (Fatorachian and Kazemi, 2021) or to sustainability (Müller, Kiel, and Voigt, 2018), ensuring a more comprehensive analysis.

Second, the study integrates the literature on barriers to Industry 4.0 adoption, combining to a qualitative analysis (Horváth and Szabó, 2019; Raj et al., 2020) a quantitative analysis on large and fresh data on more than 1300 manufacturing firms, and expanding the analysis not only to SMEs (Stentoft et al., 2020) but also to different firms' sizes. In addition, the research takes a step forward from previous research, not merely identifying a list of barriers weighed or not by their respective importance. In fact, the thesis: (i) reclassifies the barriers into several categories (refining and detailing the classification into only two macro categories made by Chauhan, Singh, and Luthra (2021); (ii) empirically verifies the different impacts of the different barriers both on performance and on incentives; (iii) distinguishes the categories of barriers on different levels that reflect those followed by the incentives put in place by worldwide industrial plans. In this way, the analysis opens up future research on the deep interconnections between perception of barriers and adoption of incentives.

Third, the work is one of the first one in the management research field, to the author's knowledge, that quantitatively analyzes the role of incentives for manufacturing firms in three different areas: (i) Industry 4.0 adoption; (ii) incentives compliance in solving problems related to barriers; (iii) achieving performance.

Fourth, the analysis widens the literature on SMEs perceiving more barriers to Industry 4.0 adoption than larger firms (Horváth and Szabó, 2019), identifying not only upstream barriers to industry 4.0 adoption – mainly related to lack of economic, financial and human resources – but also downstream barriers to Industry 4.0 implementation, that may limit the achievement of performance despite the adoption of Industry 4.0. These downstream barriers are related to the weak readiness of SMEs in manage complexity in Industry 4.0. This fourth research stream on complexity management in Industry 4.0 is quite unexplored in management studies and it is at the early stage of engineering research (Mourtzis et al., 2019).

As far as the practical implications are concerned, the research, clarifying the main driving forces and constraints to Industry 4.0 adoption, may also have relevant impact in the field of innovation management and strategies, and in the field of complex systems engineering. In particular, from one side, the work suggests to mangers to adopt more 4.0 technologies to more value chain phases, considering firms' characteristics, to improve manufacturing performance. From the other side, the thesis shows to policy makers the main weakness in incentives development, suggesting to better communicate them – even and above all to SMEs – and creating incentives more tailored on real firms' constraints which also consider the management of the increased complexity.

Finally, it is possible to identify the main strength of the thesis, which largely depends on its dual soul allowed by the international collaboration between Management Department of the Università degli Studi di Torino and the Laboratoire de Génie Industriel of CentralSupélec, Universitè Paris Saclay. In fact – combining a dual perspective on management and complex systems engineering in a new and original way – the thesis analyzes in a holistic way performance, barriers, incentives and complexity of Industry 4.0. Moreover, it carries out both a qualitative and a quantitative analysis, shedding light on the mutual interrelationships between the above concepts and paving the way for promising future studies on the topic.

Limitations and future research

Since the research is a continuous process of improvement, the thesis has some limitations to date, that can be overcome with future research. Some of the major limitations and some possible improvements are critically listed below.

Starting from the qualitative analysis, it might be interesting to compare findings of case studies, focus group and semi-structured in-depth interviews to have a more integrated vision of firms' perception on industry 4.0 driving forces and constraints.

As far as the quantitative analysis is concerned, there are several issues to consider.

The first one is that it is based on perceived variables. Considering the subjectivity of the variables analyzed, it may be useful to control for a variable on the firms' awareness. In fact, if a firm is not aware about what Industry 4.0 is, it will be less aware about performance, barriers and incentives too. Moreover, not all the barriers are under the firm control. For this reason, it might be useful to separate internal and external barriers – as the third paper does from a qualitative point of view – also in the quantitative analysis on the relationships between barriers, incentives and performance. Finally, of course, in the future might be useful to understand if these perceptions are verified analyzing more objective variables.

