UNIVERSIDADE PAULISTA – UNIP

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ESTRATÉGIA DE MANUFATURA NA INDÚSTRIA 4.0: PROPOSTA E VALIDAÇÃO DE UM MODELO CONCEITUAL PARA PRIORIDADES COMPETITIVAS OPERACIONAIS

SÃO PAULO

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Orientadora: Profa. Dra. Ana Lúcia Figueiredo Facin

Área de Concentração: Gestão de Sistemas e Operação

Linha de pesquisa: Linha 1 - Redes de Empresas e Planejamento da Produção

Projeto de Pesquisa: Transformação Digital

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DEDICATÓRIA

Em memória do meu pai, Pedro Carlos.

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RESUMO

O ambiente empresarial vivencia profundas alterações com o avanço das tecnologias da Indústria 4.0, alterações que representam uma ruptura nos modos de produção e paradigmas vigentes e exige a reavaliação da estratégia de manufatura. Apesar do avanço significativo na literatura, persiste uma lacuna teórica na explanação dos mecanismos de integração pelos quais o potencial tecnológico da I4.0 é traduzido em desempenho estratégico e na incorporação formal de novas prioridades competitivas emergentes. Neste sentido, o propósito principal deste trabalho é propor e validar um modelo conceitual (*framework*), fundamentado teórica e empiricamente e validado por especialistas que explicitam como a implementação de tecnologias habilitadoras da Indústria 4.0 influencia e configura a reorganização estratégica, com ênfase nas prioridades competitivas da manufatura. O delineamento da pesquisa é exploratório e sequencial, articulado em três artigos. O Artigo 1 elaborou uma Revisão Sistemática da Literatura (RSL), que estabeleceu a fundação teórica do *framework* e propôs a Perspectiva Dual das interações (Escopo Tecnológico e Escopo Gerencial). O Artigo 2 foi desenvolvido por meio de um Estudo de Múltiplos Casos Exploratórios para fundamentação empírica e elucidação dos mecanismos de integração. Já o Artigo 3 empregou o Painel de Especialistas (Método Delphi) para a validação final e o refinamento do modelo conceitual. Os resultados demonstram que a influência da I4.0 na reorganização estratégica da manufatura é estrategicamente contingente, mediada pelo Escopo Gerencial. Na sua vez, o Escopo Gerencial é classificado como o mecanismo de integração determinante, pois orquestra e traduz o potencial tecnológico em desempenho estratégico. Para a teoria, o modelo conceitual contribui ao expandir o conteúdo da estratégia de manufatura. Além das prioridades competitivas tradicionais (Custo, Qualidade, Entrega e Flexibilidade), o estudo consolidou empiricamente Inovatividade, Servitização e Sustentabilidade como prioridades competitivas de primeira ordem na era digital. Em termos de contribuições para a prática gerencial, a validação do *framework* por especialistas acadêmicos e profissionais fortalece sua aplicabilidade em cenários reais de manufatura. Serve ainda como referência estratégica para a tomada de decisão e a otimização de investimentos em tecnologias habilitadoras da I4.0, alinhadas aos objetivos competitivos.

PALAVRAS CHAVES: Estratégia de Produção. Prioridades Competitivas Operacionais. 4ª Revolução Industrial.

ABSTRACT

The business environment is undergoing profound transformations with the advancement of Industry 4.0 technologies, changes that represent a rupture in prevailing production modes and paradigms and demand a reassessment of manufacturing strategy. Despite significant progress in the literature, a theoretical gap persists in explaining the integration mechanisms through which the technological potential of Industry 4.0 is translated into strategic performance, as well as in the formal incorporation of new emerging competitive priorities. In this context, the primary purpose of this study is to propose and validate a conceptual model (framework), theoretically and empirically grounded and validated by experts, that clarifies how the implementation of Industry 4.0 enabling technologies influences and shapes strategic reorganization, with emphasis on manufacturing competitive priorities. The research design is exploratory and sequential, articulated across three articles. Article 1 conducted a Systematic Literature Review (SLR), which established the theoretical foundation of the framework and introduced the Dual Perspective of interactions (Technological Scope and Managerial Scope). Article 2 was developed through an Exploratory Multiple Case Study to provide empirical grounding and elucidate the integration mechanisms. Article 3 employed an Expert Panel (Delphi Method) for the final validation and refinement of the conceptual model. The results demonstrate that the influence of Industry 4.0 on the strategic reorganization of manufacturing is strategically contingent, mediated by the Managerial Scope. The Managerial Scope is identified as the decisive integration mechanism, as it orchestrates and translates technological potential into strategic performance. From a theoretical standpoint, the conceptual model contributes by expanding the content of manufacturing strategy. In addition to the traditional competitive priorities (Cost, Quality, Delivery, and Flexibility), the study empirically consolidated Innovativeness, Servitization, and Sustainability as first-order competitive priorities in the digital era. In terms of managerial contributions, the validation of the framework by academic and professional experts strengthens its applicability in real manufacturing contexts. It further serves as a strategic reference for decision-making and for optimizing investments in Industry 4.0 enabling technologies aligned with competitive objectives.

KEYWORDS: Production Strategy. Operational Competitive Priorities. 4th Industrial Revolution.

UTILIDADE

O presente trabalho de pesquisa, ao propor e validar um modelo conceitual para a Estratégia da Manufatura na Indústria 4.0, estabelece alinhamento multifacetado com a Agenda 2030 para o Desenvolvimento Sustentável, promovida pela Organização das Nações Unidas. A tese contribui de forma significativa para o equilíbrio das três dimensões do desenvolvimento sustentável — econômica, social e ambiental — ao reconfigurar as prioridades competitivas da manufatura na era digital.

O foco da pesquisa na integração e orquestração estratégica das tecnologias habilitadoras da I4.0 para otimizar o desempenho, converge com vários ODS, destacando-se primariamente os Objetivos 12, 9 e 8.

ODS 12: Assegurar padrões sustentáveis de consumo e de produção

A contribuição mais explícita da tese reside no Objetivo 12 (Consumo e Produção Responsáveis), que visa a assegurar padrões sustentáveis de consumo e de produção. O estudo consolida, de forma empírica e validada por especialistas, a Sustentabilidade como uma prioridade competitiva de primeira ordem na manufatura I4.0.

O *framework* final detalha o Escopo Gerencial da Sustentabilidade, que inclui práticas estratégicas com foco na eficiência de recursos, na redução de resíduos e na minimização da pegada ambiental, além da conformidade ambiental de longo prazo. Essas práticas gerenciais, suportadas por tecnologias como monitoramento em tempo real (IoT) e análise de dados *(Big Data Analytics)*, permitem que as empresas otimizem o uso de energia e controlem o desperdício. Isso atende diretamente às metas do ODS 12, especialmente à meta de alcançar a gestão sustentável e o uso eficiente dos recursos naturais e à meta de reduzir significativamente a geração de resíduos por intermédio da prevenção e redução. A integração de sistemas e o uso de dados para gerir o consumo e o impacto ambiental reforçam o alinhamento da manufatura com o desenvolvimento sustentável.

ODS 9: Construir infraestrutura resiliente, promover industrialização inclusiva e sustentável e fomentar a inovação

O trabalho se alinha integralmente ao Objetivo 9 (Indústria, Inovação e Infraestrutura), que busca promover a industrialização inclusiva e sustentável e fomentar a inovação, uma vez que a tese aborda a reorganização estratégica da manufatura impulsionada pelas tecnologias I4.0, promovendo a modernização e a sustentabilidade dos setores industriais. O *framework* detalha como a I4.0 permite que os setores de infraestrutura se tornem mais sustentáveis e eficientes no uso de recursos

O estudo legitima, ainda, a Inovatividade como uma prioridade competitiva central. O foco na Inovatividade (aceleração de ciclos de design, integração de inovação nas rotinas diárias e a criação de diferenciação de mercado), utilizando tecnologias como Inteligência Artificial e Manufatura Aditiva, contribui para a ampliação da pesquisa científica e para a alavancagem das capacidades tecnológicas dos setores industriais, estimulando a inovação.

ODS 8: Promover o crescimento econômico sustentado, inclusivo e sustentável

Por fim, a pesquisa apoia o Objetivo 8 (Trabalho Decente e Crescimento Econômico), ao focar na melhoria da competitividade e da produtividade. A busca por desempenho estratégico por meio do alinhamento tecnológico-gerencial traduz-se em maior produtividade e eficiência. Este avanço tecnológico e organizacional visa a alcançar níveis mais elevados de produtividade das economias por meio da atualização e inovação tecnológica. Adicionalmente, o foco na Servitização, que transforma produtos em plataformas de valor agregado contínuo, reflete a busca por um crescimento econômico sustentado e sustentável através da diversificação e agregação de valor.

Em suma, a tese articula as dimensões tecnológica e gerencial para demonstrar que o sucesso na Indústria 4.0 é alcançado por meio de um alinhamento intencional que, além dos ganhos tradicionais de Custo, Qualidade, Entrega e Flexibilidade, consolida a Sustentabilidade e a Inovação como imperativos estratégicos essenciais para a competitividade em mercados dinâmicos e ecologicamente conscientes, reforçando, assim, o compromisso com a Agenda 2030.

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AM (*Additive Manufacturing* / Manufatura Aditiva)

AI (*Artificial Intelligence* / Inteligência Artificial)

AIR (Automação e Robótica Industrial)

AR (*Augmented Reality*)

BC (*Block Chain*)

BDA (*Big Data Analytics*)

CP (Prioridade Competitiva)

CPS (*Cyber-Physical Systems* / Sistemas Ciberfísicos)

CSR (*Corporate Social Responsibility*)

EA (Especialista Acadêmico)

EM (Estratégia de Manufatura)

EP (Especialista Praticante)

IIoT (*Industrial Internet of Things*)

IoS (*Internet of Services*)

IoT (*Internet of Things*)

KIBS (*Knowledge-Intensive Business Services*)

MaaS (*Manufacturing-as-a-Service*)

M&S (Modelagem e Simulação)

MCTIC (Ministério da Ciência, Tecnologia, Inovações e Comunicações)

MDIC (Ministério do Desenvolvimento, Indústria, Comércio e Serviços)

ME (Ministério da Economia)

MES (*Manufacturing Execution System*)

MS (Estratégia de Manufatura)

ODS (Objetivos de Desenvolvimento Sustentável)

OE (Objetivo Específico)

OTD (*On Time Delivery*)

PCs (Prioridades Competitivas)

PSS (*Product-Service Systems*)

RSL (Revisão Sistemática da Literatura)

SLR (*Systematic Literature Review*)

SMEs (*Small and Medium-sized Enterprises*)

VR (*Virtual Reality*)
WoS (*Web of Science*)

SUMÁRIO

PARTE I - VISÃO GERAL INTEGRATIVA

1 CONSIDERAÇÕES INICIAIS

Este capítulo introduz o tema central da pesquisa e evidencia a relevância da Indústria 4.0 e seu impacto na Estratégia de Manufatura. No contexto de uma tese integrada, o presente capítulo cumpre a função de articular a narrativa geral, situar o problema de pesquisa e a lacuna teórica, além de explicitar os objetivos geral e específicos. Adicionalmente, justifica sua pertinência acadêmica e gerencial, apresenta a estrutura sequencial da tese e demonstra como os artigos se articulam para compor o trabalho como um todo.

1.1 Introdução

A Indústria 4.0 é considerada uma nova etapa na evolução industrial na qual se destaca uma maior integração entre os sistemas de operações da manufatura e as tecnologias de informação e de comunicação. Ela visa à melhoria do desempenho das indústrias. No contexto operacional, as tecnologias digitais têm sido empregadas com o propósito de reduzir o tempo de preparação de máquinas, os custos de mão de obra e de materiais, o tempo de processamento e de aumentar a produtividade dos processos de produção (DALENOGARE *et al*., 2018; TIAN *et al*., 2023).

O termo em alemão *Industrie 4.0* ganhou notoriedade em 2011 como parte integrante da estratégia de alta tecnologia da Alemanha comportada pelo *High-Tech Strategy 2020 Action Plan* (SANTOS *et al*., 2018; OZTEMEL e GURSEV, 2020). A ideia ultrapassou fronteiras e foi incorporada por outros países.

Nos Estados Unidos, por exemplo, ainda em 2011, foi desenvolvido o projeto denominado *Advanced Manufacturing Partnership* que conta com a participação do ambiente acadêmico, da indústria e do governo. Na sua vez, na China, o programa *Made in China 2025* foi elaborado pelo Ministério da Indústria e Tecnologia da Informação juntamente com a Academia Chinesa de Engenharia (ASSAD NETO, 2018; WANG *et al*., 2020). Tais nações têm adotado programas especificamente focados na Indústria 4.0 e, vale ressaltar, que elas aparecem no topo da lista de países com maior índice de competitividade em nível mundial.

No Brasil, uma iniciativa conjunta entre o Ministério da Ciência, Tecnologia, Inovações e Comunicações (MCTIC) e o Ministério da Economia (ME) resultou, em abril de 2019, a criação da Câmara Brasileira da Indústria 4.0. Composta por representantes do governo e da academia, essa instância tem como propósito formular e articular ações voltadas ao desenvolvimento dos setores empresariais em direção ao ambiente da Indústria 4.0 (Ministério do Desenvolvimento, Indústria, Comércio e Serviços – MDIC, 2019).

Esse movimento institucional é acompanhado por um crescente interesse no meio acadêmico, em que se observa um aumento significativo no volume de pesquisas sobre o tema. Em termos de produção científica, China, Itália, Estados Unidos e Alemanha lideram, até o momento, o número de publicações relacionadas à Indústria 4.0 (SOUZA e SANTOS, 2021).

1.2 Problematização e Lacuna de Pesquisa

A Indústria 4.0 (I4.0) representa uma ruptura com os paradigmas de produção vigentes e é uma força transformadora que exige a reavaliação da estratégia de manufatura para alavancar tecnologias digitais. Esta transformação é caracterizada pela integração de sistemas ciberfísicos e tecnologias digitais avançadas, com o propósito de otimizar processos, aumentar a transparência operacional e reconfigurar as cadeias de valor com agilidade.

As tecnologias habilitadoras da I4.0 impactam diretamente as prioridades competitivas (PC) da manufatura, como custo, qualidade, entrega e flexibilidade (ABDULLAH *et al*., 2022; ENRIQUE *et al*., 2022). Contudo, a literatura aponta que esta relação não é direta ou determinística, mas sim multifacetada e sistêmica. O sucesso estratégico da I4.0 não se deve apenas à adoção tecnológica (o 'o quê'), mas ao seu alinhamento com o propósito organizacional e com a complexidade do ambiente operacional. Portanto, o foco da lacuna teórica reside em discutir o mecanismo de integração pelo qual o potencial tecnológico é traduzido e aplicado para configurar o desempenho estratégico em relação às prioridades competitivas da manufatura.

Apesar do avanço significativo na literatura, que teve seus primeiros artigos publicados em 2019, a pesquisa sobre as inter-relações entre Indústria 4.0 e Estratégia de Manufatura ainda constitui um campo recente e carente de validação empírica. Os modelos conceituais propostos até o momento são predominantemente teóricos e não foram testados em situações reais, o que limita sua aplicabilidade e entendimento prático. Há, portanto, uma vasta lacuna de pesquisa que necessita de estudos empíricos (ANCARANI *et al*., 2019; SALAM, 2021; DOHALE *et al*., 2023; TORTORELLA *et al*., 2022).

Além disso, torna-se necessário incorporar prioridades competitivas emergentes — como inovatividade, servitização, sustentabilidade, desempenho ambiental, customização e responsabilidade social — na análise da estratégia de manufatura (LEONG *et al*., 1990; NETLAND e FRICK, 2016; VIVARES *et al*., 2022). A Indústria 4.0 amplia o escopo estratégico das organizações e exige modelos que transcendam as dimensões clássicas e reflitam as novas demandas do ambiente produtivo (GARVIN, 1993; SILVA *et al*., 2009; ABDULLAH *et al*., 2022).

Com respeito à contribuição para a prática gerencial, a proposição de um modelo validado pode ampliar a capacidade das empresas de direcionar seus recursos para tecnologias habilitadoras da Indústria 4.0 que estejam mais alinhadas aos seus objetivos competitivos.

Desta forma, esta tese busca fornecer o embasamento teórico e empírico necessário para o desenvolvimento de um *framework*, e o foco da pesquisa pode ser sintetizado pela seguinte questão central: *Como o uso de tecnologias habilitadoras da Indústria 4.0 influencia a reorganização estratégica, com ênfase nas prioridades competitivas da manufatura?*

1.3 Objetivo

O principal propósito deste trabalho é desenvolver e validar um modelo conceitual (*framework*) que sirva como referência estratégica para empresas manufatureiras que navegam pela transformação digital. Neste sentido, o objetivo geral da tese é propor um modelo conceitual (*framework*) que, fundamentado teórica e empiricamente e validado por especialistas, explicite como a implementação de tecnologias habilitadoras da Indústria 4.0 influencia e configura a reorganização estratégica, com ênfase nas prioridades competitivas da manufatura.

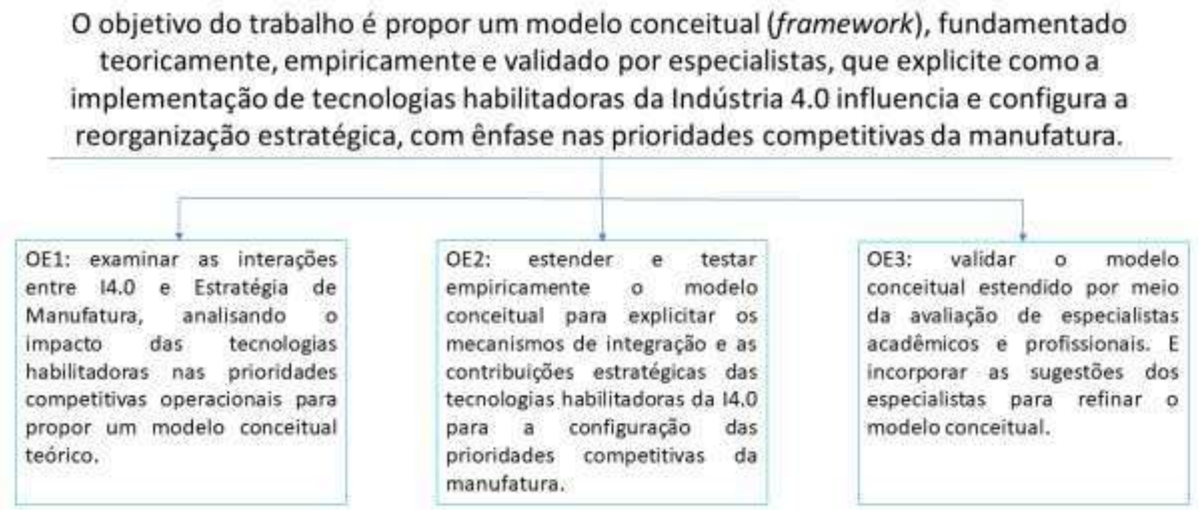
Conforme ilustrado na Figura 1, para o alcance do Objetivo Geral, definiram-se três Objetivos Específicos (OEs), que se encontram alinhados em correspondência biunívoca com as etapas e artigos que compõem a tese:

• OE1: Examinar as interações entre I4.0 e Estratégia de Manufatura, com a análise do impacto das tecnologias habilitadoras nas prioridades competitivas para propor um modelo conceitual teórico.

• OE2: Estender e testar empiricamente o modelo conceitual para explicitar os mecanismos de interação e as contribuições estratégicas das tecnologias habilitadoras da I4.0 para a configuração das prioridades competitivas da manufatura.

• OE3: Validar o modelo conceitual estendido por meio da avaliação de especialistas acadêmicos e profissionais e incorporar as sugestões dos especialistas para refinar o modelo conceitual.

Figura 1 – Desdobramento do Objetivo Geral da tese em Objetivos Específicos

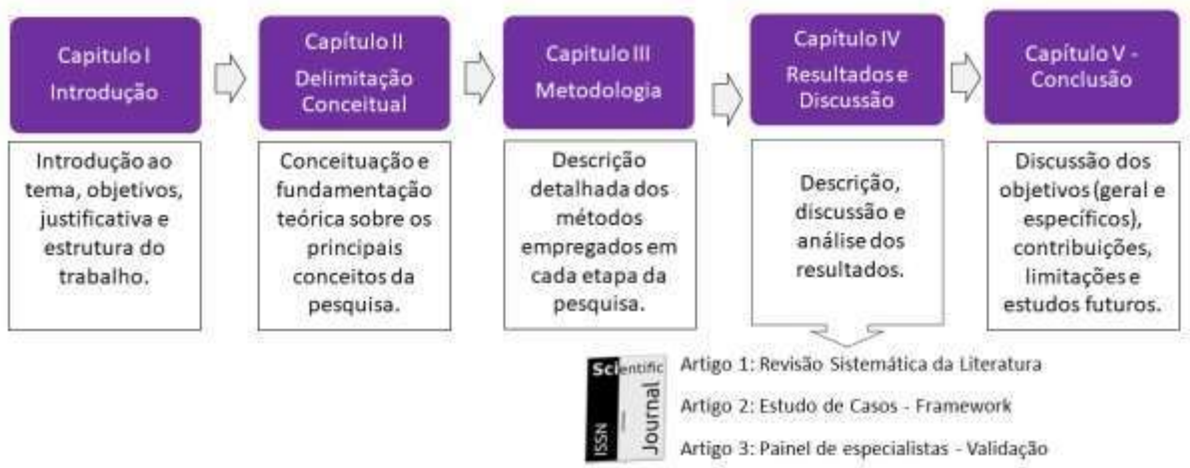


Fonte: a autora

1.4 Delineamento Metodológico Sequencial e Estrutura da Tese

A presente pesquisa adota o formato de Tese Integrada por Artigos, na qual o trabalho é estruturado em duas partes principais: Parte I - Visão Geral Integrativa e Parte II - Artigos da Tese. A Visão Geral Integrativa (Capítulos I a V, conforme Figura 2) tem o propósito de unificar a narrativa, os objetivos e os métodos de pesquisa. Ela demonstra como os estudos individuais (Artigos) se articulam de forma sequencial para responder à Questão Central e alcançar o Objetivo Geral da tese.

Figura 2 – Composição da Parte I: Visão Geral Integrativa



Fonte: a autora

Seriam, então,

• Capítulo I: Considerações Iniciais - apresenta a contextualização do tema, a problematização, a Questão Central da pesquisa, os Objetivos (Geral e Específicos), a Justificativa e a estrutura do trabalho, conforme o modelo de tese integrada.

• Capítulo II: Delimitação Conceitual e Fundamentação Teórica - contempla a fundamentação teórica da pesquisa; delimita os conceitos de Estratégia de Manufatura (MS), Indústria 4.0 (I4.0) e suas tecnologias habilitadoras, e a interconexão estratégica entre eles.

• Capítulo III: Metodologia - descreve em detalhe o delineamento geral da tese (sequencial) e a metodologia específica empregada em cada etapa (RSL, Estudo de Múltiplos Casos e Painel de Especialistas) e evidencia a contribuição de cada artigo para o avanço da pesquisa.

• Capítulo IV: Resultados e Discussão - apresenta a síntese dos achados de cada artigo. Os resultados são discutidos de forma integrada; foca-se na progressão do conhecimento: da proposta do *framework* teórico (Artigo 1) à elaboração e à fundamentação empírica do mecanismo de integração (Artigo 2) e à avaliação do modelo conceitual (Artigo 3).

• Capítulo V: Conclusões, Limitações e Implicações - sintetiza as principais conclusões; destaca o alcance do Objetivo Geral da tese e as contribuições acadêmicas e gerenciais (com inclusão do novo *framework*). Apresenta as limitações da pesquisa e propõe uma agenda para estudos futuros.

O delineamento geral da pesquisa é exploratório e sequencial e segue uma progressão lógica de desenvolvimento, fundamentação empírica e avaliação do modelo conceitual, conforme estabelecido nos Objetivos Específicos (OEs) da tese.

A coerência da pesquisa é estabelecida por meio da correspondência biunívoca de cada artigo aos Objetivos Específicos (OEs), de forma que cada etapa é necessária e suficiente para o avanço da pesquisa. A integração é conduzida conforme ilustrado no Quadro 1.

Quadro 1 – Correspondência entre os Objetivos Específicos e os artigos

Etapa	Objetivo Específico	Artigo Correspondente	Função na Tese (Delineamento Sequencial)
I	OE1: examinar as interações entre I4.0 e Estratégia de Manufatura, com a análise do impacto das tecnologias habilitadoras nas prioridades competitivas para propor um modelo conceitual teórico.	Artigo 1: Revisão Sistemática da Literatura (RSL)	Estabelece a fundação teórica; mapeia a intersecção entre I4.0 e Estratégia de Manufatura (MS).
II	OE2: estender e testar empiricamente o modelo conceitual para explicitar os mecanismos de interação e as contribuições estratégicas das tecnologias habilitadoras da I4.0 para a configuração das prioridades competitivas da manufatura.	Artigo 2: Estudo de Múltiplos Casos	Elabora e fundamenta empiricamente o *framework*. Utiliza a Metodologia Gioia para elucidar o mecanismo de intercoxeção, o qual é classificado como o Escopo Gerencial, que traduz o potencial tecnológico em desempenho estratégico.
III	OE3: validar o modelo conceitual estendido por meio da avaliação de especialistas.	Artigo 3: Painel de Especialistas (Método Delphi)	Avalia, discute e refina o *framework* conceitual proposto; fortalece sua aplicabilidade prática em cenários reais de manufatura.

Fonte: a autora

Este sequenciamento garante que o modelo conceitual seja desenvolvido com rigor teórico (Artigo 1), fundamentado em evidências do mundo real (Artigo 2) e avaliado por *experts* (Artigo 3), e isto culmina no alcance do Objetivo Geral da tese.

Já a PARTE II: ARTIGOS DA TESE contém os artigos (Artigo 1, Artigo 2 e Artigo 3), apresentados na ordem sequencial em que foram desenvolvidos.

2 DELIMITAÇÃO CONCEITUAL E FUNDAMENTAÇÃO TEÓRICA

Este capítulo estabelece a fundamentação teórica da pesquisa; delimita os conceitos essenciais que suportam a elaboração e a validação do modelo conceitual, conforme estabelecido no Objetivo Geral da tese. O estudo da literatura é central para a primeira etapa da pesquisa (Artigo 1), que quer mapear o estado da arte e identificar as lacunas que justificam a busca por evidências empíricas.

A estrutura é dedicada a examinar três eixos conceituais principais: a Estratégia de Manufatura (MS), a Indústria 4.0 (I4.0) e, crucialmente, a Interação estratégica entre as tecnologias habilitadoras da I4.0 e as prioridades competitivas da manufatura.

2.1 Estratégia de Manufatura

Em seu trabalho de 1969, *Manufacturing – missing link in corporate strategy,* Skinner, um estudioso do assunto *estratégia*, deu início às discussões em relação à utilização da área operacional como fonte de vantagem competitiva (SKINNER, 1969). O autor desenvolve argumentos a favor da elaboração de um plano estratégico para as atividades operacionais e, mais ainda, descreve a importância da integração de tal plano ao planejamento do negócio e da organização, de modo que haja harmonização entre os planos em diferentes níveis empresariais.

De acordo com Slack *et al*. (1997, p. 92), uma estratégia operacional configura "o conjunto de políticas, planos e comportamentos que a produção escolhe para seguir". Os mesmos autores comentam que, ao desenvolver uma estratégia de operações, há dois conjuntos de questões que devem ser considerados: as questões relativas ao conteúdo da estratégia e as questões relativas ao processo de sua formulação. Os fatores relativos ao conteúdo de uma estratégia de operações determinam a tomada de decisões que direcionam os processos decisórios cotidianos. Já os tópicos relacionados ao processo de formulação referem-se ao modo de elaboração desta estratégia e são abordados na pesquisa de Mills, Platts e Gregory (1995) entre outras pesquisas.

As prioridades competitivas ou os objetivos de desempenho da função de operações, ponto de maior interesse neste trabalho, estão incluídos no composto de itens pertinentes ao conteúdo de uma estratégia de operações e, quando aplicadas no nível funcional, caracterizam-se como “um conjunto consistente de prioridades que a indústria terá para competir no mercado” (PIRES, 1995, p. 51).

As prioridades competitivas operacionais aqui estudadas contemplam as dimensões predominantemente citadas na literatura sobre o tema: custo, qualidade, entrega (ou desempenho de entregas) e flexibilidade. Tais prioridades são exploradas de forma mais específica no Quadro 2.

Quadro 2 – Prioridades competitivas da manufatura

Prioridades Competitivas Operacionais e seus componentes
Custo: Envolve o custo de compra, bem como os custos de utilização e manutenção do item ao longo de seu ciclo de vida. Neste quesito, o elemento essencial é que a forma como a empresa gerencia seus custos na área produtiva deve lhe possibilitar reduzi-los de forma a habilitá-la a alcançar um desempenho competitivo melhor que o de seus concorrentes no que diz respeito ao preço final do produto. Citado por: (1), (2), (3*), (4), (5), (6), (7), (8), (9) * utilizam o termo Preço
Qualidade: Envolve a entrega de produtos com baixa taxa de defeitos, alta performance no que diz respeito às características básicas e adicionais, conformidade com o projeto, alta durabilidade, alto índice de confiabilidade, estética. Aqui, incluem-se ainda a qualidade dos serviços pós-venda (como assistência técnica) e uma imagem da marca bem estabelecida no mercado. Citado por: (1), (2), (3), (4), (5), (6), (7), (8), (9), (10)
Entrega: Consiste em entregar o que foi acordado com precisão e rapidez (velocidade), apresentar confiabilidade nos prazos, quantidades e qualidade de entrega. Outros aspectos envolvidos são facilidade de pedido e flexibilidade de pedido, assim como flexibilidade de expedição e acesso à informação (rastreabilidade). Citado por: (1), (2), (3), (4), (5), (6), (7), (8), (9*) *aplicam o termo Rapidez
Flexibilidade: Contempla a velocidade de lançamento de novos produtos (ou novas versões), a capacidade de oferecer customização e/ou executar modificações conforme necessidade específica do consumidor. Neste quesito, a aptidão para disponibilizar uma ampla variedade do composto e das linhas de produtos também deve ser considerada. É preciso levar em conta ainda a celeridade em responder a alterações nos volumes de produção em reação a mudanças na demanda. Citado por: (1), (2), (3), (4), (5), (6), (7), (8), (9), (10)

Nota: (1) Garvin (1993), (2) Dohale *et al*. (2023), (3) Kim e Arnold (1996), (4) Ward e Duray (2000), (5) Dangayach e Deshmukh (2006), (6) Urgal-Gonzáles e García-Vázquez (2007), (7) Wang e Cao (2008), (8) Martín-Peña e Díaz-Garrido (2008), (9) Silva *et al*. (2009), (10) Enrique *et al*. (2022).

Fonte: a autora

Vale comentar a alusão a outros pontos pertinentes às prioridades competitivas operacionais presentes na literatura, uma vez que dimensões da manufatura, como inovatividade (LEONG *et al*., 1990; ABDULLAH *et al*., 2022), serviços (GARVIN, 1993), performance ambiental (ou gestão ambiental ou sustentabilidade) (SILVA *et al*., 2009; KHAN *et al*., 2023), customização e responsabilidade social têm crescido em importância (NETLAND e FRICK, 2016).

2.2 Indústria 4.0

A Indústria 4.0 (I4.0), também referenciada na literatura como sendo uma iniciativa estratégica (WANG *et al*., 2016), se manifesta como o paradigma de manufatura da 4ª Revolução Industrial. Sua aplicação faz amplo uso da conectividade resultante principalmente do emprego da internet (BRETTEL *et al*., 2014), e os conceitos a ela associados apresentam um extenso leque de aplicações (ZHENG *et al*., 2018). Certo conjunto de iniciativas tecnológicas tem sido relacionado como fator habilitador para sua adoção. Estas tecnologias são elencadas e resumidamente descritas no Quadro 3.

Quadro 3 – Tecnologias habilitadoras da Indústria 4.0

Tecnologias habilitadoras da I4.0
Sistemas ciberfísicos (*Cyber Physical Systems – CPS*): termo que se refere à combinação e à coordenação de recursos computacionais e elementos físicos. Por meio de sensores e atuadores, sistemas automatizados conectam operações da realidade com infraestrutura de computação e comunicação. Desenvolve-se assim uma rede que integra vários dispositivos. Citado por: (1), (2), (3), (4), (5), (6)
Internet das Coisas (*Internet of Things – IoT*): combina diversas tecnologias com o objetivo de conectar dispositivos entre si. Promove comunicação entre máquinas, bem como entre máquinas e humanos. Citado por: (1), (2), (3), (6), (7), (8), (9)
Internet dos Serviços (*Internet of Services – IoS*): viabiliza disponibilização, contratação/comercialização e entrega/distribuição de serviços pela internet (REIS *et al*., 2022). Tais serviços podem ou não estar agregados a produtos. Citado por: (10), (11), (12), (13)
Inteligência Artificial: aplica-se a máquinas, equipamentos ou a qualquer tipo de dispositivo que possua a capacidade de simular o raciocínio humano. Some-se a isso a habilidade de aprender (*machine learning*). Citado por: (1), (2), (8), (14)
Manufatura aditiva: contempla um conjunto de tecnologias de fabricação nas quais a produção de um item é feita pela deposição de material camada por camada, o que permite a fabricação de objetos 3D. Citado por: (1), (2), (5), (8), (10), (14), (15)
Modelagem e simulação: diz respeito à 'virtualização' por meio de modelagem matemática e computacional. Possibilita testagem de produtos, equipamentos, sistemas produtivos e, de modo geral, diferentes situações antes que elas se tornem realidade (ABDULLAH *et al*., 2022). Citado por: (1), (2), (3), (5), (15)
Computação em Nuvem: empresas especializadas disponibilizam, via internet, serviços em nuvem que podem ser acessados por qualquer dispositivo, de qualquer local. Uma de suas vantagens é a possibilidade de otimização do esforço computacional.

Citado por: (2), (5), (8), (10), (15)
Realidade Aumentada e Realidade Virtual: a primeira permite a inserção de elementos virtuais em um ambiente real. Já o segundo caso é um ambiente totalmente virtual. Citado por: (1), (2), (3), (5), (8), (10), (15)
***Big Data Analytics* (*BDA*):** diz respeito à capacidade de coletar, armazenar e tabular uma grande quantidade de informações. Citado por: (3), (5), (10), (13), (15)
***Block Chain* (*BC*):** mais utilizado até o momento na realização de transações; codifica informações no formato criptografado e monta blocos. Tem como características: durabilidade, transparência, integridade de processo, imutabilidade e rastreabilidade (ABDULLAH *et al*., 2022). Citado por: (5), (6), (7), (8), (9).

Nota: (1) Enrique *et al*. (2022), (2) Muhuri *et al*. (2019), (3) Kamble *et al*. (2018), (4) Schneider (2018), (5) Abdullah *et al*. (2022), (6) Martins *et al*. (2019), (7) Zhang e Chen (2020), (8) Javaid *et al*. (2021), (9) Alladi *et al*. (2019), (10) Kang *et al*. (2016), (11) Brettel *et al*. (2014), (12) Thoben *et al*. (2017), (13) Lu (2017), (14) Zheng *et al*. (2018), (15) Oztemel e Gursey (2020).

Fonte: a autora

O grupo de tecnologias aqui listado possivelmente não esgota a relação de iniciativas tecnológicas aplicáveis à I4.0, especialmente quando se considera que podem despontar novas tecnologias a ser integradas a este conjunto, como também podem ser elaborados novos usos para as atuais tecnologias.

A Indústria 4.0 traz consigo ainda promessa de promover: i. integração horizontal (THOBEN *et al*., 2017; BONILLA *et al*., 2018), por estimular o trabalho conjunto entre organizações, com a constituição de redes colaborativas (BRETTEL *et al*., 2014), além de possivelmente resultar o surgimento de novas redes de valores e de modelos de negócios (WANG *et al*., 2016; BRETTEL *et al*., 2014); ii. integração vertical, com fluxo de dados estabelecido entre os diferentes níveis hierárquicos de planejamento (THOBEN *et al*., 2017; BONILLA *et al*., 2018), o que viabiliza a operação de sistemas produtivos reconfiguráveis e com capacidade de auto- organização (WANG *et al*., 2016).

No que concerne especificamente à função de produção no cenário da Indústria 4.0, percebe-se a necessidade de uma mudança de paradigma da manufatura automatizada para o conceito de manufatura inteligente (*smart manufacturing*) (THOBEN *et al*., 2017). Esta última, por vezes, é entendida como uma das forças propulsoras da nova revolução industrial (KANG *et al*., 2016). Considerando que sistemas do tipo *smart manufacturing* apresentam habilidade de responder de forma assertiva e com maior rapidez às variações da demanda de mercado (ZHENG *et al*., 2018; KANG *et al*., 2016), é plausível ponderar que sua aplicação acarreta melhores condições competitivas para as empresas que os implementam.

Sistemas produtivos tradicionais, em muitos contextos, tendem a operar com recursos predeterminados e a estabelecer processos de produção que seguem rotas mais fixas. Estes sistemas, frequentemente, utilizam controle e comunicação entre máquinas e equipamentos de forma independente, sem a adoção de uma infraestrutura de comunicação integrada.

Por outro lado, sistemas de manufatura com características *smart* operam com um variado conjunto de recursos e propiciam a diversificação do roteiro de produção de acordo com a necessidade do processo produtivo (WANG *et al*., 2016). Esses sistemas empregam redes que conectam e integram máquinas, produtos, sistemas de informação e pessoas, de modo que possibilitam que o controle seja compartilhado pelas entidades do processo e empreendem sistemas de comunicação integrados com capacidade de coletar e analisar uma grande quantidade de dados (*Big Data*) (WANG *et al*., 2016).

Neste contexto de interação sistêmica, a I4.0 transcende a mera agregação de tecnologias isoladas; o seu valor reside na orquestração e na integração entre as esferas gerencial e tecnológica. As ferramentas elencadas no Quadro 2 são habilitadoras que servem aos princípios de auto-organização e integração.

Essa natureza pervasiva e multifacetada das tecnologias indica que o desempenho da Indústria 4.0 envolve uma relação complexa e não uniforme. Assim, a obtenção de resultados estratégicos depende da configuração dessas tecnologias em alinhamento com a intenção organizacional, o que torna necessária a identificação de mecanismos de integração que transcendam a simples adoção tecnológica.

A aplicação combinada e integrada das tecnologias habilitadoras da I4.0 gera uma série de expectativas em relação ao processo produtivo. As perspectivas em relação à adoção dos conceitos e práticas da Indústria 4.0 apontam também para a viabilidade de implementação de uma manufatura com características sustentáveis decorrente do emprego de sistemas produtivos. Estes sistemas fazem uso eficiente de recursos e reduzem a emissão de substâncias danosas, bem como fazem uso de materiais *amigos do meio ambiente* e de capacidade de otimização dos processos de fabricação (KANG *et al*., 2016).

2.3 Tecnologias habilitadoras da Indústria 4.0 e Prioridades Competitivas da Manufatura

A literatura apresenta evidência de como as tecnologias habilitadoras da I4.0 reforçam e expandem a capacidade das empresas de atender as prioridades tradicionais – custo, qualidade, entrega e flexibilidade. O Artigo 1 da presente tese, baseado em uma Revisão Sistemática da Literatura, demonstrou que as inter-relações entre as Prioridades Competitivas e as Tecnologias Habilitadoras da I4.0 operam em uma natureza dual. Essa interação abrange dois domínios distintos: o escopo gerencial, que inclui a integração de sistemas de informação e a otimização de recursos, e o escopo tecnológico, que engloba inovações, como Sistemas Ciberfísicos (CPS), Internet das Coisas (IoT) e Manufatura Aditiva (AM), dentre outras inovações.

2.3.1 Prioridade Competitiva Custo

A competitividade baseada no custo está intimamente associada às tecnologias da I4.0, pois elas permitem a produção de itens eficientes, individualizados e customizados a um custo razoável. A manufatura é assistida por tecnologias como Automação, Internet das Coisas (IoT), Sistemas Ciberfísicos (CPS), Inteligência Artificial, *Big Data Analytics* (BDA) e Modelagem e Simulação (M&S).

Modelagem e Simulação (M&S) demonstram o significativo potencial de eficiência de custos entre as tecnologias I4.0. Essas ferramentas simplificam o projeto, a implementação e o teste de sistemas de manufatura, além de auxiliar na redução de custos de estocagem ao otimizar o manuseio de materiais (ABDULLAH *et al*., 2022; ABDULLAH *et al*., 2023).

Automação e Robótica Industrial (AIR) contribuem para a redução de custos ao promover a diminuição da taxa de defeitos e do desperdício (ABDULLAH *et al*., 2022).

O *Big Data Analytics* (BDA) possibilita que os fabricantes minimizem custos ao descobrir, processar e analisar vastos volumes de dados (ABDULLAH *et al*., 2022).

Os Sistemas Ciberfísicos (CPS) oferecem benefícios em tempo real relacionados à utilização de recursos e à eficiência de custos quando comparados a sistemas de produção tradicionais (SALAM, 2021).

Os sistemas de Internet das Coisas (IoT), ao incorporar algoritmos avançados de *machine learning*, podem assistir as indústrias na obtenção de um *trade-off* ideal entre eficiência e flexibilidade, e isto possibilita a redução de custos ao mesmo tempo em que aprimora as oportunidades de customização (GUPTA e GUPTA, 2021).

A Inteligência Artificial (IA), implementada por meio de tecnologias cognitivas, auxilia na redução de custos operacionais e de investimento de capital (SALAM, 2021).

2.3.2 Prioridade Competitiva Qualidade

A I4.0 permite às organizações alcançar níveis mais elevados de qualidade de produto e excelência operacional. A qualidade na I4.0 visa à conformidade com as especificações de *design* e ao atendimento ou superação das expectativas do cliente em termos de desempenho, confiabilidade e durabilidade (ABDULLAH *et al*., 2022; GUPTA e GUPTA, 2021). A tecnologia I4.0 transforma o controle de qualidade de um modelo reativo em um modelo proativo e preventivo.

Os Sistemas Ciberfísicos (CPS) são identificados como um habilitador-chave para a melhoria da qualidade (ABDULLAH *et al*., 2022; ABDULLAH *et al*., 2023). Eles permitem o monitoramento e o controle em tempo real dos processos de fabricação, o que garante consistência e contribui significativamente para reduzir as taxas de defeitos.

Automação e Robótica Industrial (AIR) melhoram a qualidade por meio de uma produção orientada pela precisão e pelos mecanismos robustos de redução de defeitos, com a minimização do erro humano (ABDULLAH *et al*., 2022).

Big Data Analytics (*BDA*) capacita as empresas a analisar vastos volumes de dados de produção; revela padrões ocultos que podem indicar potenciais problemas de qualidade antes que eles se agravem (ABDULLAH *et al*., 2022).

A conectividade e a integração de tecnologias I4.0 (IoT, CPS e BDA) são instrumentais na transformação dos sistemas de gestão da qualidade, com a promoção do monitoramento em tempo real e a detecção preditiva de falhas (ABDULLAH *et al*., 2022).

Adicionalmente, estudos empíricos confirmam que uma melhor qualidade na manufatura tem um impacto positivo no desempenho dos fornecedores da I4.0 (*i4.0SP*) (GUPTA e GUPTA 2021; SALAM, 2021).

2.3.3 Prioridade Competitiva Entrega

A Internet das Coisas (IoT) é fundamental para otimizar o processo de entrega, pois permite a comunicação e a interação em tempo real entre objetos inteligentes, o que é essencial para o rastreamento e o monitoramento contínuo de pedidos (ABDULLAH *et al*., 2022; ABDULLAH *et al*., 2023; SALAM, 2021; GUPTA e GUPTA, 2021).

Big Data Analytics (BDA) aprimora o desempenho de entrega ao fornecer *insights* aprofundados para a tomada de decisão sobre prazos e ao facilitar a detecção precoce de falhas para minimizar interrupções (ABDULLAH *et al*., 2022).

A Automação (AIR) contribui significativamente para o desempenho de entrega ao agilizar e otimizar toda a cadeia de entrega, desde o pedido até a distribuição eficiente (GUPTA e GUPTA, 2021; ABDULLAH *et al*., 2022; ABDULLAH *et al*., 2023).