The second issue is that the analysis is carried out on two separate years (2018 in the first paper and 2019 in the second one). In future research, a longitudinal analysis, comparing different years, may be carried out. Another possible analysis that might be perfomed in future studies is a cluster analysis, exploring the variety of different profile of firms and the consequent effects on the explored relationships.

The third issue is related to the sample. In particular, the quantitative analysis is based on a single region (Piedmont, Northern Italy) and the qualitative analysis is based on a two countries perspective (France and Italy). To overcome the regional data limit, a research agreement has already been activated with Centro Studi delle Camere di Commercio G. Tagliacarne. This collaboration will help in analyzing data at a national level. However, the best research perspective should be to compare similar regions, in terms of manufacturing and level of innovation, across Europe.

In addition to the possible future research lines hinted in response to the limitations of current research, three main future research lines are opened up by the current work. The first one concerns the concept introduced by the third paper on complexity. The second one concerns the need for a supporting theory for Industry 4.0. The third one concerns an in-depth analysis on the effects of Industry 4.0 on international business, through a combination of qualitative and quantitative literature review methodologies.

As far as the first point is concerned, the third paper on complexity highlights that Industry 4.0 increases complexity of systems, making possible to improve communication and data exchange in real time. However, from the qualitative analysis of the third paper, emerges that SMEs are not able to benefit from this increased complexity. Starting from this mismatch between potential possibilities of Industry 4.0 and real capabilities of SMEs, it might be very interesting to deeply explore the role of complexity in Industry 4.0 based systems. For this purpose, the adoption of a design perspective might help to understand what is complexity in Industry 4.0 and to explore new kind of interoperability, new languages and new knowledge. Possible research questions might be: RQ1 – How do barriers act on access to new knowledge and concepts? RQ2 – How can incentives for Industry 4.0 adoption reduce complexity? In this research line a useful support theory may be C-K design theory (Hatchuel andWeil 2003, 2009), and a qualitative approach seems to be more adapt to obtain a precise description of this new form of complexity 4.0.

As far as the second point is concerned, possible theories in support of Industry 4.0 might be ecosystem (Benitez, Ayala, and Frank, 2020) and platform (Cusumano and Gawer, 2019) theories. Focusing on ecosystem theory, two main aspects should be considered. The first one concerns the ecosystem per se, which includes the role of different actors, the role of the firms in the value chain, the role of buyers and suppliers, and the role of institutions. The second aspect is related to the geographical dimension of the ecosystem that may include the existence of place based incentives and specific infrastructural and legal barriers, depending on the countries. In this line of research, a fourth paper is under development as systematic literature review to create an ecosystem 4.0. This fourth paper is actually submitted as extended abstract to the R&D Management Conference 2021 (Castagnoli et al., 2021) and will be further implemented in the future.

The third line of research opened up deals – once again as the second line of research above mentioned – with the methodology of literature review applied to the macro topic of Industry 4.0. In particular, it focuses on the effects of Industry 4.0 on international business, combining a detailed qualitative systematic literature review with a strong quantitative methodology of bibliometric review and machine learning analysis. The mixed methodology adopted for this research line is once again the result of the collaboration between the two research units involved in the international thesis co-direction. In particular, it comes from a joint work with Rongyan Zhou which performed a similar methodology in his doctoral thesis (Zhou, 2021). In this line of research, a fifth paper, submitted and presented as extended abstract at the Digital Transformation Conference of the Università degli Studi di Pavia (Zhou et al., 2021), is under development. This opens the way to a new line of research in the field of international business, but above all it allows to obtain an extremely detailed view of the Industry 4.0 phenomenon, comparing two methodologies of literature review currently not pursued in the thesis.