Os Sistemas Ciberfísicos (CPS) desempenham um papel elementar; integram processos físicos com sistemas digitais para otimizar a produção e o fluxo de dados e suportam resultados de entrega eficientes (GUPTA e GUPTA, 2021; ABDULLAH *et al*., 2022; ABDULLAH *et al*., 2023).

2.3.4 Prioridade Competitiva Flexibilidade

A flexibilidade é uma prioridade crítica para a adaptação a condições de mercado dinâmicas e demandas de customização e é significativamente aprimorada pela I4.0. Ela abrange a capacidade de responder de forma rápida e com boa relação custo-benefício a mudanças (flexibilidade de máquina e de roteiro) (SALAM, 2021).

A Manufatura Aditiva (AM) é uma tecnologia de significativa influência na melhoria da flexibilidade. Ela é frequentemente vista como uma estratégia proativa que facilita a prototipagem rápida e a customização; permite ajustes rápidos para atender a demandas específicas (ABDULLAH *et al*., 2022). A AM é classificada como a principal tecnologia I4.0 para essa prioridade (ABDULLAH *et al*., 2023).

Os Sistemas Ciberfísicos (CPS) e a Integração de Sistemas são essenciais para alcançar a flexibilidade operacional (ABDULLAH *et al*., 2022; SALAM, 2021). Os CPS permitem a rápida reconfiguração e o ajuste dos processos de fabricação; reduzem o tempo de *setup* e melhoram a flexibilidade de mix e de volume (ABDULLAH *et al*., 2023).

A integração de IoT com CPS fomenta a rápida implementação de reconfigurações; ela aumenta a capacidade da organização de entregar produtos customizados e de oferecer linhas de produtos mais amplas (ABDULLAH *et al*., 2022; ABDULLAH *et al*., 2023).

Em síntese, CPS e IoT destacam-se como pilares transversais da Indústria 4.0 e promovem avanços consistentes nas dimensões essenciais da competitividade: redução de custos, melhoria da qualidade, agilidade na entrega e aumento da flexibilidade.

3 METODOLOGIA

Esta pesquisa adota uma abordagem exploratória e sequencial, estruturada em etapas interdependentes, com o intuito de desenvolver, fundamentar empiricamente e avaliar um modelo conceitual que explicite as interações entre as tecnologias habilitadoras da Indústria 4.0 e as prioridades competitivas da manufatura.

Este capítulo detalha o método geral da tese; demonstra a integração dos estudos que a compõem e prove a fundamentação teórica para os métodos específicos utilizados em cada etapa. O detalhamento minucioso dos procedimentos metodológicos busca garantir o rigor e a repetibilidade do trabalho.

3.1 Delineamento geral e sequenciamento da pesquisa

O método geral da tese é sequencial, articulado para responder à Questão de Pesquisa e atender o Objetivo Geral. A coerência da pesquisa é estabelecida por meio da correspondência biunívoca de cada artigo aos Objetivos Específicos (OEs) da tese. Para ilustrar essa integração, o sequenciamento da pesquisa é visualmente representado na Figura 3, que relaciona os OEs da tese, os artigos e as respectivas metodologias.

Figura 3 – Sequenciamento Metodológico da Tese

Fonte: a autora

3.2 Etapa I - Revisão Sistemática da Literatura

O Artigo 1, intitulado *"Manufacturing Strategy in Industry 4.0: A Conceptual Framework and Future Research Avenues",* atende o OE1 da tese. A revisão sistemática da literatura (RSL) é um método fundamental para aprofundar um tema na literatura e garantir o rigor, a transparência e a replicabilidade da pesquisa (Brignardello-Petersen *et al*., 2025).

A revisão sistemática da literatura conduzida neste estudo seguiu as diretrizes metodológicas propostas por Tranfield *et al*. (2003); ela contempla as etapas de planejamento, de execução e de elaboração do relatório, conforme o ilustrado na Figura 4.

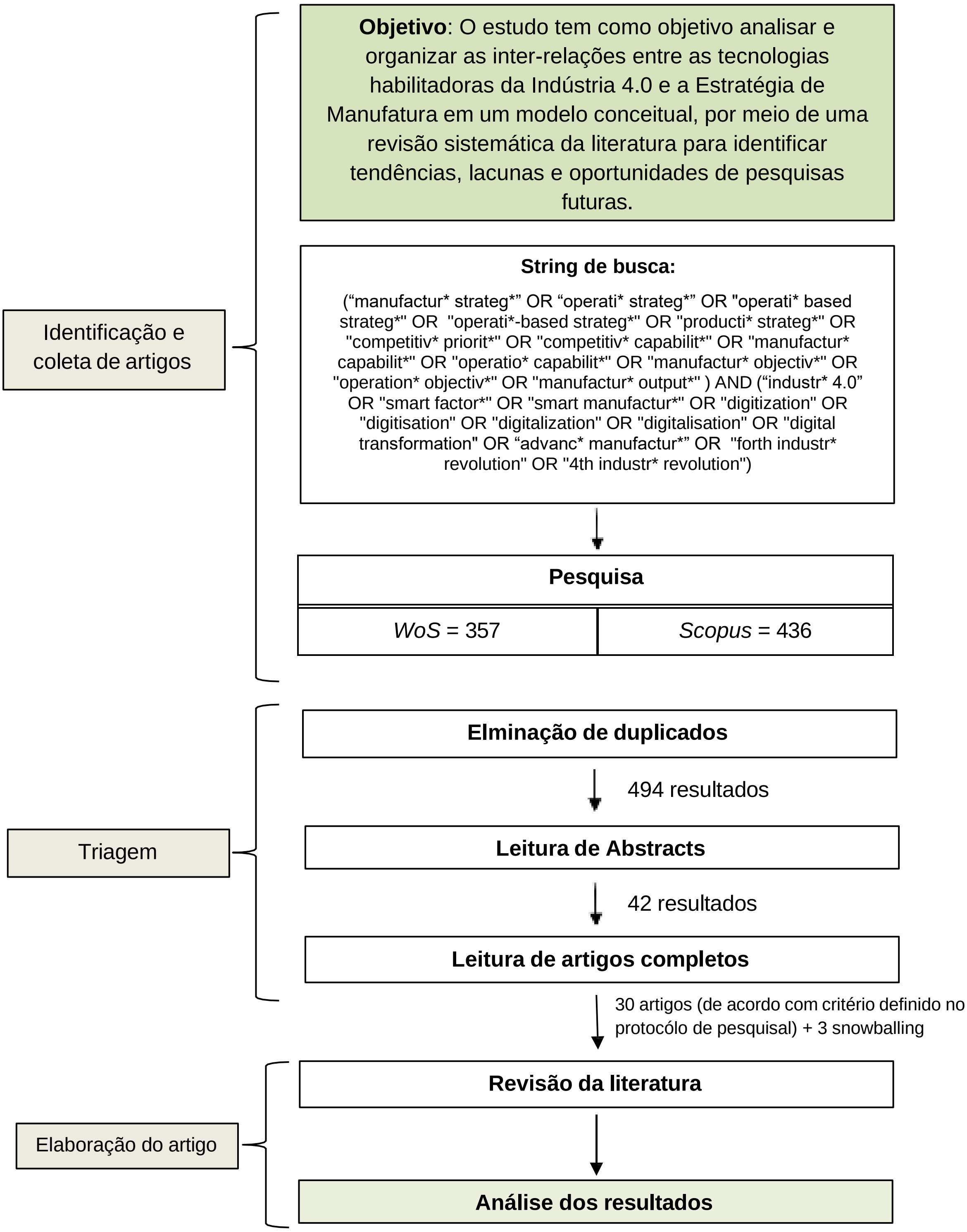
Contempla, então, especificamente,

i. Fontes de dados e estratégia de busca: a busca bibliográfica foi realizada nas bases *Web of Science* (*WoS*) e *Scopus*, reconhecidas por sua abrangência e rigor na indexação de artigos revisados por pares. Foram selecionados 33 artigos publicados entre 2019 e 2024, alinhados ao escopo temático da pesquisa;

ii. Critérios de inclusão e exclusão: para assegurar a qualidade e a relevância dos estudos analisados, foram adotados critérios específicos de seleção. Foram incluídos artigos acadêmicos publicados em periódicos científicos revisados por pares, redigidos em inglês, que abordassem conceitual ou empiricamente a relação entre as tecnologias habilitadoras da Indústria 4.0 e a estratégia de manufatura. Foram excluídos anais de conferências, capítulos de livros, artigos não submetidos à revisão por pares e duplicatas;

iii. Triagem e refinamento do corpus: a estratégia de busca foi deliberadamente ampla; ela incorporou termos como *digitization* e *digital transformation*, com o objetivo de capturar sinônimos e variações conceituais relevantes à evolução da Indústria 4.0. Embora essa abordagem tenha ampliado o escopo inicial, a triagem rigorosa — baseada na leitura integral dos textos e na análise da aderência temática — assegurou que o foco permanecesse centrado na estratégia de produção e nas tecnologias habilitadoras da I4.0. O refinamento metodológico aplicado nesta etapa foi essencial para garantir a consistência e a relevância do *corpus* final;

Figura 4 - Procedimento de Revisão Sistemática da Literatura



Fonte: a autora

iv. Análise dos resultados: a análise dos 33 artigos selecionados foi conduzida por meio de codificação temática; ela considerou os constructos centrais da pesquisa: tecnologias habilitadoras da Indústria 4.0 e estratégia de manufatura. Os estudos foram classificados segundo a abordagem metodológica, o tipo de contribuição (conceitual ou empírica) e o escopo tecnológico abordado. A triangulação entre essas categorias permitiu identificar padrões de associação entre tecnologias habilitadoras da I4.0, prioridades competitivas e áreas de decisão da manufatura, além de evidenciar lacunas na literatura, especialmente em relação à integração sistêmica destas tecnologias na área operacional.

3.3 Etapa II - Estudo de casos

O Artigo 2, "*Enabling technologies of Industry 4.0 and manufacturing competitive priorities: An exploratory multiple-case study"*, foi elaborado para atender o Objetivo Específico 2 (OE2). Por meio dele, se quis estender e testar empiricamente o modelo conceitual proposto no Artigo 1, a fim de explicitar os mecanismos de integração e as contribuições estratégicas das tecnologias habilitadoras da I4.0 para a configuração das prioridades competitivas da manufatura.

Neste sentido, o Artigo 2 teve como objetivo principal desenvolver e propor um *framework* conceitual, o qual é empiricamente fundamentado em múltiplos estudos de caso exploratórios, que elucidam os mecanismos de interconexão e as contribuições prioritárias da I4.0 para as prioridades competitivas da manufatura em diversos contextos operacionais

O estudo utilizou um delineamento exploratório de Estudo de Múltiplos Casos, e esta modalidade de estudo de caso é apropriada para investigar a complexidade e a dinâmica de um fenômeno em seu contexto natural (EISENARDT, 1989).

A escolha do método é fundamentada na sua capacidade de construir teoria a partir da pesquisa empírica (*theory building from case study research*), modalidade referenciada na literatura (RIDDER, 2017). Tal capacidade permite o desenvolvimento de um modelo conceitual que não seja apenas descritivo, mas que demonstre o papel do escopo gerencial como mecanismo integrativo (o como) das relações entre as tecnologias habilitadoras da I4.0 e as prioridades competitivas da manufatura.

A amostra objeto de estudo constituiu-se de quatro empresas manufatureiras com operação no Brasil. A coleta de dados primários se deu por meio de entrevistas semiestruturadas com múltiplos informantes-chave (gerentes e líderes operacionais) em cada empresa, complementadas por fontes secundárias (relatórios e websites) para triangulação.

Já a análise dos dados utilizou a Metodologia Gioia, um processo sistemático *bottom-up* que garante o rigor qualitativo e a rastreabilidade da teoria construída (GIOIA *et al*., 2013). Este processo envolveu

i. Codificação de Primeira Ordem: codificação inicial descritiva, o que preservou a terminologia original dos participantes;

ii. Temas de Segunda Ordem: abstração conceitual, o que identificou padrões e ligou os códigos a construtos teóricos;

iii. Dimensões Agregadas: desenvolvimento de temas de nível superior que representam as implicações estratégicas da I4.0 nas Prioridades Competitivas.

3.4 Etapa III – Avaliação por painel de especialistas

O Artigo 3, "*A Delphi study on the extended manufacturing competitive priorities framework in the Industry 4.0 era"*, foi concebido para atender o OE3 e utilizou o Painel de Especialistas (Método *Delphi*), com o objetivo de avaliar, discutir e refinar o modelo conceitual.

O Método *Delphi*, uma técnica de pesquisa de natureza exploratória, é recomendado para problemas com incerteza e teoria incompleta. O mesmo método baseia-se na opinião de especialistas para buscar consenso por meio de (1) respostas anônimas via questionário formal; (2) interação e *feedback* controlado; (3) análise estatística dos resultados (OKOLI e PAWLOW, 2004).

Foi utilizada uma amostragem intencional para selecionar especialistas. O painel foi dividido em dois grupos:

• Praticantes: com experiência profissional em gestão e atuação em empresas com iniciativas ou fornecedoras de tecnologias da I4.0.

• Acadêmicos: com titulação de doutorado ou pós-doutorado e linha de pesquisa sobre I4.0 e áreas afins à Engenharia de Produção.

O painel final foi composto por seis especialistas (N=6). O rigor da seleção é demonstrado pelo alto nível de qualificação: todos os participantes possuíam o mais alto nível de formação acadêmica (Doutorado ou Pós-Doutorado). A experiência profissional total variava até 38 anos, e a experiência referida é específica ao tema de Indústria 4.0 e/ou Manufatura Avançada de até 25 anos.

O processo *Delphi* seguiu fases que incluíram a formulação e a submissão das questões, o ranqueamento das respostas e o fechamento com convergência. O estudo utilizou duas rodadas. A Rodada 1 permitiu a avaliação inicial das assertivas e a coleta de comentários qualitativos, essenciais para identificar ambiguidades e sugestões de aprimoramento. Já a Rodada 2 reavaliou formalmente as assertivas que exigiam maior clareza conceitual após a incorporação das sugestões dos especialistas

O protocolo de pesquisa detalhou que o processo visava ao alcance do Índice *Cronbach* (valor 0,7) e um nível de concordância superior a 75% para as assertivas, com a garantia da consistência interna e do consenso informado.

4 RESULTADOS E DISCUSSÃO

O objetivo deste capítulo é apresentar e discutir, de forma integrada e sequencial, os resultados obtidos nos artigos que compõem a tese. A articulação das evidências visa a demonstrar a progressão do conhecimento desde a base teórica até a validação do modelo conceitual. O desenvolvimento da tese segue um encadeamento lógico, no qual os artigos se inter-relacionam para atingir o objetivo geral da tese, conforme ilustrado na Figura 5.

Figura 5 – Contribuição de cada artigo para o atendimento do OG da tese

Fonte: a autora

Dando início à discussão, a Seção 4.1 apresenta os achados do Artigo 1 (Revisão Sistemática da Literatura), que estabeleceu o fundamento teórico necessário e propôs o modelo conceitual preliminar.

4.1 Artigo 1: Revisão Sistemática da Literatura

O Artigo 1, intitulado *“Manufacturing strategy in Industry 4.0: A conceptual framework and future research avenues”*, consiste em uma Revisão Sistemática da Literatura (RSL), publicada na *Management Review Quarterly* (Fator de Impacto 9,0; *CiteScore* 6,3). A pesquisa seguiu as diretrizes metodológicas de Tranfield *et al.*

(2003) e avaliou 33 artigos publicados entre 2019 e 2024, oriundos das bases *Web of Science* e *Scopus*. Esse rigor na seleção e na análise do *corpus* assegurou a consistência e a relevância da base conceitual para o desenvolvimento do *framework* preliminar.

O artigo cumpriu o papel de mapear a literatura e identificar o estado da arte. Para tal, examinou a interseção entre a I4.0 e a Estratégia de Manufatura (EM) e analisou o impacto das tecnologias habilitadoras sobre prioridades competitivas e áreas de decisão estratégicas. Os achados da RSL indicaram que a I4.0 representa mais do que um aprimoramento tecnológico; ela é uma força transformadora que exige a reavaliação da estratégia de manufatura.

As prioridades clássicas — custo, qualidade, entrega e flexibilidade — permanecem centrais, mas o estudo demonstrou empiricamente a expansão do escopo estratégico das organizações ao consolidar prioridades emergentes. O artigo constatou o crescimento da Inovatividade, da Servitização e da Sustentabilidade como novas dimensões competitivas na era digital.

Para mais, o modelo conceitual preliminar elaborado no artigo 1 associou a I4.0 à estratégia de manufatura; explorou como tais tecnologias habilitadoras podem ser implementadas de forma estratégica para alcançar prioridades operacionais desejadas. Os resultados evidenciaram que as inter-relações entre as tecnologias habilitadoras da I4.0 e as prioridades competitivas são multifacetadas, de forma que o sucesso estratégico da I4.0 não se deve apenas à adoção tecnológica (o 'quê'), mas ao seu alinhamento com o propósito organizacional e com a complexidade do ambiente operacional.

Por isso, o *framework* preliminar introduziu a perspectiva dual das interações; abrangeu o escopo tecnológico (as tecnologias habilitadoras em si) e o escopo gerencial (a integração de sistemas de informação e a otimização de recursos). A identificação desses dois escopos ressaltou a necessidade de aprofundamento empírico para explicitar o Escopo Gerencial como o mecanismo mediador que orquestra e traduz o potencial da I4.0 em desempenho estratégico.

O Quadro 4 sintetiza destaques e contribuições centrais do artigo 1.

Quadro 4 – Síntese do Artigo 1

Artigo 1	***Manufacturing strategy in Industry 4.0: A conceptual framework and future research avenues***
Estrutura	O artigo está estruturado em cinco seções principais. A Seção 1 apresenta uma introdução ao tema. A Seção 2 discute as bases conceituais da I4.0 e dos constructos da Estratégia de Manufatura (EM). A Seção 3 detalha a metodologia da revisão sistemática da literatura, com a inclusão das etapas e dos procedimentos de busca. A Seção 4 apresenta a análise descritiva e discute as implicações das tecnologias da I4.0 na EM; ela abrange prioridades competitivas, áreas de decisão e o processo de formulação estratégica e se conclui com o *framework* conceitual e as perspectivas para pesquisas futuras. A Seção 5 apresenta as contribuições e limitações do estudo.
Resumo	A Indústria 4.0 representa uma mudança de paradigma na gestão da manufatura, caracterizada pela integração de sistemas ciberfísicos, Internet das Coisas e outras tecnologias avançadas aos processos produtivos. Essa transformação exige a reavaliação da estratégia de manufatura para aproveitar essas tecnologias e melhorar o desempenho organizacional. Este artigo apresenta uma revisão sistemática da literatura que examina a interseção entre Indústria 4.0 e estratégia de manufatura; ele analisa o impacto das tecnologias da Indústria 4.0 sobre as prioridades competitivas e áreas de decisão estratégica na função de manufatura. Foram analisados 33 artigos provenientes das bases de dados *Web of Science* e *Scopus*, publicados entre 2019 e 2024. Os resultados indicam que, embora as prioridades competitivas clássicas — custo, qualidade, entrega e flexibilidade — continuem centrais à estratégia de manufatura, há uma ênfase crescente em prioridades emergentes, como inovação, serviços e sustentabilidade ambiental. Além disso, o artigo apresenta um modelo conceitual que associa a Indústria 4.0 à estratégia de manufatura; explora como as tecnologias habilitadoras da Indústria 4.0 podem ser implementadas estrategicamente para alcançar as prioridades operacionais desejadas. O estudo oferece implicações gerenciais; fornece *insights* para tomadores de decisão que buscam aproveitar a transformação digital para otimizar os resultados da manufatura. Adicionalmente, propõe-se uma agenda de pesquisa, que destaca a necessidade de validação empírica em diferentes contextos industriais. De forma geral, este estudo contribui para uma compreensão mais profunda da relação evolutiva entre Indústria 4.0 e estratégia de manufatura; ele oferece subsídios tanto para acadêmicos, quanto para profissionais que enfrentam os desafios e as oportunidades da quarta era industrial.
Palavras chave	Revisão da literatura. Estratégia operacional. Indústria 4.0. Dimensões competitivas. Era digital.
Contribuição para o OG da tese	Fornece a **Fundamentação Teórica** do *framework* final. Traz o entendimento aprofundado da relação entre I4.0 e Estratégia de Manufatura; é a fonte primária de embasamento teórico necessária para a construção do modelo conceitual final.
Contribuição para os OEs	**OE1:** examinar as interações entre I4.0 e Estratégia de Manufatura, com a análise do impacto das tecnologias habilitadoras nas prioridades competitivas para propor um modelo conceitual teórico.
Foco do artigo	**Pergunta de pesquisa:** Como as tecnologias habilitadoras da Indústria 4.0 interagem com os elementos da estratégia de manufatura, com a inclusão de prioridades competitivas, de áreas de decisão e de processos de formulação estratégica?

	Objetivo do artigo: Compreender, de maneira sistemática, como as tecnologias habilitadoras da Indústria 4.0 influenciam as prioridades competitivas e as áreas de decisão no âmbito das estratégias de manufatura, culminando na construção de um *framework* conceitual capaz de orientar simultaneamente o avanço teórico e a implementação prática.
Resultados	As prioridades competitivas clássicas (custo, qualidade, entrega e flexibilidade) permanecem centrais. Contudo, verifica-se uma ênfase crescente em prioridades emergentes, destacando-se inovação, servitização e sustentabilidade. Foi introduzido um modelo conceitual que associa as tecnologias habilitadoras da I4.0 às prioridades competitivas da manufatura. Esse *framework* indica que as inter-relações entre prioridades competitivas e tecnologias habilitadoras da I4.0 abrangem tanto aspectos gerenciais, quanto tecnológicos. Sistemas Ciberfísicos (CPS) e Internet das Coisas (IoT) destacam-se como tecnologias habilitadoras transversais, com impacto positivo nas quatro prioridades competitivas tradicionais. A aplicação das tecnologias habilitadoras da I4.0 impacta significativamente as áreas de decisão (estruturais e infraestruturais) da EM.

Fonte: adaptado de Ribeiro *et al.* (2025)

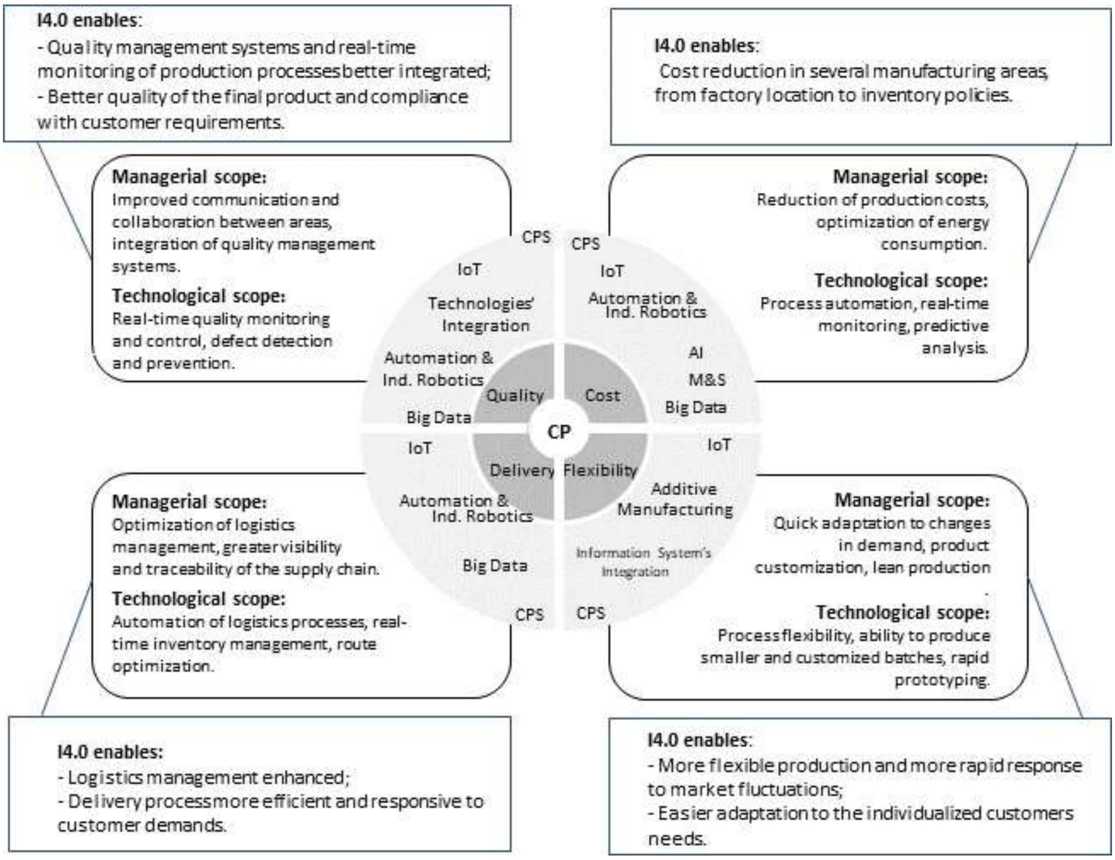
É fundamental apresentar uma síntese das interações identificadas entre as tecnologias habilitadoras da I4.0 e as prioridades competitivas clássicas, ilustradas no Modelo 1.0 (Figura 6).

Em relação à prioridade competitiva Custo, as tecnologias da I4.0 viabilizam a produção de itens eficientes e customizados a um custo razoável. O estudo destaca o papel de tecnologias, como a Modelagem e a Simulação (M&S), que simplificam o projeto e otimizam o manuseio de materiais, o que auxilia na redução de custos de estocagem. O *Big Data Analytics* (*BDA*) minimiza custos ao processar vastos volumes de dados, enquanto a Automação e a Robótica Industrial (AIR) contribuem diretamente para a redução de custos ao diminuir a taxa de defeitos e desperdícios. Adicionalmente, Sistemas Ciberfísicos (CPS) e Inteligência Artificial (IA) oferecem benefícios em tempo real e auxiliam na redução de custos operacionais e de investimento de capital.

Para a prioridade Qualidade, a I4.0 permite que as organizações atinjam níveis mais elevados de excelência operacional e de qualidade de produto. A qualidade na I4.0 é definida pela conformidade com as especificações - desempenho, confiabilidade e durabilidade. A implementação das tecnologias transforma o controle de qualidade; de modo que o mesmo é levado a migrar de um modelo reativo para um modelo proativo e preventivo.

No que concerne à prioridade Entrega, a I4.0 suporta o fornecimento pontual e eficiente de bens e serviços, com foco na redução de *lead time*. A Internet das Coisas (IoT) é relevante para otimizar o processo, ao permitir a comunicação em tempo real e o monitoramento contínuo de pedidos. Similarmente, os Sistemas Ciberfísicos (CPS) integram processos físicos com sistemas digitais para otimizar a produção e o fluxo de dados e suportam resultados de entrega eficientes.

Figura 6 – Modelo 1.0



Fonte: Ribeiro *et al*. (2025)

A Manufatura Aditiva (AM) se destacou como a tecnologia mais influente para a melhoria da prioridade Flexibilidade; é vista como uma estratégia proativa que facilita a prototipagem rápida e a customização. A flexibilidade é crítica para a adaptação a condições de mercado dinâmicas e demandas específicas de customização.

Em uma síntese transversal, o Artigo 1 identificou que os Sistemas Ciberfísicos (CPS) e a Internet das Coisas (IoT) consistentemente emergiram como tecnologias habilitadoras transversais, o que demonstra contribuição positiva em todas as quatro prioridades competitivas clássicas.

Para mais, os achados da Revisão Sistemática consolidaram que as prioridades competitivas clássicas (Custo, Qualidade, Entrega e Flexibilidade) permanecem essenciais, mas o estudo revelou uma expansão do escopo estratégico. Emergem a Inovatividade, a Servitização e a Sustentabilidade como prioridades competitivas de primeira ordem na era digital. Um ponto central da discussão foi a proposição da Perspectiva Dual, que diferencia o Escopo Tecnológico (as ferramentas – o ‘o que’) do Escopo Gerencial (os processos de decisão – o ‘como’), identificando este último como o mecanismo de integração entre tecnologia e estratégia.

As sugestões de pesquisas futuras delineadas no item 4.7 do artigo serviram como o fio condutor metodológico para o desenvolvimento das etapas subsequentes desta tese, de modo que integração se deu da seguinte forma:

i. Da Abstração à Empiria: O artigo identificou que a maioria dos modelos existentes é predominantemente teórica e carece de testes em situações reais. Em resposta direta a essa lacuna, a presente tese avançou para o Estudo de Múltiplos Casos (Artigo 2), visando transpor a teoria para a realidade industrial brasileira.
ii. Contingência Estratégica e Heterogeneidade: O Artigo 1 questionou se modelos genéricos seriam aplicáveis a todos os contextos industriais. Isso motivou a investigação de como a lógica de produção influencia a adoção tecnológica.
iii. O Fator Humano e a Gestão: A necessidade de investigar o impacto da I4.0 na gestão de recursos humanos foi sinalizada no Artigo 1 como uma fronteira do conhecimento. Esse elemento foi incorporado na tese através do refinamento do Escopo Gerencial, conforme discutido no Artigo 3, que incluiu explicitamente a segurança do trabalho e o desenvolvimento de competências no mecanismo de integração.
iv. Redefinição do Paradigma de Trade-off: O artigo propôs investigar como a sinergia tecnológica reduz os conflitos tradicionais entre metas operacionais. Esta tese utilizou essa provocação para explorar como a I4.0 atua de forma transversal, impactando múltiplas prioridades simultaneamente através, por exemplo, de Sistemas Ciberfísicos (CPS) e IoT.

Desta forma, o Artigo 1 não é apenas um resultado isolado, mas o diagnóstico crítico que revelou os mecanismos internos de integração tecnológica. A transição para o item 4.2 representa, portanto, o movimento de resolução das incertezas e desafios apontados no item 4.7 daquela publicação original.

4.2 Artigo 2: Estudo de Múltiplos Casos

O Artigo 2, intitulado "*Enabling technologies of Industry 4.0 and manufacturing competitive priorities: An exploratory multiple-case study*", atende o Objetivo Específico 2 (OE2) e é a etapa de fundamentação empírica da tese.

O mesmo artigo foi planejado para estender, agregando base empírica, o modelo conceitual preliminar proposto no Artigo 1. Ele alcança o OE2 ao apresentar:

1. Fundamentação Empírica do Modelo: o estudo empregou um delineamento exploratório de Estudo de Múltiplos Casos em quatro empresas manufatureiras brasileiras. A escolha deste método é apropriada para investigar a complexidade de um fenômeno em seu contexto natural e para a construção de teoria a partir da pesquisa empírica (*theory building from case study research*);

2. Elucidação dos Mecanismos de Integração: o principal objetivo do Artigo 2 foi desenvolver um *framework* que elucide os mecanismos de integração. Através da análise dos dados, o artigo demonstrou o mecanismo (o "como") da relação entre as tecnologias da I4.0 e as prioridades competitivas da manufatura. Este mecanismo é classificado como o Escopo Gerencial, que engloba as práticas e os processos organizacionais necessários para traduzir o potencial tecnológico em desempenho estratégico.

O Quadro 5 sumariza os dados do artigo 2.

Quadro 5 – Síntese do Artigo 2

Artigo 2	***Enabling technologies of Industry 4.0 and manufacturing competitive priorities: An exploratory multiple-case study***
Estrutura	O artigo é estruturado em seis seções principais: seção 1, Introdução, apresenta o problema de pesquisa e os objetivos; seção 2, Revisão de Literatura, revisa os fundamentos teóricos dos impactos estratégicos da implementação das tecnologias habilitadoras da I4.0 nas prioridades competitivas da manufatura; seção 3, Métodos, detalha o delineamento da pesquisa qualitativa, os procedimentos metodológicos do estudo de múltiplos casos e a utilização da Metodologia Gioia; seção 4 apresenta os resultados empíricos da análise e discorre sobre os desdobramentos do *framework* conceitual para cada uma das prioridades competitivas; seção 5, discussão, discute os achados à luz das perspectivas teóricas existentes e as implicações para a adoção da I4.0; seção 6 sumariza as principais contribuições, reconhece as limitações e sugere futuras avenidas de pesquisa.
Resumo	O aproveitamento bem-sucedido da I4.0 depende de um alinhamento multidimensional entre habilitadores tecnológicos, organizacionais e gerenciais. No entanto, pouca atenção tem sido dedicada a compreender como essas tecnologias influenciam a orientação estratégica das operações de manufatura. Cabe também dizer que ainda falta clareza teórica sobre como as empresas utilizam estrategicamente as tecnologias da I4.0 para buscar resultados competitivos específicos, de acordo com seus contextos operacionais. Este estudo aborda essa lacuna crítica ao investigar os mecanismos de integração e as contribuições prioritárias que surgem da implementação das tecnologias habilitadoras da I4.0. Trata ainda de que maneiras essas tecnologias influenciam a configuração das prioridades competitivas (PCs). Nesse sentido, o objetivo é desenvolver e propor um *framework* conceitual empiricamente fundamentado em estudos de caso múltiplos exploratórios. Empregamos um desenho de pesquisa qualitativa baseado em estudo de caso múltiplo de quatro empresas brasileiras de manufatura que atuam em distintos setores industriais. Os resultados oferecem duas contribuições principais. Primeiro, o estudo demonstra empiricamente que a adoção da I4.0 é estrategicamente contingente, configurada de forma diferente na dependência da lógica de produção e de orientação estratégica de cada empresa. Segundo, propõe um *framework* conceitual abrangente que expande as PCs tradicionais ao incorporar dimensões empiricamente estabelecidas de Sustentabilidade, Inovação e Servitização. Crucialmente, o *framework* articula a realização estratégica da vantagem competitiva por meio de uma perspectiva dupla — o Escopo Tecnológico e o Escopo Gerencial. O Escopo Gerencial é identificado como o mecanismo crítico de integração que traduz o potencial tecnológico em desempenho estratégico, o que demonstra que os resultados de desempenho não são alcançados apenas pela adoção tecnológica, mas pelo alinhamento intencional dessas tecnologias com a lógica de produção e os objetivos organizacionais. O *framework* conceitual fornece uma compreensão refinada para profissionais e pesquisadores; ele enfatiza a importância de orquestrar estrategicamente tecnologias, pessoas e processos para criar caminhos resilientes e diferenciados rumo à competitividade.
Palavras chave	Dimensões Competitivas da Manufatura. Transformação Digital. Sustentabilidade. Servitização. Inovatividade.

Contribuição para o OG da tese	Desenvolve a **Fundamentação Empírica**; garante que o modelo não seja apenas descritivo, mas que demonstre como se dão as relações entre as tecnologias habilitadoras da I4.0 e as prioridades competitivas da manufatura.
Contribuição para os OEs	**OE2:** Estender e testar empiricamente o modelo conceitual para explicitar os mecanismos de interação e as contribuições estratégicas das tecnologias habilitadoras da I4.0 para a configuração das prioridades competitivas da manufatura.
Foco do artigo	**Perguntas de pesquisa:** Quais são os mecanismos de integração e as contribuições prioritárias que surgem da implementação de tecnologias habilitadoras da Indústria 4.0? De que maneiras essas tecnologias influenciam a configuração das prioridades competitivas na manufatura? **Objetivo do artigo:** Desenvolver e propor um *framework* conceitual, empiricamente fundamentado em múltiplos estudos de caso exploratórios, que articule os mecanismos de integração e as contribuições prioritárias das tecnologias habilitadoras da Indústria 4.0 com as prioridades competitivas da manufatura.
Resultados	1. O modelo conceitual (*framework*) é estrategicamente contingente; ele depende da lógica de produção e da orientação estratégica da empresa. 2. O *framework* estendido incorpora Sustentabilidade, Inovatividade e Servitização como Prioridades Competitivas. 3. O desempenho é alcançado por meio da perspectiva dual (Escopo Tecnológico e Escopo Gerencial), e este último é o mecanismo de integração determinante.

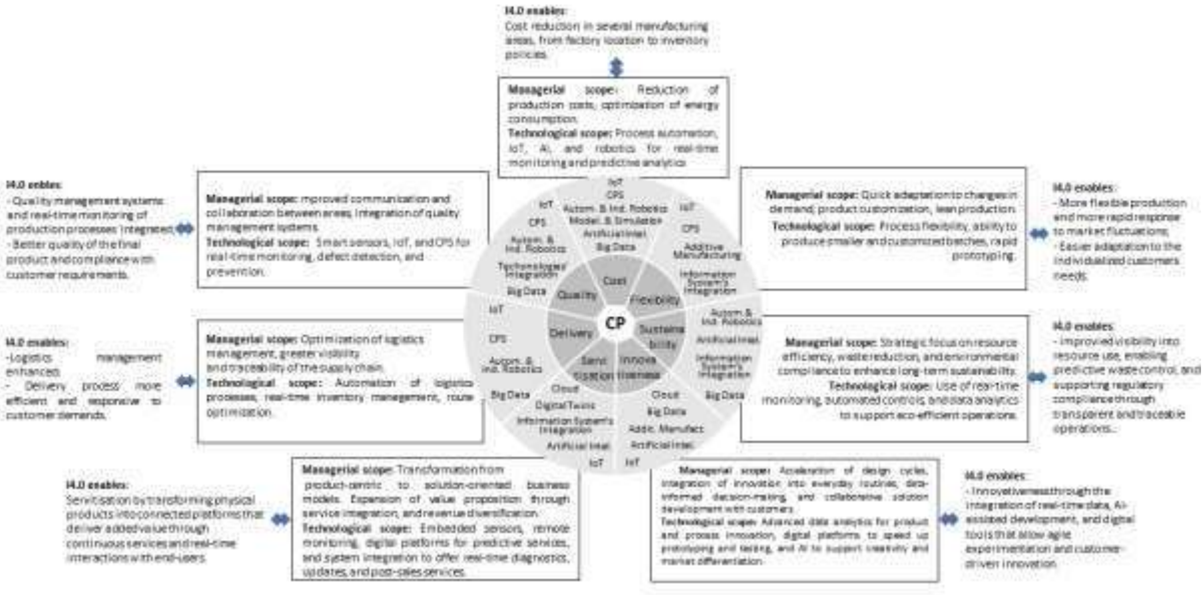
Fonte: a autora

Os achados do Artigo 2 trouxeram contribuições robustas para a teoria da Estratégia de Manufatura na era digital, uma vez que o estudo indutivo revelou sete dimensões agregadas que compõem o escopo estratégico da manufatura: as prioridades clássicas (Custo, Qualidade, Entrega e Flexibilidade) e as prioridades emergentes (Sustentabilidade, Inovatividade e Servitização).

A inclusão destas últimas três como prioridades competitivas da manufatura é uma contribuição teórica primária, pois demonstra empiricamente uma transformação evolucionária no *framework* de prioridades competitivas, conforme Modelo 2.0 (Figura 7).

Para mais, o *framework* proposto no Artigo 2 enfatiza a perspectiva dual - Escopo Tecnológico (as tecnologias) e Escopo Gerencial (práticas gerenciais, coordenação, capacidade de resposta), e isto reforça que o desempenho é impulsionado pelo alinhamento dessas tecnologias com o intento organizacional. Neste sentido, o Artigo 2 tem contribuição essencial para a construção do *framework* final e liga o arcabouço teórico (Artigo 1) à validação (Artigo 3).

Figura 7 – Modelo 2.0



Fonte: a autora

4.3 Artigo 3: Avaliação e Validação por Painel de Especialistas

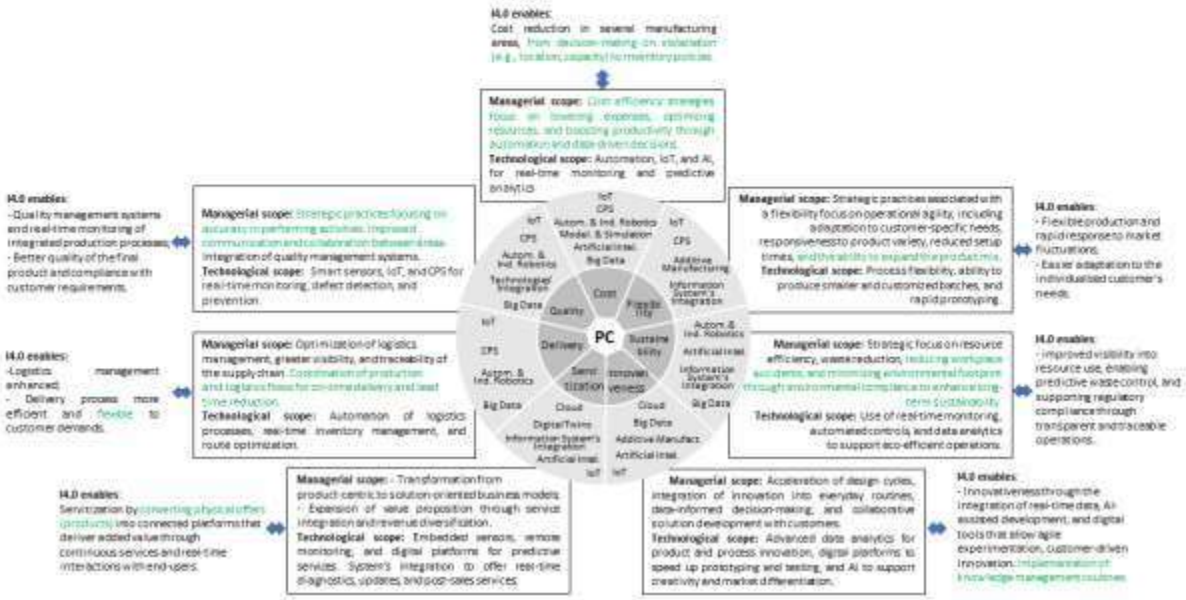
O Artigo 3, "*A Delphi study on the extended manufacturing competitive priorities framework in the Industry 4.0 era",* etapa final do delineamento sequencial da tese, consistiu na submissão do modelo conceitual, fundamentado teoricamente (Artigo 1) e empiricamente (Artigo 2), à validação de especialistas, conforme previsto no OE3**.** Um Painel de Especialistas (Método *Delphi*) foi utilizado para avaliar, discutir e refinar o *framework* proposto.

O Painel *Delphi* foi composto por seis especialistas (N = 6) com alta qualificação, todos com nível de formação acadêmica de Doutorado ou Pós-Doutorado e significativa experiência profissional (até 38 anos) e específica no tema de Indústria 4.0 e Manufatura Avançada (até 25 anos). A participação incluiu três especialistas acadêmicos (EA), que atuam como professores pesquisadores, e três especialistas praticantes (EP), na posição de diretores executivos e de Manufatura, o que garante uma avaliação que contemplou tanto o rigor teórico, quanto a aplicabilidade de mercado.

O protocolo de pesquisa visou ao alcance de um nível de concordância superior a 75% para as assertivas, patamar que foi amplamente atingido na maioria das prioridades competitivas, com muitas assertivas em 100% ou 83% de concordância nas prioridades Custo, Qualidade e Sustentabilidade, por exemplo.

O rigor do processo *Delphi*, realizado em duas rodadas, permitiu a incorporação de sugestões qualitativas cruciais, o que resultou no Modelo 3.0 (Final, Validado por Especialistas), ilustrado na Figura 8**.** Os principais refinamentos e discussões focaram em aprimorar a precisão do Escopo Gerencial e a do Escopo Tecnológico em relação às sete prioridades competitivas da manufatura.

Figura 8 – Modelo 3.0



Fonte: a autora

O painel, em geral, concordou que o framework proposto está “muito bem estruturado”. O conceito de que as tecnologias habilitadoras da I4.0 “não apenas contribuem, mas são essenciais para atingir níveis de competitividade da manufatura”. O valor do Alpha de Cronbach para a consistência interna no estudo Delphi, utilizando as 23 afirmações, é de aproximadamente 0,88. Esse resultado indica um nível de consistência interna classificado como “bom” a “muito bom”, superando significativamente o limite de 0,7 estabelecido para a confiabilidade do instrumento (George; Mallery, 2003), o que sugere que os itens do questionário estão medindo de forma coesa o construto subjacente, ou seja, a validade do framework conceitual.