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Thesis annexes

Annex I – Survey Congiuntura Industriale in Piemonte by Unioncamere Piemonte 2018 and 2019, thematic section on Industry 4.0[4]

Industry 4.0 (Impresa 4.0) refers to an emerging paradigm that determines the transformation of the entire sphere of production (new production factors, new technologies, new work organizations), creating business realities and entrepreneurial territories, truly integrated and connected by "enabling factors" such as interconnection, knowledge, collaboration and security.
On these issues, we will propose a few simple questions below, in order to take a picture of what the current situation of the Piedmontese production system is and what trends are expected in the near future.

1. Is your company sufficiently familiar with the Impresa 4.0 national plan?
❑ Yes
❑ No
(for information see the link of the Ministry of Economic Development: http://www.sviluppoeconomico.gov.it/index.php/it/industria40)

2. Your company has already introduced or will introduce technologies related to Industry 4.0?

Already introduced ❑ Yes ❑ No

Will introduce ❑ Yes ❑ No

[if negative answer go to question 5]

3. Which of the following enabling technology innovations has the company already adopted or will adopt?

	Already adopted		*Future investments planned*		
	Yes, please specify in which areas	*NO*	*Yes, soon (within 1 year)*	*Yes, in the medium term (within the next 3 years)*	*No investments planned*
Advanced Manufacturing solution	❑ Production ❑ R&D ❑ Logistics and warehouse ❑ Purchases ❑ Sales ❑ Administration	❑	❑	❑	❑
Augmented Reality	❑ Production ❑ R&D ❑ Logistics and warehouse	❑	❑	❑	❑

[4] The survey is the same for 2018 and 2019, except from the performance *Increased human resources productivity*, which is added in 2019.

	❑ Purchases ❑ Sales ❑ Administration				
Internet of Things (Iot)	"" ""	❑	❑	❑	❑
Big Data and Analytics	"" ""				
Cloud computing	"" ""				
Cyber-security	"" ""				
Additive manifacturing	"" ""				
Simulation	"" ""				
Horizontal/Vertical integration	"" ""				
Agrifood, bio-based economy and energy consumption oprimization technologies	"" ""				

[if no technological solution adopted, proceed to question 5]

4. With reference to the technological innovations you have adopted, can you indicate the main benefits you have derived from them?

- Increased flexibility through small batch production at large scale costs
- Increased speed from prototype to mass production through innovative technologies
- Greater output capacity
- Rreduced set-up times, errors and downtime
- Improved quality and reduced scrap through sensors that monitor production in real time
- Customer's improved opinion on products
- Increased human resources productivity
- (Other (specify)

5. What do you consider to be the main obstacles to the introduction of technological innovations in the enterprise?

- Little information on the potential of the 4.0 enabling technologies
- Little information on public facilities to support investments in I4.0
- Insufficient know-how/lack of internal skills
- Few competences on I4.0 on the labor market
- Insufficient economic resources within the company
- Insufficient external financing (banks, venture capital, etc.)
- Inefficiency of ultra-broadband internet connection
- Legal uncertainties (regarding patent protection)
- Difficulties in relationships with research centers
- Lack of unambiguous standards in the IoT field
- Lack of flexibility of human resources in the decision to apply I4.0 technologies
- The business sector of my company does not need I4.0 investments

- Other (specify)

6. Thanks to the National Plan Impresa 4.0, firms have a wide range of incentives available for innovation and automation, what incentives has the firm already used or will use?

Incentives	*Already used*	*Will use in the next three years*	*Has not used and has no intention of using*
Super-depreciation			
Iper-depretiation			
Nuova Sabatini			
Guarantee fund			
R&D tax credit			
Extraordinary plan made in Italy			
Tax credit Training 4.0			
Fund for intangible capital			
Other			

7. Is the company aware of the fact that a PID (Digital Enterprise Point), an information and assistance point for firms on digitization processes, is operating at the local Chamber of Commerce?

❑ Yes
❑ No

(for information see the link https://www.puntoimpresadigitale.camcom.it/)

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