O Quadro 6 apresenta aspectos relevantes do Artigo 3.

Quadro 6 – Síntese do Artigo 3

Artigo 3	***A Delphi Study on the Extended Manufacturing Competitive Priorities Framework in the Industry 4.0 Era***
Estrutura	A Introdução estabelece a necessidade de validar o modelo conceitual derivado de pesquisa empírica. A seção 2, de Fundamentação Teórica, apresenta o modelo conceitual que serve como *input* para o estudo *Delphi*. A seção seguinte, Metodologia, detalha a escolha e o processo do Método *Delphi*; explicita o rigor estatístico e a estratégia de amostragem por conveniência (*purposive sampling*). A Seção de Resultados apresenta os achados quantitativos (consenso/concordância) e os ajustes qualitativos por prioridade competitiva. Na seção 5, Discussão, analisa-se a validação da Perspectiva Dual e da Contingência Estratégica e se exprimem as contribuições para a teoria e a prática gerencial. Finalmente, a seção de Conclusão reafirma o atingimento do objetivo do artigo.
Resumo	Utilizou-se o Método *Delphi* em duas rodadas, uma técnica, exploratória adequada para buscar consenso em temas com incerteza. O painel foi composto por seis especialistas (N=6) com alta titulação acadêmica e experiência significativa em Manufatura Avançada. O rigor metodológico incluiu a medição de convergência por meio de análise estatística. Para isto, exigi-se um nível de concordância superior a 75%. Os resultados demonstraram alto consenso, com o painel na confirmação de que o *framework* está *super bem estruturado* e serve como *a base conceitual para se investigar as relações* entre I4.0 e as prioridades competitivas da manufatura. Crucialmente, o processo de *feedback* permitiu refinamentos conceituais críticos. A validação externa confirma a robustez do modelo; fortalece a tese central de que o sucesso da I4.0 é estrategicamente contingente; depende do Escopo Gerencial como mecanismo de integração. O *framework* final oferece uma referência validada para o planejamento estratégico e a melhoria da competitividade na era digital.
Palavras chave	Validação. Pesquisa *Dephi*. *Framework* Conceitual. Contingência Estratégica.
Contribuição para o OG da tese	Avalia, discute e refina o ***framework*** conceitual proposto; fortalece sua aplicabilidade prática em cenários reais de manufatura; garante que o modelo final esteja fundamentado teorica e empiricamente e seja validado por especialistas**.**
Contribuição para os OEs	**OE3:** Valida o modelo conceitual estendido por meio da avaliação de especialistas acadêmicos e profissionais; incorpora as sugestões dos especialistas para refinar o modelo conceitual.
Foco do artigo	**Perguntas de pesquisa:** Qual é o grau de validade, robustez e aplicabilidade do modelo conceitual estendido, conforme a avaliação e o consenso de especialistas acadêmicos e profissionais? Quais ajustes conceituais são requeridos para o refinamento final do *framework*? **Objetivo do artigo:** Validar o modelo conceitual estendido por meio da avaliação de acadêmicos e profissionais e incorporar as sugestões dos especialistas para refinar o modelo conceitual.
Resultados	A pesquisa alcançou seu objetivo ao validar e refinar o modelo conceitual estendido, ao utilizar um painel de seis especialistas (N=6) com alta titulação, o que trouxe alto nível de concordância. O *framework* foi validado com forte consenso; foi considerado *bem estruturado* e essencial para *investigar as relações* entre I4.0 e as prioridades competitivas da manufatura. O consenso reforçou a validade da Perspectiva Dual; confirmou o Escopo Gerencial como o mecanismo de integração. Desta forma, o modelo final comprovou-se teoricamente bem

	construído, empiricamente fundamentado e formalmente validado por especialistas.

Fonte: a autora

Deste modo, o Artigo 3 proporcionou a validação externa do modelo; efetivou a validade da Perspectiva Dual e a natureza estrategicamente contingente da I4.0. Adicionalmente, o consenso obtido em torno dos refinamentos do Escopo Gerencial confirma sua relevância como mecanismo de integração. Tal mecanismo evidencia que o desempenho estratégico não é alcançado apenas pela adoção tecnológica. É alcançado também pelo alinhamento intencional dessas tecnologias com a lógica de produção e com a intenção organizacional.

Para mais, a validação estatística e o consenso sobre as prioridades competitivas emergentes (Sustentabilidade, Inovatividade e Servitização) legitimaram sua inclusão no *framework* final como prioridades de primeira ordem. O debate sobre Servitização, que culmina no ajuste do Escopo Gerencial, garantiu que o modelo refletisse as limitações práticas e de mercado para a plena transição para serviços.

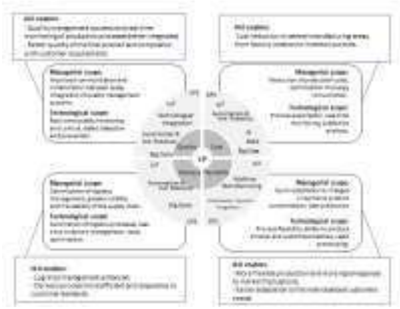
O sucesso na obtenção do consenso e a incorporação dos refinamentos conceituais validam o *framework* como a proposta final da tese; explicita como a implementação das tecnologias habilitadoras da I4.0 influencia e configura a reorganização estratégica da manufatura.

4.4 Trajetória Evolutiva do Modelo Conceitual

A construção do Modelo Conceitual Final (*framework*) desta tese resultou de um delineamento de pesquisa sequencial e integrada, conforme ilustrado na Figura 9, composto por três etapas (Artigos 1, 2 e 3). Esta seção descreve o desenvolvimento progressivo do modelo; destaca as contribuições incrementais de cada etapa e denota como os resultados de cada artigo serviram de insumo e refinamento para a etapa seguinte.

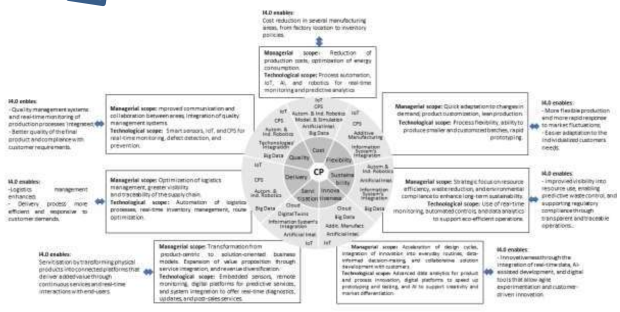
No Estágio I, por meio de uma Revisão Sistemática da Literatura, o Artigo 1 estabeleceu a fundamentação teórica do *framework*; identificou com base na literatura as relações conceituais iniciais entre as tecnologias habilitadoras da I4.0 e as prioridades competitivas da manufatura.

Figura 9 – Trajetória evolutiva do *framework*

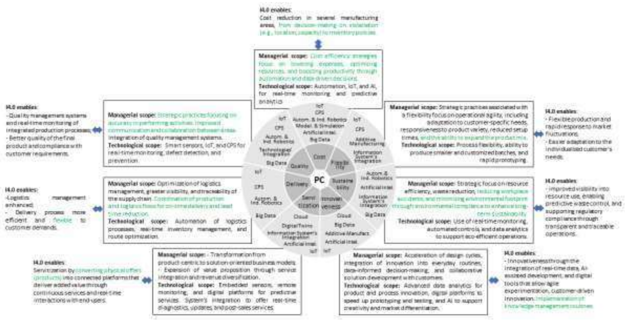


Modelo 1.0 - Teórico Hipotético
- Identificação dos 4 PC's Tradicionais (Custo, Qualidade, Entrega, Flexibilidade);
- Proposição da Perspectiva Dual.

Modelo 2.0 – Empiricamente Fundamentado
- Fundamentação Empírica;
- Inclusão das Prioridades Emergentes;
- Elucidação dos mecanismos de integração.



Modelo 3.0 – Validado por especialistas
- Validação por Consenso.;
- Refinamento dos Escopos Tecnológicos e Gerenciais;
- Inclusão de ressalvas conceituais.



Fonte: a autora

Como ponto de partida, o modelo inicial, Modelo 1.0, estava centrado nas quatro Prioridades Competitivas tradicionais (Custo, Qualidade, Entrega e Flexibilidade) e guardava a preeminência de tais prioridades conforme apontado pela literatura. A Revisão da Literatura permitiu propor a ideia da Perspectiva Dual, o que segmentou as contribuições da I4.0 em Escopo Tecnológico, ou seja, o uso das tecnologias em si, e Escopo Gerencial, aquele que diz respeito ao conjunto de práticas desejáveis para que a tecnologia gere valor estratégico. Neste estágio, o *framework* apresentava características predominantemente descritivas e hipotéticas e definia os domínios de intervenção da I4.0.

No Estágio II, o Artigo 2 utilizou um delineamento exploratório para testar e estender o modelo inicial por meio da análise empírica em quatro empresas manufatureiras brasileiras, o que permitiu a construção de teoria a partir dos dados; resultou o Modelo 2.0, expandiu-o e fundamentou-o empiricamente.

Os achados empíricos validaram a Perspectiva Dual e detectaram o papel do Escopo Gerencial como mecanismo de integração. Os resultados apontaram que a performance é alcançada por meio do alinhamento intencional das tecnologias habilitadoras da I4.0 com a lógica de produção e a intenção estratégica organizacional.

O estudo de casos revelou, indutivamente, que a I4.0 permite que as empresas persigam três novas dimensões estratégicas que haviam sido indicadas como emergentes, mas não estavam explicitamente categorizadas como prioridades competitivas da manufatura de primeira ordem na literatura inicial: Sustentabilidade, Inovatividade e Servitização. Mais ainda: nesta segunda etapa, ficou estabelecido que a adoção da I4.0 é estrategicamente contingente; configurou-se de maneiras distintas e na dependência do contexto operacional.

O Modelo 2.0 apresenta, portanto, perspectiva descritiva e explicativa; integra as sete prioridades competitivas (tradicionais e emergentes) e detalha seus respectivos Escopos Tecnológico e Gerencial.

No desenvolvimento do Estágio III, o Artigo 3 submeteu o Modelo 2.0 à avaliação de um Painel de Especialistas; utilizou o Método *Delphi* para obter consenso e validar a robustez do modelo.

O estudo alcançou altos níveis de consenso e confiabilidade, via índices estatísticos; confirmou que o *framework* está *bem estruturado* e que a validade da Perspectiva Dual e a inclusão das prioridades competitivas emergentes foram confirmadas. Para o mais, o processo de execução da pesquisa *Delphi* permitiu refinamentos conceituais; levou a ajustes cruciais (conforme Quadro 7) para a precisão conceitual do modelo, especialmente em assertivas ambíguas.

O Modelo 3.0 é, portanto, o resultado de uma construção progressiva que passou pelo crivo teórico, pela fundamentação empírica de campo e pelo consenso de especialistas. Ele apresentou uma visão prescritiva e robusta da Estratégia de Manufatura na era I4.0.

Quadro 7 – Descrição comparativa dos modelos 2.0 e 3.0

Prioridade	Elemento	Modelo 2.0	Modelo 3.0	Refinamento
Custo	Escopo Gerencial	"Reduction of production costs, optimization of energy consumption."	**"Cost efficiency strategies focus on lowering expenses, optimizing resources, and boosting productivity through automation and data-driven decisions."**	**Expansão Conceitual:** O escopo gerencial é expandido para incluir o foco estratégico em redução de despesas, otimização de recursos e aumento da produtividade baseada em automação e dados.
	I4.0 habilita	"Cost reduction in several manufacturing areas, from factory location to inventory policies."	"Cost reduction in several manufacturing areas, from **decision-making on installation (e.g., location, capacity)** to inventory policies."	**Detalhe Adicionado:** Inclusão de exemplos específicos de áreas de redução de custos, como decisão sobre a instalação (por exemplo, localização, capacidade).
Qualidade	Escopo Gerencial	"Improved communication and collaboration between areas, integration of quality management systems."	"**Strategic practices focusing on accuracy in performing activities.** Improved communication and collaboration between áreas. Integration of quality management systems."	**Adição de Foco:** Inclusão da ênfase em **"práticas estratégicas com foco na precisão da execução de atividades"**.
Entrega	Escopo Gerencial	"Optimization of logistics management, greater visibility, and traceability of the supply chain."	"Optimization of logistics management, greater visibility, and traceability of the supply chain. **Coordination of production and logistics flows for on-time delivery and lead time reduction.**"	**Expansão Escopo:** O escopo gerencial foi expandido para incluir explicitamente a **"Coordenação de fluxos de produção e logística para entrega no prazo e redução de *lead time*.**"
	I4.0 habilita	"Delivery process more efficient and **responsive** to customer demands."	"Delivery process more efficient and **flexible** to customer demands."	**Substituição Terminológica:** Uso da palavra ***flexible*** (*flexível*).

Flexibili-dade	Escopo Gerencial	"Quick adaptation to changes in demand, product customization, lean production."	"**Strategic practices associated with a flexibility focus on operational agility, including adaptation to customer-specific needs, responsiveness to product variety, reduced setup times, and the ability to expand the product mix.**"	**Expansão Detalhada:** O escopo é expandido, detalhado e enfatiza aspectos, como **agilidade operacional**, **necessidades específicas do cliente**, **variedade de produtos e expansão do *mix***.
Sustentabi-lidade	Escopo Gerencial	"Strategic focus on resource efficiency, waste reduction, and environmental compliance to enhance long-term sustainability."	"Strategic focus on resource efficiency, waste reduction, **reducing workplace accidents, and minimizing environmental footprint** through environmental compliance to enhance long-term sustainability."	**Aumento da Abrangência:** Adição de **"redução de acidentes de trabalho"** e **"minimização da pegada ambiental"**, o que amplia o escopo para além da eficiência e da conformidade.
Inovativi-dade	I4.0 habilita	"... and digital tools that allow agile experimentation and customer-driven innovation."	"... digital tools that allow agile experimentation, customer-driven innovation. **Implementation of knowledge management routines.**"	**Adição de Rotinas:** Inclusão da **"Implementação de rotinas de gestão do conhecimento"** no que a I4.0 habilita.
Servitiza-ção	I4.0 habilita	"Servitisation by transforming physical products into connected platforms that deliver added value through continuous services and real-time interactions with end-users."	"Servitization by **converting physical offers (products)** into connected platforms that deliver added value through continuous services and real-time interactions with end-users."	**Adequação Terminológica:** Substituição do termo produtos físicos por ofertas físicas.

Fonte: a autora

5 CONCLUSÕES, CONTRIBUIÇÕES E PESQUISAS FUTURAS

O presente capítulo cumpre a função de encerrar a Parte I - Visão Geral Integrativa da tese. Seu propósito principal é retratar as conclusões do trabalho e o alcance do Objetivo Geral da pesquisa. Ele destaca as contribuições do *framework* final (Modelo 3.0) para a teoria e a prática gerencial, além de abordar as limitações do estudo e delinear a agenda para trabalhos futuros.

5.1 Conclusões

Por meio de um delineamento exploratório e sequencial, a presente pesquisa desenvolveu, fundamentou e validou o Modelo Conceitual Final (Modelo 3.0), com a explicitação de como a implementação de tecnologias habilitadoras da I4.0 influencia e configura a reorganização estratégica, com ênfase nas prioridades competitivas da manufatura. Desta forma, o trabalho mostrou atingir integralmente seu objetivo principal.

Em um contexto de mercado, distinguido por uma ruptura com os modos de produção e paradigmas vigentes, isto pede uma reavaliação da estratégia de manufatura. O modelo conceitual aqui elaborado serve como referência planejada para empresas manufatureiras na transformação digital.

A coerência da pesquisa foi estabelecida pela correspondência biunívoca de cada artigo elaborado no processo de desenvolvimento da pesquisa aos Objetivos Específicos (OEs) da tese. O fato garantiu que cada etapa fosse necessária e suficiente para o avanço do conhecimento. Sendo assim, o *framework* resultante é produto de uma construção progressiva que passou pelo crivo teórico (Artigo 1), pela fundamentação empírica de campo (Artigo 2) e pelo consenso de especialistas (Artigo 3).

Tal modelo demonstrou que a influência das tecnologias habilitadoras da I4.0 na reorganização estratégica da manufatura ocorre de forma pensada e contingente, mediada pela Perspectiva Dual e composta pelo Escopo Tecnológico e pelo Escopo Gerencial. O sucesso não advém apenas da adoção tecnológica (o “o quê”), mas também do alinhamento intencional dessas tecnologias com a lógica de produção e os objetivos organizacionais (o "como"). O Escopo Gerencial é classificado como o mecanismo de integração determinante.

As principais contribuições teóricas da pesquisa concentram-se em expandir o conhecimento sobre a intersecção entre a Estratégia de Manufatura e a I4.0 e em abordar lacunas identificadas na literatura. Primeiramente, o modelo conceitual contribui ao revelar que, além das prioridades competitivas tradicionais (custo, qualidade, entrega e flexibilidade), novas prioridades competitivas, entre elas, inovatividade, servitização e sustentabilidade, podem ser alavancadas pela aplicação de tecnologias habilitadoras da I4.0. Esta expansão, fundamentada empiricamente e validada por especialistas, consolida estas dimensões como prioridades de primeira ordem na era digital.

Para mais, o estudo avançou sobre modelos conceituais anteriores, que eram predominantemente teóricos, ao explicitar o mecanismo de interconexão entre as tecnologias e as prioridades competitivas. O modelo demonstra que o Escopo Gerencial tem importante papel; atua como mecanismo de integração que traduz o potencial tecnológico em desempenho estratégico.

A pesquisa confirmou, ainda, que o desempenho estratégico não é alcançado apenas pela adoção tecnológica (o “o quê”), mas pelo alinhamento intencional dessas tecnologias com a lógica de produção e os objetivos organizacionais (o “como”). Essa validação formal, obtida por consenso de especialistas, reforça que a adoção da I4.0 é estrategicamente contingencial, configurada de forma diferente na dependência da orientação adotada por cada empresa.

Adicionalmente, esta tese oferece contribuições práticas significativas. Para começar, vale ressaltar que a validação do *framework* fortaleceu sua aplicabilidade em cenários reais de manufatura; tornou-o capaz de auxiliar empresas na tomada de decisão estratégica quanto à implantação de tecnologias habilitadoras da I4.0.

O modelo serve como referência validada para o planejamento estratégico e a melhoria da competitividade na era digital. Ele permite que as empresas direcionem seus esforços para as tecnologias habilitadoras da I4.0 que estejam adequadamente alinhadas às suas prioridades competitivas.

O *framework* final oferece uma compreensão mais refinada e prescritiva; enfatiza a importância de orquestrar com estratégia tecnologias, processos e práticas gerenciais.

5.2 Limitações e Agenda para Estudos Futuros

Apesar do seu rigor metodológico e da ampla validação do modelo, esta pesquisa apresenta limitações inerentes ao seu desenho e escopo. Deve-se considerar que a etapa de fundamentação empírica (Artigo 2) utilizou um delineamento exploratório de Estudo de Múltiplos Casos em quatro empresas manufatureiras brasileiras. Embora esta abordagem seja adequada para a construção de teoria, o número restrito de casos e o foco geográfico (Brasil) limitam a generalização estatística dos resultados para outros contextos geográficos e industriais.

O foco do estudo nos mecanismos de integração (o "como") exigiu uma abordagem qualitativa. Embora o Artigo 3 tenha introduzido rigor estatístico (consenso e *Alpha Cronbach*), a tese não operacionaliza ou testa quantitativamente a força das relações entre as variáveis do *framework* (Tecnologias, Escopos e Prioridades Competitivas).

A Indústria 4.0 é um campo em constante evolução. As tecnologias habilitadoras e suas aplicações se expandem continuamente, o que implica que a lista de tecnologias e os refinamentos conceituais estejam sujeitos a novas atualizações.

Desta forma, com o modelo conceitual final (Modelo 3.0) devidamente fundamentado e validado, é recomendável que a agenda de pesquisa futura se concentre na validação da operacionalização e no teste das relações causais propostas.

Sugere-se, portanto, a efetivação de teste quantitativo das relações por meio de pesquisas em larga escala, como *surveys*, para testar e mensurar a intensidade das interrelações propostas no Modelo 3.0. O foco deve estar na verificação da hipótese central da tese, na busca de aprofundar o entendimento sobre o impacto do Escopo Gerencial como mediador entre a adoção tecnológica da I4.0 e o desempenho das prioridades competitivas da manufatura.

É necessário também realizar a validação empírica do *framework* em diferentes contextos industriais (além dos ambientes estudados no Artigo 2) e em diferentes regiões geográficas globais, a fim de verificar se a natureza contingente do modelo se mantém.

Considerando as observações levantadas pelo Painel *Delphi* sobre a Servitização, estudos futuros devem investigar os fatores de contingência que tornam a transição para modelos de negócio orientados a serviços viável em diferentes setores, com ênfase na aplicabilidade prática em contextos manufatureiros.

REFERÊNCIAS BIBLIOGRÁFICAS – PARTE I

ABDULLAH, F. M.; AL-AHMARI, A.M.; ANWAR, S. A Hybrid Fuzzy Multi-Criteria Decision-Making Model for Evaluating the Influence of Industry 4.0 Technologies on Manufacturing Strategies. **Machines**, v. 11, n. 2, p. 310, 2023.

ABDULLAH, F. M.; AL-AHMARI, A.M.; ANWAR, S. The Impact of Industry 4.0 Technologies on Manufacturing Strategies: Proposition of Technology-Integrated Selection. **IEEE Access**, v. 10, p. 21574-21583, 2022.

ALLADI T.; CHAMOLA V.; PARIZI R. M.; CHOO K. R. Blockchain Applications for Industry 4.0 and Industrial IoT: a Review. **IEEE Access**, v. 7, p. 176935-176951, 2019.

ANCARANI, A.; DI MAURO, C.; MASCALI, F. Backshoring strategy and the adoption of Industry 4.0: Evidence from Europe. **Journal of World Business**, v. 54, n. 4, p. 360-371, 2019.

ASSAD NETO, A. et al. A busca de uma identidade para a indústria 4.0. **Brazilian Journal of Development**, Curitiba, v. 4, n. 4, p. 1379-1395, jul./set. 2018.

BONILLA S. H.; SILVA H. R. O.; SILVA M. T.; GONÇALVES R. F; SACOMANO J. B. Industry 4.0 and Sustainability Implications: A Scenario-Based Analysis of the Impacts and Challenges. **Sustainability**, v. 10, n. 10, p. 3740, 2018.

BRETTEL M.; FRIEDERICHSEN N.; KELLER M.; ROSENBERG M. How Virtualization, Decentralization and Network Building Change the Manufacturing Landscape: an Industry 4.0 Perspective. **International Journal of Information and Communication Engineering,** v. 8, n. 1, p. 37-44, 2014.

BRIGNARDELLO-PETERSEN, Romina; SANTESSO, Nancy; GUYATT, Gordon H. Systematic reviews of the literature: an introduction to current methods. **American Journal of Epidemiology**, v. 194, n. 2, p. 536-542, 2025.

DALENOGARE, Lucas Santos et al. The expected contribution of Industry 4.0 technologies for industrial performance. **International Journal of production economics**, v. 204, p. 383-394, 2018.

DANGAYACH, S.; DESHMUKH, S. G. An exploratory study of manufacturing strategy practices of machinery manufacturing companies in India, **Omega,** v. 34, n. 3, p. 254-273, 2006.

DOHALE V.; VERMA, P.; GUNASEKARAN, A.; AKARTE, M. M. Manufacturing strategy 4.0: a framework to usher towards industry 4.0 implementation for digital transformation. **Industrial Management & Data Systems,** v. 123, n. 1, p. 10-40, 2023.

EISENHARDT, K. M. Building theories from case study research. **Acad. Manag. Rev.** v. 14, n. 4, p. 532–550, 1989.

ENRIQUE D. V.; MARODIN G. A.; SANTOS F. B. C.; FRANK A. G. Implementing industry 4.0 for flexibility, quality, and productivity improvement: technology arrangements for different purposes. **International Journal of Production Research,** 2022.

GARVIN, D. A. Manufacturing Strategy Planning. **California Management Review,** v. 35, n. 4, p. 85-106, 1993.

GIOIA, D. A., CORLEY, K. G., HAMILTON, A. L. Seeking qualitative rigor in inductive research: Notes on the Gioia methodology. **Organ. Res. Methods,** v. 16, n. 1, p. 15–31, 2013.

GUPTA, A. K.; GUPTA, N. (2021) Manufacturing Strategy Dimensions as I4. 0 Performance Antecedents in Developing Economies. In Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems: IFIP WG 5.7 International Conference, **APMS 2021**, Nantes, France, September 5–9, 2021, Proceedings, Part I (pp. 171-179). Springer International Publishing.

JAVAID M.; HALEEM A.; SINGH R. P.; KHAN S.; SUMAN R. Blockchain Technology Applications for Industry 4.0: a Literature-Based Review. **Blockchain: Research and Applications,** v. 2, n. 4, p. 100027, 2021.

KAMBLE S. S.; GUNASEKARAN A.; GAWANKAR S. A. Sustainable Industry 4.0 Framework: A Systematic Literature Review Identifying the Current Trends and Future Perspectives. **Process Safety and Environmental Protection,** v. 117, p. 408-425, 2018.

KANG H. S.; LEE J. Y.; CHOI S.; KIM H.; PARK J. H.; SON J. Y.; KIM B. H.; NOH S. D. Smart Manufacturing: Past Research, Present Findings, and Future Directions. **International Journal of Precision Engineering and Manufacturing-Green Technology,** v. 3, p. 111-128, 2016.

KHAN, Iqra Sadaf; AHMAD, Muhammad Ovais; MAJAVA, Jukka. Industry 4.0 innovations and their implications: An evaluation from sustainable development perspective. **Journal of Cleaner Production**, v. 405, p. 137006, 2023.

KIM, J. S.; ARNOLD P. Operationalizing manufacturing strategy – an exploratory study of constructs and linkage. **International Journal of Operations & Production Management,** v. 16, n. 12, p. 45-73, 1996.

LEONG G. K.; SNYDER D. L.; WARD P. T. Research in the Process and Content of Manufacturing Strategy. **Omega International Journal of Management Science,** v. 18, n. 2, p. 109-122, 1990.

LU Y. Industry 4.0: a Survey on Technologies, Applications and Open Research Issues. **Journal of Industrial Information Integration,** v. 6, p. 1-10, 2017.

MARTÍN-PEÑA, M. L.; DÍAZ-GARRIDO E. A taxonomy of manufacturing strategies in Spanish companies. **International Journal of Operations & Production Management,** v. 28, n. 5, p. 455-477, 2008.

MARTINS G. D.; GONÇALVES R. F.; PETRONI B. C. Blockchain in Manufacturing Revolution Based on Machine to Machine Transaction: a Systematic Review. **Brazilian Journal of Operations & Production Management,** v. 16, p. 294-302, 2019.

MILLS, J.; PLATTS, K.; GREGORY, M. A framework for the design of manufacturing strategy process: a contingency approach. **International Journal of Operations & Production Management**, v. 15, n. 4, p. 17-49, 1995.

MINISTÉRIO DO DESENVOLVIMENTO, INDÚSTRIA, COMÉRCIO E SERVIÇOS. Câmara Brasileira da Indústria 4.0: estrutura e objetivos. Brasília: MDIC, 2019. Disponível em: https://www.gov.br/mdic/pt-br/assuntos/industria/industria-4-0/camara-brasileira-da-industria-4-0 . Acesso em: 7 nov. 2025.

MUHURI P. K.; SHUKLA A. K.; ABRAHAM A. Industry 4.0: a Bibliometric Analysis and Detailed Overview. **Engineering Applications of Artificial Intelligence,** v. 78, p. 218-235, 2019.

NETLAND, T. H.; FRICK, J. Trends in manufacturing strategies: A longitudinal investigation of the International Manufacturing Strategy Survey. *In:* CHIARINI A.; VECCHI A.; BRENNAN L. (Eds.). **International manufacturing strategy in a time of great flux.** Springer, 2016.

OKOLI, Chitu; PAWLOWSKI, Suzanne D. The Delphi method as a research tool: an example, design considerations and applications. **Information & management**, v. 42, n. 1, p. 15-29, 2004.

OZTEMEL E.; GURSEV S. Literature Review of Industry 4.0 and Related Technologies. **Journal of Intelligent Manufacturing,** v. 31, p. 127-182, 2020.

PIRES, S. R. I. **Gestão Estratégica da Produção***,* Piracicaba: Unimep, 1995.

REIS J. Z.; GONÇALVES R. F.; SILVA M. T. da; KAZANTSEV N. Business Models for the Internet of Services: State of the Art and Research Agenda. **Future Internet,** v. 14, n. 3, p. 74, 2022.

RIBEIRO, A. C. E.; FACIN, A. L. F.; GONÇALVES, R. F.; NÄÄS, I. A. Manufacturing strategy in industry 4.0: a conceptual framework and future research avenues. **Manag Rev Q,** 2025.

RIDDER, Hans-Gerd. The theory contribution of case study research designs. **Business research**, v. 10, n. 2, p. 281-305, 2017.

SALAM, M. A. Analyzing manufacturing strategies and Industry 4.0 supplier performance relationships from a resource-based perspective. **Benchmarking: An International Journal**, v. 28, p1697-1716, 2021

SANTOS, B. P. et al. Indústria 4.0: Desafios e Oportunidades. **Revista Produção e Desenvolvimento**, v. 4, n. 1, p. 111-124, 2018.

SCHNEIDER, Paul. Managerial challenges of Industry 4.0: an empirically backed research agenda for a nascent field. **Review of Managerial Science**, v. 12, n. 3, p. 803-848, 2018.

SILVA, E. M.; JABBOUR, C. J. C.; SANTOS, F. C. A. Integrating environmental management and manufacturing strategy: an emerging competitive priority. **International Journal of Environmental Technology and Management,** v. 10, n. 3-4, p. 397-411, 2009.

SKINNER, W. Manufacturing - missing link in corporate strategy. **Havard Business Review**, mai-jun, 1969.

SLACK, N. et al. **Administração da produção***.* São Paulo: Atlas, 1997.

SOUZA, M. T.; SANTOS, F. C. A. Analysis of the World Scientific Production on the Topic of Industry 4.0 From 1990 to 2020. **Revista Gestão da Produção Operações e Sistemas,** v. 16, n. 2, p. 153, 2021.

TIAN, Meng et al. The role of digital transformation practices in the operations improvement in manufacturing firms: A practice-based view. **International Journal of Production Economics**, p. 108929, 2023.

THOBEN K.; WIESNER S.; WUEST T. 'Industrie 4.0' and smart manufacturing-a review of research issues and application examples. **International Journal of Automation Technology,** v. 11, n. 1, p. 4-16, 2017.

TORTORELLA, G.; KURNIA, S.; TRENTIN, M.; OLIVEIRA, G. A.; SETTI, D. Industry 4.0: What is the relationship between manufacturing strategies, critical success factors, and technology adoption? **J. Manuf. Technol. Manag.**, v. 33, p. 1407–1428, 2022.

TRANFIELD D.; DENYER D.; SMART P. Towards a methodology for developing evidence-informed management knowledge by means of systematic review. **Br. J. Manag,** v. 14, p. 207-222, 2003.

URGAL-GONZÁLEZ, B.; GARCÍA-VÁZQUEZ, J. M. The strategic influence of structural manufacturing decisions. **Internacional Journal of Operations & Production Management,** v. 27, n. 6, p. 605-626, 2007.

WANG S.; WAN J.; LI D.; ZHANG C. Implementing Smart Factory of Industrie 4.0: an Outlook. **International Journal of Distributed Sensor Networks,** v. 12, n. 1, p. 3159805, 2016.

VIVARES, J. A.; AVELLA, L.; SARACHE, W. Trends and challenges in operations strategy research: Findings from a systematic literature review. **Cuad. Gest.** v. 22, p. 81–96, 2022.

WANG, J.; CAO, D. Relationships between two approaches for planning manufacturing strategy: a strategic approach and a paradigmatic approach. **International Journal of Production Economics,** v. 115, n. 2, p. 349-361, 2008.

WANG, J.; WU, H.; CHEN, Y. Made in China 2025 and manufacturing strategy decisions with reverse QFD. **International Journal of Production Economics,** v. 224, p. 107539, 2020.

WARD, T. P.; DURAY, R. Manufacturing strategy in context: environment, competitive strategy and manufacturing strategy. **Journal of Operations Management,** v. 18, n. 2, p. 123-138, 2000.

ZHANG C.; Chen Y. A review of research relevant to the emerging industry trends: Industry 4.0, IoT, Blockchain, and Business Analytics. **Journal of Industrial Integration and Management,** v. 5, n. 01, p. 165-180, 2020.

ZHENG P.; WANG H.; SANG Z.; ZHONG R. Y.; LIU Y.; LIU C.; MUBAROK K.; YU S.; XU X. Smart manufacturing systems for Industry 4.0: Conceptual framework, scenarios, and future perspectives. **Frontiers of Mechanical Engineering**, v. 13, p. 137-150, 2018.

PARTE II – ARTIGOS DA TESE

6 ARTIGO 1 - MANUFACTURING STRATEGY IN INDUSTRY 4.0: A CONCEPTUAL FRAMEWORK AND FUTURE RESEARCH AVENUES

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Manufacturing strategy in industry 4.0: a conceptual framework and future research avenues

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Abstract

Industry 4.0 represents a paradigm shift in manufacturing management, characterised by the integration of cyber-physical systems, the Internet of Things, and other advanced technologies into production processes. This transformation necessitates reevaluating manufacturing strategy to leverage these technologies for enhanced organisational performance. This paper presents a systematic literature review that examines the intersection of Industry 4.0 and manufacturing strategy, analysing the impact of Industry 4.0 technologies on competitive priorities and strategic decision areas within the manufacturing function. We analysed 33 articles sourced from Web of Science and Scopus databases, published between 2019 and 2024. The findings indicate that while the classic competitive priorities—cost, quality, delivery, and flexibility—remain central to manufacturing strategy, there is an increasing emphasis on emerging priorities such as innovativeness, service, and environmental sustainability. Furthermore, the paper introduces a conceptual framework that associates Industry 4.0 with manufacturing strategy, exploring how Industry 4.0 enabling technologies can be strategically implemented to achieve desired operational priorities. The study offers managerial implications, providing insights for decision-makers aiming to leverage digital transformation to optimise manufacturing outcomes. Additionally, a research agenda is proposed, highlighting the need for empirical validation across diverse industrial contexts. Overall, this study contributes to a deeper understanding of the evolving relationship between Industry 4.0 and manufacturing strategy, providing insights for both academics and practitioners navigating the challenges and opportunities of the fourth industrial era.

Keywords Literature review. Operational strategy. Industrie 4.0. Competitive dimensions. Digital era.

7 ARTIGO 2 - ENABLING TECHNOLOGIES OF INDUSTRY 4.0 AND MANUFACTURING COMPETITIVE PRIORITIES: AN EXPLORATORY MULTIPLE-CASE STUDY

Abstract

Industry 4.0 represents a transformative shift in the manufacturing landscape, characterized by the convergence of digital technologies, cyber-physical systems, and data-driven intelligence. Successfully leveraging I4.0 depends on a multidimensional alignment between technological, organizational, and managerial enablers. However, limited attention has been devoted to understanding how these technologies influence the strategic orientation of manufacturing operations, and theoretical clarity remains lacking on how firms strategically leverage I4.0 technologies to pursue targeted competitive outcomes based on their specific operational contexts. This study addresses this critical gap by investigating the integration mechanisms and priority contributions that arise from the implementation of I4.0 enabling technologies, and in what ways these technologies influence the configuration of competitive priorities (CPs). Accordingly, the objective is to develop and propose a conceptual framework empirically grounded in exploratory multiple-case studies. We employed a qualitative research design based on a multiple-case study of four Brazilian manufacturing firms operating across distinct industrial sectors. The findings offer two main contributions. First, the study empirically demonstrates that I4.0 adoption is strategically contingent, configured differently depending on each firm's production logic and strategic orientation. Second, it proposes a comprehensive conceptual framework that expands traditional CPs by incorporating the empirically established dimensions of Sustainability, Innovativeness, and Servitization. Crucially, the framework articulates the strategic realization of competitive advantage through a dual perspective—the Technological Scope and the Managerial Scope. The Managerial Scope is identified as the critical integration mechanism that translates technological potential into strategic performance, demonstrating that performance outcomes are realized not solely through technological adoption but through the purposeful alignment of these technologies with organizational intent and production logic. The conceptual framework provides a nuanced understanding for practitioners and researchers, emphasizing the importance of strategically orchestrating technologies, people, and processes to create resilient and differentiated paths to competitiveness.

Keywords: Manufacturing Competitive Dimensions; Digital Transformation; Sustainability; Servitization; Innovativeness.

1 Introduction

Industry 4.0 (I4.0) represents a transformative shift in the manufacturing landscape, characterized by the convergence of digital technologies, cyber-physical systems, and data-driven intelligence. This emerging industrial paradigm goes beyond conventional automation by fostering interconnected, autonomous, and adaptive production environments. Core enabling technologies, such as the Internet of Things (IoT), artificial intelligence (AI), cloud computing, and advanced robotics allow firms to optimize processes, increase operational transparency, and reconfigure value chains with unprecedented agility (Hermann et al., 2016; Elnadi and Abdallah, 2024).

Competitive priorities (CPs)—such as quality, cost, delivery, and flexibility—are fundamental attributes that define the strategic focus of manufacturing operations (Prabhu et al., 2020; Moeuf et al., 2020). Successfully leveraging I4.0 depends on a multidimensional alignment between technological, organizational, and managerial enablers (Elnadi and Abdallah, 2024). Furthermore, in emerging economy contexts like Brazil, CPs are often influenced by specific institutional conditions and resource constraints, necessitating context-sensitive approaches to strategic alignment (Reis and Camargo Júnior, 2024).

Existing literature has focused on the technological foundations and implementation challenges of I4.0, including readiness models, adoption barriers, and maturity frameworks (Frank et al., 2019; Machado et al., 2020). Consequently, limited attention has been devoted to understanding how these technologies influence the strategic orientation of manufacturing operations, particularly regarding how firms reconfigure their competitive priorities in response to digital transformation. Theoretical clarity remains lacking on how firms strategically leverage I4.0 technologies to pursue targeted competitive outcomes based on their specific operational contexts and business strategies. This significant gap highlights the need for empirical investigation to elucidate the underlying mechanisms that translate technological potential into measurable competitive strategic performance.

This study addresses this critical gap by investigating the following research question:

RQ: What are the integration mechanisms and priority contributions that arise from the implementation of Industry 4.0 enabling technologies, and in what ways do these technologies influence the configuration of competitive priorities in manufacturing?

Accordingly, the objective is to develop and propose a conceptual framework, empirically grounded in multiple and exploratory case studies, that articulates the integration mechanisms and the priority contributions of I4.0 enabling technologies to manufacturing competitive priorities.

To achieve this objective, we employ a rigorous qualitative research design based on a multiple-case study of four Brazilian manufacturing firms operating across distinct production environments and strategic contexts.

This study offers two main contributions. First, by applying an inductive methodology, it extends the literature on manufacturing strategy by empirically demonstrating that I4.0 adoption is not uniform but strategically contingent; enabling technologies are configured differently depending on each firm's production logic and strategic orientation. Second, it proposes a comprehensive conceptual framework that expands the traditional competitive priorities by incorporating the empirically established dimensions of Sustainability, Innovativeness, and Servitization. This framework provides a comprehensive perspective on how digital transformation strategically (re)shapes competitive dynamics by highlighting the role of the managerial scope in realizing competitive advantages.

The remainder of this paper is structured as follows. Section 2 reviews the theoretical foundations of I4.0 and manufacturing strategy. Section 3 outlines the research design and methodological procedures. Section 4 presents the empirical findings and the resulting data structure. Section 5 discusses the findings in light of existing theoretical perspectives, highlighting implications for I4.0 adoption. Finally, Section 6 concludes the paper by summarizing key contributions, acknowledging limitations, and suggesting avenues for future research

2 Literature review

2.1 Industry 4.0 enabling technologies

The I4.0 ecosystem is characterized by the convergence of intelligent, self-regulating systems that enable seamless interaction among humans, machines, and digital environments. This paradigm is underpinned by a layered technological architecture, as proposed by Frank et al. (2019), which differentiates between front-end applications. Such as Smart Manufacturing and Smart Products, and foundational technologies that support systemic integration and drive digital transformation.

At the core of I4.0 lie foundational technologies that enable the seamless integration of physical and digital domains. The Internet of Things (IoT) embeds sensors and interfaces into physical assets, enabling real-time data exchange and synchronization (Elnadi and Abdallah, 2024; Bhatia and Kumar, 2020). Cyber-Physical Systems (CPS) serve as an interface between the physical and computational realms, allowing machinery to communicate bidirectionally with digital networks (Maretto et al., 2023). Cloud computing provides scalable and secure infrastructure for data storage and processing, thereby facilitating the integration of diverse digital tools (Götz and Jankowska, 2020).

Big Data empowers firms to extract predictive insights from large-scale datasets, thereby enhancing the decision-making process and operational foresight (Götz and Jankowska, 2020). Simulation technologies support strategic planning by enabling virtual modeling of production scenarios and resource allocation (Arcidiacono et al., 2023; Abdullah et al., 2022), while Digital Twins offer real-time virtual representations of physical systems, facilitating continuous performance monitoring and optimization (Lattanzi et al., 2021).

Additive Manufacturing (AM), commonly known as 3D printing, introduces scalable and material-efficient production capabilities, supporting customization and agility (Enrique et al., 2022). Augmented Reality (AR) and Virtual Reality (VR) enhance human-machine collaboration by creating immersive environments for training, maintenance, and real-time operational support (Chiarini and Kumar, 2021; Maretto et al., 2023). Cybersecurity plays a critical role in safeguarding digital infrastructures against breaches, ensuring data protection and operational integrity (Arcidiacono et al., 2023).

Emerging technologies such as blockchain offer secure and transparent mechanisms for data exchange and supply chain validation (Dohale et al., 2022).

Artificial Intelligence (AI) plays a transformative role by enabling systems to learn from data, recognize patterns, and make autonomous decisions. AI-driven applications in I4.0 include predictive maintenance, defect detection, demand forecasting, and adaptive process control, each contributing to improved productivity, quality assurance, and operational responsiveness (Johanesa et al., 2024; Wan et al., 2021).

Taken together, these enabling technologies and their systemic integration constitute the backbone of I4.0, driving the transition toward intelligent, adaptive, and sustainable manufacturing systems.

2.2 Strategic impact of I4.0 on manufacturing competitive priorities

Industry 4.0 signifies a paradigm shift in manufacturing, redefining how firms conceptualize and operationalize competitive priorities (Abdullah et al., 2023). By integrating digital and physical technologies, organizations can enhance conventional performance indicators while simultaneously developing novel strategic capabilities. This dual impact underscores I4.0 as more than a technological enhancement; it serves as a transformative force in the reconfiguration of manufacturing strategy.

Recent literature indicates that I4.0 technologies contribute positively to operational performance through improvements in productivity, quality, and flexibility. In this sense, Enrique et al. (2022) caution against standardized implementation approaches, emphasizing that technology configurations must be purpose-driven and tailored to the specificities of individual production environments. Their findings underscore the limitations of generalized models, which may fail to capture strategic subtleties, particularly within diverse manufacturing contexts. This perspective reinforces the notion that enabling technologies should be deliberately aligned with specific competitive priorities, rather than applied as a one-size-fits-all solution.

While the principle of strategic alignment is established, theoretical clarity remains absent concerning the precise integration mechanisms that translate technological potential into competitive strategic outcomes. The realization of performance gains is not solely driven by technological adoption, but by the alignment of these technologies with organizational intent and production logic.

Empirical investigation is therefore required to fully elucidate the role of the managerial scope as the critical mediating mechanism that orchestrates this interaction and determines the strategic configuration of I4.0.

2.2.1 Enhancing Traditional Competitive Priorities

Industry 4.0 technologies have emerged as critical enablers in advancing traditional manufacturing priorities, notably cost efficiency, quality assurance, timely delivery, and operational flexibility (Abdullah et al., 2022). Through intelligent automation and advanced data analytics, firms can achieve real-time resource monitoring and energy optimization, thereby reducing operational costs across production systems (Götz and Jankowska, 2020). In parallel, Additive Manufacturing (AM) contributes to cost-effectiveness by minimizing material waste and simplifying logistics (Abdullah et al., 2023).

Quality improvement in manufacturing is increasingly driven by the integration of advanced technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI), which enable real-time process monitoring and predictive defect detection. These capabilities foster greater consistency and reliability across the production system by facilitating proactive quality control. In addition, robotics and immersive technologies, including Augmented Reality (AR) and Virtual Reality (VR), contribute to error reduction and process standardization, not only within manufacturing operations but also in workforce training environments (Enrique et al., 2022).

Delivery performance and time-to-market are accelerated through Cyber-Physical Systems (CPS) and the Industrial Internet of Things (IIoT), which facilitate dynamic scheduling and seamless data exchange across interconnected production networks (Dohale et al., 2023). Flexibility is enhanced by intelligent production planning systems and reconfigurable machinery, enabling rapid responsiveness to evolving product designs and customization requirements. Additionally, AI-driven collaborative robots bolster production agility by supporting scalable and adaptive manufacturing processes (Abdullah et al., 2022).

2.2.2 Fostering Emerging Competitive Priorities

Beyond optimizing conventional manufacturing objectives, I4.0 technologies empower firms to pursue emerging strategic directions aligned with evolving market dynamics. Innovativeness has become a central competitive priority, supported by Big Data Analytics, which provides continuous market intelligence and accelerates product development cycles. AM technologies further reinforce this innovation orientation by enabling rapid prototyping and design flexibility, embedding agility and experimentation into the core of manufacturing strategy (Dohale et al., 2023).

Servitization has also gained strategic prominence within the I4.0 landscape, as manufacturers increasingly leverage digital technologies to deliver value beyond physical products. Data-driven services, such as predictive maintenance, remote diagnostics, and performance analytics, are enabled by advanced connectivity and analytics platforms, enhancing operational efficiency and customer responsiveness (Achouch et al., 2022; Ramesh et al., 2020). The emergence of Product-Service Systems (PSS) and models like Manufacturing-as-a-Service (MaaS) exemplifies this transformation, allowing firms to offer customized digital services that enhance customer engagement and operational efficiency (Gaiardelli et al., 2021; Tedaldi and Miragliotta, 2023). This evolution is increasingly supported by knowledge-intensive business services (KIBS), which play a strategic role in enabling digital servitization and business model innovation (Paiola et al., 2024).

Sustainability has become a strategic imperative for manufacturing firms, and I4.0 technologies offer robust tools for aligning industrial practices with environmental goals. Through real-time data management and intelligent automation, organizations can achieve significant reductions in waste, enhance energy efficiency, and minimize carbon emissions, contributing to resource conservation and ecological stewardship (Yilmaz et al., 2022; Arcidiacono et al., 2023).

In sum, these developments illustrate how I4.0 technologies not only reinforce traditional manufacturing priorities, such as cost, quality, delivery, and flexibility, but also enable firms to pursue emerging strategic directions. By fostering innovation, supporting digital servitization, and advancing sustainability, I4.0 expands the strategic scope of manufacturing organizations, equipping them to compete in increasingly dynamic, service-driven, and environmentally conscious markets.

3 Methods

The research adopts an exploratory case study design, examining four manufacturing organizations based in Brazil. The case study methodology was selected as it allows for an in-depth, contextualized analysis of how I4.0 enabling technologies influence competitive manufacturing priorities (Eisenhardt, 1989). This approach is particularly effective for investigating multifaceted organizational phenomena within specific environmental contexts. As emphasized by Sousa et al. (2025), qualitative methods, especially those grounded in expert interviews, are indispensable for uncovering the subtleties of I4.0 implementation. They enable the exploration of industrial realities and provide a holistic understanding of technological adoption and its strategic implications.

To analyze the empirical data, this study employed the Gioia methodology (Gioia et al., 2013), a structured approach widely recognized for enhancing qualitative rigor. This method facilitates the systematic identification of emergent patterns and supports robust theory development by organizing raw data into a hierarchical framework. The analytical process involves the construction of first-order codes, second-order themes, and aggregate dimensions, enabling a transparent and traceable pathway from data to theoretical insight. This framework proved particularly effective in capturing organizational transformations associated with the implementation of I4.0 technologies.

3.1 Case selection and data collection

A purposive sampling strategy was employed to select four manufacturing firms operating in Brazil, chosen for their relevance to the sector and demonstrated adoption of I4.0 enabling technologies. The selected companies exhibit diverse strategic orientations and varying levels of digital maturity, allowing for a nuanced exploration of I4.0 implementation across different organizational contexts. This sampling approach facilitated comparative insights, ranging from long-established firms undergoing digital transformation (e.g., Firms

A and B, with operational histories of 20 to 35 years) to newer enterprises that incorporated advanced digital capabilities from their inception (e.g., Firms C and D, founded in 2012 and 2016, respectively). Table 1 provides a consolidated overview of the case study firms, outlining their respective industry sectors, production models, organizational descriptions, and the profiles of the informants interviewed.

Data collection involved semi-structured interviews with two key informants from each company. The informants, senior managers or executives, were selected based on their strategic oversight of both technological implementation and manufacturing policy, ensuring a holistic perspective that links technology with organizational strategy. They held responsibilities spanning strategic decision-making, manufacturing policy formulation, and implementation of technological initiatives. To enrich and triangulate the interview data, supplementary secondary sources were consulted, including company reports, public databases, and official corporate websites. This additional material provided critical context regarding each firm's historical trajectory, product portfolios, and publicly stated commitments to I4.0 adoption.

Before conducting the interviews, participants received a structured briefing document outlining the study's objectives, designed to foster engagement and improve the quality of responses. All interviews were audio-recorded, transcribed verbatim, and analyzed using the Gioia methodology, which provided a systematic framework for coding and interpretation, thereby ensuring analytical rigor and consistency.

To validate the interview protocol and refine its structure, a pilot test was conducted. The finalized protocol is available in Appendix A.

Table 1 - Case study companies' profile

Company	Sector	Production model	Description	Informants
A	Process Instrumentation	Customized items with client-specified features	A member of a global industrial group, the company is recognized as a leading provider of measurement technologies, specializing in pressure, temperature, and level instrumentation for applications in the energy, chemical, and broader industrial sectors.	Director of Industry for Latin America (LA); Innovation Manager
B	Industrial Automation	Production is aligned with forecasted demand in the automotive segment, while customized components are manufactured specifically for the compressor product line to meet tailored specifications.	A Brazilian company specializing in advanced solutions for reciprocating compressors and precision machining, serving a wide range of industrial applications with high-performance components and engineering expertise.	Industrial Engineering and Innovation Manager; Production Manager
C	Automotive Manufacturing	The company integrates demand-forecast-driven production for standardized volumes with a dynamic customization capability, enabling tailored solutions that meet evolving customer-specific requirements.	Operating within the automotive sector, this Brazilian subsidiary has progressively adopted a flexible manufacturing strategy, balancing conventional mass production with an expanding capability for customization and agile responsiveness to evolving market demands.	Production Manager: Painting; Production Manager: Stamping
D	Automotive Manufacturing	Production is organized using a pull-based system, initiated directly by dealership orders.	As a subsidiary of a leading global automotive manufacturer, the company integrates lean production methodologies with advanced customization capabilities.	Quality Manager – Projects; Engineering Manager of Projects and Production

3.2 Data analysis

The data analysis was conducted using the structured Gioia methodology, which facilitates a rigorous and transparent progression from raw qualitative data into theoretical insights. This approach unfolded across three analytical stages:

1. First-order coding: Initial descriptive coding based on interview transcripts, preserving participants' original terminology.
2. Second-order themes: Conceptual abstraction by identifying broader patterns and linking first-order concepts to theoretical constructs.
3. Aggregate dimensions: Development of higher-level themes representing the strategic implications of I4.0 adoption on manufacturing competitive priorities.

This methodological approach enabled the identification of key transformations in manufacturing competitive priorities, providing empirical insights on how I4.0 technologies reshape cost structures, enhance productivity, refine quality management practices, and stimulate strategic innovation.

The trustworthiness of the findings was strengthened by data triangulation, accomplished by interviewing two key informants from each participating firm. This approach enabled cross-validation of perspectives and enhanced the reliability of interpretations. Additionally, the structured application of the Gioia methodology, with its multi-tiered coding process, contributed to the dependability and confirmability of the analysis. By maintaining a clear audit trail from raw data to theoretical constructs, the study ensured that its insights were both transparent and empirically grounded.

4 Findings

This section presents the results of the multiple-case study, grounded in the structured application of the Gioia methodology. Drawing on interview data and supplementary documentation, the findings reveal how I4.0 enabling technologies are being implemented across diverse production settings and how they influence manufacturing competitive priorities. The cross-case analysis synthesizes evidence from firms operating in distinct productive contexts, offering insight into strategic orientations, technological capabilities, and operational performance outcomes.

4.1 Data Structure and Thematic Analysis - Gioia Method

This section details the outcomes of the Gioia-based coding process, which progressed through iterative cycles of data structuring, moving from first-order codes to second-order themes, and culminating in the development of aggregate dimensions. The analysis was guided by the central research question: *What are the integration mechanisms and priority contributions that arise from the implementation of Industry 4.0 enabling technologies, and in what ways do these technologies influence the configuration of competitive priorities in manufacturing across distinct production contexts?*

The first-order codes emerged directly from the *in vivo* expressions of managers, technicians, and senior operational leaders across the four case firms. These informant-driven insights were systematically grouped into conceptually aligned second-order themes, which were then subsequently abstracted into the final aggregate dimensions. This structured progression, presented in Table 2, serves as the robust analytical foundation for the conceptual framework presented in Section 4.3.

The cross-case analysis yielded seven aggregate dimensions: Quality, Cost, Delivery, Flexibility, Sustainability, Innovativeness, and Servitization.

The first four dimensions reflect classical manufacturing competitive priorities; however, their empirical manifestations revealed a strong interdependence with digital capabilities enabled by I4.0. Crucially, the latter three dimensions—Sustainability, Innovativeness, and Servitization—emerged as contemporary, first-order competitive priorities, increasingly salient in digitally transformed production environments. Their inclusion highlights the evolving strategic scope of operations management, as firms navigate the expanded possibilities introduced by I4.0 enabling technologies.

Table 2. Gioia analysis: enabling technologies and competitive priorities in manufacturing

First-Order Quotation	**Second-Order Theme**	**Aggregate Dimension**
"So, in terms of quality, we already have all the sensors and the entire IoT system fully operational." (Director of Industry for LA – Firm A)	Quality monitoring via sensors/IoT integration for quality	Quality
"We created an artificial intelligence system where you upload photos of that damaged point, or that point that indicates the part is correct... And this helped us to guarantee better quality for our product." (Engineering Manager – Firm D)	Defect detection via AI/Enhanced quality control	
"The production cost also decreased significantly, considering only the use of labour. Before the implementation, we used 56 operators to produce 110,000 pieces/month. After the implementations, it was possible to reduce the labor to 18 operators for a production of 150,000 pieces/month." (Ind. Eng. and Innovation Manager – Firm B)	Workforce reduction/Productivity gains	Cost
"We are seeking new technologies to automate manual processes, while also aiming to reduce waste on the shop floor and optimize resource utilization." (Production Manager – Firm B)	Process Automation/ Resource Optimization	
"With sensor technology and IoT, I can now predict maintenance needs. We've already set up a control room that monitors the plant's key machines and operations. There, I analyze and can immediately identify deviations from standard parameters—this has already brought us significant benefits." (Director of Industry for LA – Firm A)	Predictive analytics for waste reduction/ Preventive maintenance	
"You can identify exactly which cars are affected by the problem. So, you don't need to recall 100% of the production - you can trace it back to the specific batch. By integrating Big Data, IoT, and everyone involved, you can achieve much more accurate traceability." (Production Manager: Stamping – Firm C)	Enhanced traceability/Data integration across the chain	Delivery
"We are using information tools to process the data and indicate to us [the problems], within hours, we can see what is happening and take quick actions." (Engineering Manager – Firm D)	Agile decision-making/Real-time production adjustments	
"We reprogrammed the factory on Friday to deliver what was needed on Monday." (Production Manager – Firm B)	Urgent rescheduling for delivery/Rapid response to orders	
"National market is more mature, and it buys in 20 days and wants to receive in 20 days. No company today is sustainable with OTD below 90%." (Director of Industry for LA – Firm A)	On Time Delivery (OTD) as a market qualifier/Maturing delivery expectation	
"Additive manufacturing, not for production process, but for supplies. […] The robot grippers are all built with the characteristics of our product. So, we do all this replacement internally here." (Production Manager – Firm B)	Additive manufacturing for internal supplies/Tooling customization	Flexibility
"About 3D printers… so, throughout the process, we use a lot of components that need to be customized… for example, car bodies are transported on carts or conveyors, and each car model has a different fixation point. With 3D printing, you can produce those fixtures or cradles to hold the car bodies." (Production Manager: Painting – Firm C)	3D printing for process fixtures/Support to customization	

"For example, when we managed to implement an idea to reduce paper use, we achieved a significant reduction by trying to digitalize some processes. Now we're aiming to structure these initiatives with a long-term perspective." (Innovation Manager – Firm A)	Digitalization to reduce waste/Systematic sustainability initiatives	Sustainability
"With the use of IoT and real-time data collection, we were able to identify issues at specific points in the process, such as energy consumption and machine or equipment maintenance. Decision-making has become more accurate and preventive, allowing us to act before digital signals turn into actual problems." (Ind. Eng. and Innovation Manager – Firm B)	Real-Time energy monitoring/Resource optimization	
"With the creation of the Innovation Department, in addition to all the ongoing continuous improvement efforts, we are now also thinking more about digitalization, about bringing new market tools into the company. This includes artificial intelligence, machine learning, and even, in some cases, simply the computerization of existing processes." (Innovation Manager – Firm A)	Digitalization for innovation/Adoption of AI and machine learning	Innovativeness
"Our Innovation Department is tasked with continuously pursuing improvements across all processes - whether in machines, equipment, and devices, or in the way production operates, including its production methodology and workflow." ((Ind. Eng. and Innovation Manager – Firm B)	Continuous improvement and process innovation / Internal innovation promotion	
"With the implementation of these new technologies, we will be able to expand and improve our service sector, where we provide maintenance and overhaul services for compressors... With the use of Edge Computing, Digital Twins, and Artificial Intelligence, data analysis will become more accurate, and we will be able to offer services and parts for this equipment before it presents critical failures that cause unplanned equipment downtime." (Production Manager – Firm B)	Deepening remote monitoring and predictive maintenance as a service	Servitization
"We want to bring greater accessibility to our customers, especially regarding the order status, allowing them to consult all the documentation of the order they bought from us... We want to make this more accessible to the customer... So, we want to implement these digitalization initiatives..." (Innovation Manager – Firm A)	Servitization via digital information access	
"But now there's also a movement where dealerships are trying to implement artificial intelligence for the customer to interact with the car. So, 'my car is making a strange noise, what could it be?' Artificial intelligence will answer you. So, some interactions of the car with the customer are starting to move in that direction." (Production Manager: Stamping – Firm C)	Servitization with customer-product interaction & AI diagnostics (market trend/future direction)	

Furthermore, this thematic analysis established the foundation for the central finding of the study: that the realization of competitive advantage is structured along a dual perspective—the Technological Scope and the Managerial Scope. The aggregate dimensions link enabling technologies (the Technological Scope) to observed practices and processes (the Managerial Scope). This dual finding is the critical empirical input for the conceptual framework, demonstrating that I4.0 performance outcomes are realized not solely through technological adoption, but through the purposeful alignment of these technologies with organizational intent and production logic.

A case in point is the Quality priority, which was closely linked to the deployment of intelligent sensors, IoT-based monitoring systems, and AI-driven defect detection tools. These technologies facilitate real-time process control and significantly reduce human error in inspection routines. By enabling continuous data collection and predictive analytics, they shift quality assurance from a reactive, end-of-line approach to a proactive, in-line model. This transformation embeds digital capabilities into the operational core and enhances the precision, responsiveness, and reliability of the manufacturing process. Table 2 provides a detailed overview of the empirical evidence (first-order quotations and second-order themes) supporting the development of all seven aggregate dimensions.

Cost reductions were frequently attributed to automation and resource optimization, with firms reporting tangible improvements in productivity. Additionally, the integration of predictive analytics and real-time monitoring technologies contributed to minimizing waste and unplanned downtime. These digital capabilities enabled more efficient asset utilization and proactive maintenance strategies, reinforcing cost as a digitally mediated performance outcome.

Delivery emerged as a key competitive priority, increasingly shaped by the integration of real-time data, dynamic production rescheduling, and advanced traceability systems. Firms emphasized the strategic value of being able to reconfigure production lines on short notice or trace affected batches with precision, using Big Data and IoT. These technologies support agile responsiveness, marking a departure from traditional, static production planning toward digitally adaptive operations.

Flexibility, particularly in customized and low-volume environments, was associated with the deployment of additive manufacturing and reconfigurable systems. Companies highlighted how 3D printing accelerated the development of custom fixtures, while collaborative robotics facilitated adaptation to shifting production requirements on the shop floor. These findings suggest that these technologies extend beyond task automation, serving as enablers of configurational flexibility, particularly in customized manufacturing contexts.

Innovativeness and Sustainability were found to be deeply embedded in daily operations through the use of data analytics, digital platforms, and continuous improvement structures. Innovation extended beyond product development to encompass digital process improvement and capability building. Similarly, sustainability was operationalized through digital tools that enabled waste minimization, tracked energy consumption, and facilitated the transition to paperless workflows. These findings suggest that digitalization not only enhances operational efficiency but also fosters a culture of proactive innovation and environmental stewardship.

Servitization, emerging as a novel aggregate dimension, reflects a strategic transformation of manufacturing firms from product-centric operations to solution-oriented business models. This transformation is enabled by technologies such as the IoT, Edge Computing, and Digital Twins, which support the deployment of digitally mediated services, including predictive maintenance and remote diagnostics. These capabilities extend the customer relationship beyond the point of sale, fostering continuous engagement and unlocking new pathways for value creation. The findings suggest that servitization, underpinned by digital infrastructure, is reshaping competitive logic by embedding service delivery into the core of manufacturing strategy.

Furthermore, this thematic analysis established the foundation for the study's central finding: the realization of competitive advantage is structured along a dual perspective—the Technological Scope and the Managerial Scope. The seven aggregate dimensions empirically link enabling technologies (Technological Scope) to the observed practices and processes (Managerial Scope). This empirical duality serves as an important input for the conceptual framework, demonstrating that I4.0 performance outcomes are realized not solely through technological adoption but through the purposeful alignment of these technologies with organizational intent and production logic. This substantiates the study's argument that I4.0 adoption is strategically contingent.

These findings collectively offer a comprehensive perspective on how I4.0 technologies enable and reshape manufacturing competitive priorities. Section 7.5.2 extends this analysis through a comparative examination of the four case firms, while Section 7.5.3 integrates these findings into a conceptual framework that reflects the contingent, dynamic, and strategic nature of I4.0 enabling technologies adoption.

4.2 Cross-case overview of strategic and operational profiles

This section synthesizes the strategic and operational profiles of the four case firms, drawing directly on the seven aggregate dimensions of manufacturing competitive priorities identified through the Gioia methodology in Section 4.1. It emphasizes how each firm's distinct production context, production logic, and strategic orientation influence its adoption of I4.0 technologies and the resulting configuration of competitive priorities. This comparative analysis provides the empirical basis necessary to demonstrate that technological choices are strategically contingent, driven by specific operational needs and intended market positioning, thereby substantiating the conceptual framework presented in Section 4.3.

Case Firm A – Precision Manufacturing for Industrial Measurement

Firm A operates under a customized production model characterized by client-specified features, low production volumes, and a need for agile responses to diverse client requirements. The firm specializes in precision instruments for industrial measurement, where Quality is the principal competitive priority, consistently identified as the primary factor influencing client purchasing decisions. Internally, quality is regarded as the most critical aspect of operations, with efforts to uphold rigorous standards permeating all organizational functions. In recent years, delivery performance has gained strategic importance. Domestic clients, especially those operating in regulated industries such as oil and gas, have heightened their expectations for lead time compliance. According to managerial accounts, this shift has intensified market competition and prompted the firm to enhance its order fulfilment and production planning processes.

Flexibility is pivotal in the Brazilian subsidiary's operations, particularly regarding volume and product configuration. The unit is internally recognized for its efficient setup performance, demonstrating the ability to rapidly adapt to diverse customer specifications while maintaining high standards of precision or traceability.

In terms of innovation, the subsidiary concentrates on operational and process enhancements rather than product development, which remains centralized at the corporate headquarters. Core initiatives, such as the ‘Inova Project’, Kaizen events, and Best Practice Exchanges (BPEs), form the backbone of its innovation strategy. Advancements in digitalization have further strengthened operational effectiveness, with specialized information systems enabling real-time data analysis. These tools enhance visibility into production bottlenecks and inventory dynamics, thereby supporting decision-making processes related to on-time delivery (OTD) and internal performance metrics.

The firm has initiated preliminary efforts to implement a Manufacturing Execution System (MES); however, financial constraints and integration complexities have hindered full-scale deployment. As a transitional measure, the organization has prioritized foundational initiatives, including the use of visual management tools to enhance line-level transparency and promote operator autonomy. Concurrently, the adoption of cloud computing infrastructure is regarded as a strategic enabler of future digitalization, particularly in facilitating the centralization and integration of data streams across production and quality management systems.

Performance within Firm A is perceived as a multidimensional construct, shaped by the interplay among its core operational priorities: Quality, Delivery, and Flexibility. This integrated perspective is reflected in managerial discourse, as one manager noted, *“Performance is the summary of the whole… I need a bit of quality, delivery, a bit of everything to have performance”.* This viewpoint underscores the firm´s commitment to consistently delivering technically advanced products, adhering to stringent lead time requirements, and maintaining adaptability to diverse client specifications, all without compromising precision or traceability, which is especially critical in highly regulated industries.

Case Firm B – Engineering and Automation Solutions

Firm B operates in two distinct segments: the standardized automotive division and the full customized compressors division, which generates the majority of revenue and involves elevated complexity and intensive customer integration. Delivery performance and Flexibility are critical competitive priorities, especially in the complex compressors segment, where urgent customer orders and frequent last-minute changes are routine.

To address flexibility, the firm strategically deploys I4.0 technologies. Additive manufacturing, for instance, is utilized to produce internal tools and robotic grippers, enhancing response times and enabling tailored engineering solutions that support customization and rapid adaptation. The digital transformation strategy follows a phased implementation model, whereby new technologies are initially tested within the more predictable automotive segment before being scaled to the more complex compressors division. This deliberate experimentation reflects a structured approach to embedding flexibility across heterogeneous operations.

Delivery performance is a critical competitive priority, particularly within the compressors segment, where urgent customer orders and frequent last-minute changes challenge the firm's responsiveness. Interviewees emphasized that clients routinely impose tight deadlines, reinforcing the need for cross-functional coordination and operational agility.

Cost efficiency also remains a central concern. Automation initiatives within the automotive division have yielded measurable benefits, including enhanced dimensional repeatability, improved quality outcomes, and a significant reduction in manual labor, collectively contributing to increased production output and operational cost savings.

Technological investments include the incremental implementation of a Manufacturing Execution System (MES), although integration challenges persist due to product variability, especially within the compressors line. The firm's pursuit of I4.0 technologies is further supported by a network of strategic partnerships involving government institutions and startups. These collaborations provide access to financial incentives, specialized technical expertise, and innovation ecosystems, thereby mitigating risk and accelerating technology adoption, an essential advantage for a medium-sized enterprise navigating the complexity of digital transformation.

Case Firm C – Hybrid Model Automotive Manufacturing

Firm C operates in a high-volume, demand-driven production environment, characterized by extensive automation and a strong emphasis on operational standardization. Despite this foundation, the firm is actively transitioning toward a hybrid production model that seeks to integrate the efficiencies of mass production with enhanced customization capabilities. A notable development in this direction is the firm´s growing ability to commercialize vehicles already in production, enabling a more flexible and market-responsive strategy.

The company exhibits a clear alignment with the cost efficiency objectives, driven by its mass production orientation. Technologies such as robotic automation, cyber-physical systems (CPS), and real-time process control systems are employed to ensure takt-time precision, minimize rework, and optimize inventory policies, supporting this strategy. Quality assurance is similarly embedded within automated and standardized processes, with welding, painting, and final assembly lines demonstrating advanced levels of process control and real-time monitoring. These capabilities contribute significantly to defect detection and prevention.

Sustainability initiatives are also present, though often framed within the context of operational efficiency and cost reduction. Technologies that reduce rework, eliminate overproduction, and optimize energy consumption indirectly contribute to resource conservation and environmental impact mitigation.

Organizational culture reinforces agility in decision-making and rapid problem-solving. Managers highlighted that this cultural orientation fosters faster operational responses, process resilience, and effective cross-departmental communication. Such agility is viewed as a key enabler of competitive performance, particularly in dynamic and quality-sensitive markets.

While the plant has made notable progress in adopting I4.0 technologies, digital maturity varies across all production areas. Welding, painting, and final assembly lines are relatively advanced in automation and process monitoring, whereas the stamping area is undergoing a more recent digital transformation, driven by specific quality and integration needs. This uneven maturity reflects a pragmatic, phased approach to digitalization, prioritizing areas with greater operational impact and readiness for change.

For Firm C, performance is closely tied to the outcomes achieved through its strategic focus on Cost, Quality, and Sustainability. The deployment of I4.0 technologies, such as robotic automation and Cyber-Physical Systems, is aimed at enhancing cost management through standardization and waste reduction, rigorous quality control via advanced monitoring systems, and advancing sustainability initiatives, even when primarily linked to efficiency and resource optimization.

Case Firm D – Smart Lean Automotive Assembly

Firm D operates a just-in-time, pull-based production system, aligning precisely with principles of Lean Manufacturing. Its operations exhibit a high degree of synchronisation between customer demand and factory activities. Once a vehicle body receives a chassis number, the product is considered sold, demonstrating a custom logic executed within a high-volume, standardized environment. The firm does not fabricate for stock; instead, it relies on precise takt-time control and supply chain coordination to sustain production flow.

Strategically, the company prioritizes Sustainability and Quality as organizational priorities, followed by Cost efficiency and people management. This hierarchy informs its investments in digital technologies and continuous improvement initiatives. Technologies supporting sustainability are deployed to reinforce lean principles, contributing to precision, stability, and flow across the production line. Rather than treating sustainability as a standalone initiative, the firm embeds it into its operational fabric. For instance, IoT-based energy tracking enables real-time consumption optimization, while automated waste separation and predictive emission control systems help meet environmental targets and integrate sustainability into routine operations.

Industry 4.0 technologies are adopted with the intent to eliminate overburden and waste. Regarding Quality, AI-enhanced camera systems have been integrated into the inspection process, enabling the automated detection of microscopic defects imperceptible to the human eye. These systems continuously learn from production data, improving their accuracy and contributing to the firm’s zero-defect objective.

Real-time data analytics is another critical capability, consolidating and visualizing data across workstations to enable rapid response to deviations, reduce downtime, and maintain productivity targets. Informants report that this capability has significantly improved operational responsiveness and decision-making quality.

Although rooted in traditional lean practices, the firm's digital transformation is deliberately structured to reinforce existing systems rather than replace them. Instead of pursuing full automation, technologies are selectively deployed to support decision-making and simplify workflows, ensuring alignment with lean principles and strategic direction. This approach reflects a balanced integration of I4.0 into a mature lean system.

From a cross-case interpretive summary perspective, each case illustrates a distinct technological trajectory aligned with strategic intent. Firm C emphasizes automation and integration to maximize efficiency in standardized, high-volume production; Firms A and B prioritize Flexibility, Quality, and Innovativeness through advanced sensing, analytics, and customization; and Firm D presents a hybrid model, combining lean practices with smart manufacturing tools to achieve both efficiency and adaptability.

These profiles reinforce the central finding of the study: the strategic deployment of I4.0 technologies is fundamentally shaped by the intersection of the production environment (e.g., custom vs. high volume) and competitive positioning. Firms are not simply adopting technologies; they are strategically configuring them to address differentiated performance priorities (Managerial Scope) and integrating them with specific digital tools (Technological Scope), as codified in the Gioia analysis. This cross-case alignment substantiates the theoretical proposition that digital transformation is best understood as a contingent, context-driven process.

Table 3 presents a comparative overview of the four companies, highlighting their distinct configurations of competitive priorities, technological emphasis, and strategic orientations. These differentiated configurations underscore the contingent nature of I4.0 adoption, revealing how firms strategically orchestrate digital technologies to reinforce their competitive positioning and demonstrate the expanded strategic scope of I4.0.

Table 3. Cross-case comparison highlighting main enabling technologies, manufacturing competitive priorities, and strategic orientations

Company	Sector	Manufacturing Competitive Priorities	Main Enabling Technologies	Strategic Orientation
A	Process Instrumentation and Industrial Measurement	Quality, Delivery	IoT, Automation, Big Data, Cloud Monitoring	Precision manufacturing with process innovation
B	Industrial Automation and Engineering Services	Flexibility, Delivery, Cost	IoT, Automation, Big Data, Additive Manufacturing	Custom engineering solutions with responsive delivery
C	Automotive Manufacturing	Cost, Quality, Sustainability	IoT, Automation, CPS, Big Data	Mass-to-Hybrid production for enhanced market agility
D	Automotive Manufacturing	Sustainability, Quality	IoT, Automation, Big Data, AI	Integrated Lean for quality and sustainability

As illustrated in Table 3, each firm’s configuration of enabling technologies, competitive priorities, and strategic orientation reveals a distinct digital trajectory shaped by its production environment and strategic intent. Although all four firms have adopted core I4.0 technologies, such as IoT, Automation, and Big Data, the emphasis placed on specific tools and their alignment with strategic objectives varies. For instance, Firm A, specializing in precision manufacturing with process innovation, prioritizes Quality and Delivery, leveraging IoT, Big Data, Cloud Monitoring, and Automation for real-time process control, enhanced traceability, and rapid adaptation to customer specifications. Firm B, focused on custom engineering solutions with responsive delivery, emphasizes Flexibility, Delivery, and Cost, deploying Additive Manufacturing, IoT, Big Data, and Automation to enable tailored solutions and enhance delivery agility. Firm C, operating in a mass-to-hybrid production model for enhanced market agility, prioritizes Cost, Quality, and Sustainability, integrating CPS, IoT, Big Data, and Automation to optimize efficiency and ensure robust quality assurance. Finally, Firm D adopts an integrated Lean approach with a strong emphasis on Sustainability and Quality, supported by AI-enhanced inspection systems, IoT-based energy tracking, Big Data, and Automation. These differentiated configurations underscore the contingent nature of I4.0 adoption, revealing how firms strategically orchestrate digital technologies to reinforce their competitive positioning.

This comparative lens underscores the role of I4.0 technologies in achieving strategic goals, illustrating how firms navigate digital transformation to sustain competitive advantage. The cross-case evidences provide the empirical basis for the conceptual framework presented in Section 4.3. This framework articulates how distinct technological configurations and strategic choices reflect contingent pathways to competitiveness, providing a nuanced understanding of how specific operational contexts shape the adoption of I4.0 and its strategic implications.

4.3 Framework: strategic implications of Industry 4.0 adoption

The conceptual framework presented in Figure 1 is the result of a bottom-up coding process based on the Gioia methodology. It synthesizes empirical insights derived from the multiple case studies detailed in Section 4.2. Critically, the framework explicates how I4.0 enabling technologies strategically support diverse manufacturing competitive priorities, demonstrating that technological implementations are shaped by each firm’s unique production environment and overarching strategic orientation. This structured approach offers a robust mapping of how specific strategic choices translate into realized competitive advantages within distinct market contexts.

The framework highlights seven competitive priorities - cost, quality, delivery, flexibility, sustainability, innovativeness, and servitization – and links them to clusters of enabling technologies and managerial practices observed in the field. The latter three (sustainability, innovativeness, and servitization) emerged as distinct, first-order competitive priorities in the I4.0 era, expanding the traditional framework. This analysis reveals a dual perspective for each priority: a Technological Scope (e.g., automation, cyber-physical systems, IoT) and a Managerial Scope (e.g., coordination, responsiveness, integration). This dual perspective is a core finding of the study, as it reinforces the proposition that performance outcomes are not solely driven by technological adoption, but by the alignment of these technologies with organizational intent and production logic. The Managerial Scope thus functions as the integration mechanism that translates technological potential into strategic performance, substantiating the study's core argument that I4.0 adoption is strategically contingent.

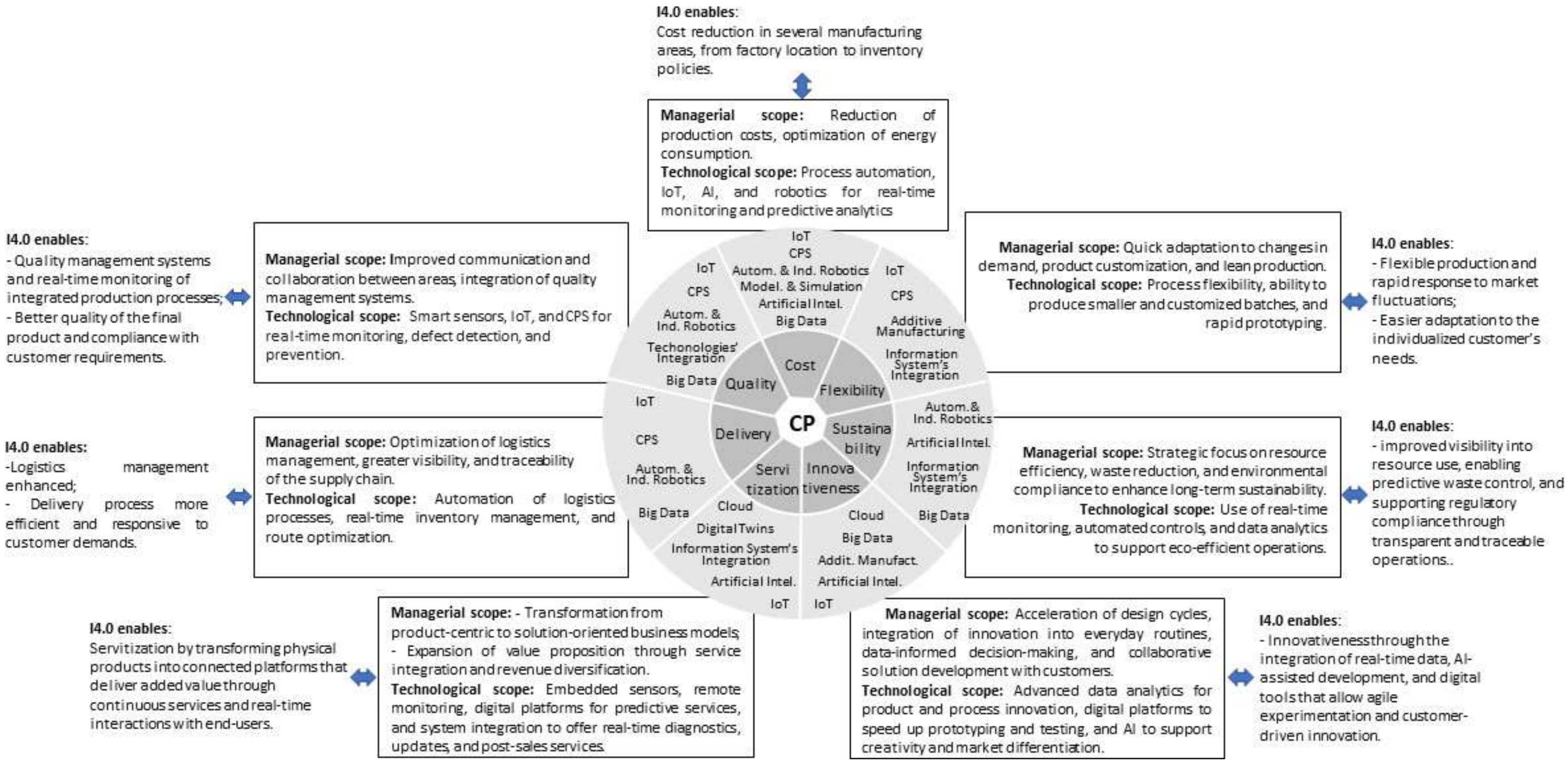
In line with the insights of Enrique *et al.* (2022), the strategic configuration of technologies must be contextually defined. Their work cautions against generic implementation models that overlook the heterogeneity of production goals across firms, emphasizing that I4.0 adoption should follow purpose-specific configurations - for example, leveraging vertical integration to support broad objectives such as productivity, or deploying online traceability or virtual manufacturing to address targeted goals like operational flexibility. This perspective further strengthens the theoretical proposition that the technological architecture of I4.0 must reflect the competitive orientation and manufacturing logic of each organization.

The next subsections unpack each competitive priority individually, linking the conceptual framework to the empirical evidence collected across the case study. Each subsection connects representative first-order quotes and second-order themes, as outlined in Table 2, with the strategic emphasis observed across the case firms (Table 3). This structure enables a granular analysis of how specific technological configurations and managerial practices support distinct performance priorities, offering insight into the contingent nature of I4.0 adoption within varied production contexts.

4.3.1 Quality priority

The integration of IoT sensors and AI-based inspection systems across the studied firms has significantly enhanced quality control by enabling real-time monitoring and defect detection. This technological shift has transformed quality assurance from a reactive to a preventive function, requiring the comprehensive embedding of digital capabilities into the operational routines and fostering stronger alignment between production teams and quality systems.

Figure 1. Conceptual Framework



• Managerial Scope: Strategic practices focusing on accuracy in performing activities, achieving and sustaining high product and process standards. This includes enhanced cross-functional communication and collaborative problem-solving, and the integration of quality management systems that promote proactive assurance and tighter coordination between production and quality functions.

• Technological Scope: The I4.0 technologies enabling quality include:

Smart Sensors and IoT: Enable real-time quality monitoring and control, and precise production data collection.

Automation & Ind. Robotics: Facilitate consistent defect detection and prevention, and support corrective actions with high precision.

Cyber-Physical Systems (CPS): Provide real-time process control and ensure product consistency across production stages.

The framework identifies quality as a core competitive priority reinforced by these technologies. They support continuous inspection, defect tracking, and process control, while also enabling improved alignment between operational and quality functions.

Empirical evidence strongly supports this dimension across all four firms, with Firms A, C, and D consistently prioritizing quality within their strategic logic. For example, Firm A utilizes embedded sensors to support quality assurance processes, while Firm D employs vision systems to detect subtle quality deviations. These technologies enable proactive identification of non-conformities, reduce human error, and improve repeatability. Informants' statements support the Quality aggregate dimension (Table 3), which links technological investments to proactive quality assurance.

From a cross-case perspective (Table 3), Firm A, with its customized high-precision products, leverages remote sensing and data analytics to meet stringent client specifications. Firm C, operating in mass automotive production, achieves quality through automation and standardization. Firm D integrates lean practices with CPS and MES to stabilise operations and uses camera systems for microscopic defect detection. Although Firm B does not explicitly prioritize quality as a primary I4.0-driven objective, its automation initiatives in the automotive segment have led to improved dimensional repeatability, thereby advancing quality performance.

4.3.2 Cost priority

Cost optimization remains a foundational dimension of manufacturing strategy, and the empirical evidence across the studied firms demonstrates that I4.0 technologies are being leveraged not only to reduce labor costs but to enable broader forms of operational efficiency. Technologies such as automation, Artificial Intelligence, and digital monitoring support more sophisticated approaches to cost control by optimizing processes, minimizing waste, and improving energy utilization.

• Managerial Scope: Strategic practices associated with the rationalization of production procedures, lowering expenses, optimizing resources, and boosting productivity through automation and data-driven decisions. This scope also includes workforce reallocation and productivity gains enabled by automation, reflecting a shift from traditional cost-cutting tactics to proactive, technology-driven strategies.

• Technological Scope: The I4.0 technologies supporting cost optimization include:

Process Automation and Robotics: Enhance process efficiency, reduce manual labor, and improve dimensional repeatability.

Real-time Monitoring (IoT/Sensors): Provide continuous oversight of operations, enabling the identification and correction of inefficiencies.

Predictive Analytics (via Big Data): Facilitate waste reduction, anticipate equipment failures, and support proactive maintenance, thereby minimizing downtime and optimizing resource allocation.

Within the Gioia structure (Table 2), cost emerged as an aggregate dimension supported by second-order themes such as Predictive Analytics and Automation. Interviewees provided concrete examples of how digital tools reduce inefficiencies and improve asset utilisation. For instance, Firm B reported substantial productivity gains through workforce reduction and increased output following automation initiatives. Predictive analytics were employed to minimise downtime and improve resource allocation, while IoT-enabled process integration supported more efficient energy usage and waste reduction.

From a cross-case perspective (Table 3), Firm C demonstrated the most direct alignment with the cost dimension, given its high-volume, standardized production model. Technologies such as robotics, CPS, and real-time process control systems are deployed to ensure takt-time precision, reduce rework, and streamline inventory policies. Firm B, which explicitly prioritizes cost alongside flexibility and delivery, achieved notable operational and economic gains through automation initiatives in its automotive line, reducing manual labor while increasing throughput. These digital interventions also improved setup times and consistency, even within its custom production environment. Firm D, while primarily focusing on sustainability and quality, also utilizes I4.0 technologies for cost control, particularly through predictive maintenance and real-time energy monitoring, to manage indirect costs and reinforce lean principles. Although Firm A does not explicitly identify cost as a primary I4.0-driven priority, its use of sensor technology and IoT for predictive maintenance contributes to cost optimization by preventing unplanned downtime and supporting its high-precision production without excessive operational expenditure. These findings underscore that digital transformation enables tailored strategies for cost efficiency, shaped by each firm's production context and strategic orientation. Rather than a one-size-fits-all approach, I4.0 technologies are configured to support differentiated cost priorities.

4.3.3 Delivery priority

Delivery performance, encompassing lead time reduction, schedule reliability, and flow synchronisation, remains a decisive competitive priority in manufacturing. Across the studied firms, digitalization and connectivity have significantly enhanced delivery capabilities by enabling real-time decision making, traceability, and agile production adjustments. I4.0 technologies support responsiveness by providing visibility, integration, and coordination across operations and supply chains.

• Managerial Scope: Strategic practices with a delivery focus on ensuring efficient and responsive supply chain operations. This strategy includes the coordination of production and logistics flows, on-time delivery (OTD), and lead time reduction. Agile decision-making and real-time production adjustments are central to managing variability and synchronizing workflows with strategic precision.

• Technological Scope: The I4.0 technologies enabling delivery performance include:

Real-time Production Visibility (via IoT/Sensors): Enhance traceability and dynamic alignment with order status and inventory levels.

Data-driven Scheduling and Production Control Systems (e.g., MES): Synchronize operations and enable rapid response to orders and urgent rescheduling.

Big Data Integration: Improve traceability and coordination across the supply chain.

Within the framework, delivery is supported by technologies that enable real-time monitoring, digital dashboards, and production control systems; tools frequently cited by interviewees as essential for managing complexity and improving delivery precision. In the Gioia structure (Table 2), delivery-related themes emerged prominently under Planning, Operational Management, and Responsiveness. Empirical evidence illustrates how I4.0 technologies facilitate dynamic alignment between production activities and external demand signals. For example, Firm C employs Big Data and IoT for batch-level recall tracking, while Firms A and B utilize digital dashboards to reprogram production flows in response to urgent customer demands. These capabilities support agile operations and high OTD performance, even under fluctuating demand conditions.

From a cross-case perspective (Table 3), the strategic role of I4.0 technologies in enhancing delivery performance is evident, though emphasized differently across firms. For Firm B, delivery is explicitly a central competitive priority, particularly in its complex compressors segment, where urgent customer demands require high responsiveness. Digital planning tools, IoT-enabled traceability, and rapid rescheduling capabilities enable real-time monitoring adjustments to meet tight deadlines. Firm A has also elevated delivery as a strategic focus, driven by rising expectations for lead time compliance in regulated sectors. It employs specialist information systems for real-time data analysis, enhancing inventory visibility and streamlining order fulfillment. Firm C, operating in a high-volume, demand-driven environment, achieves delivery reliability through technologies that support takt-time precision and inventory optimization (e.g., robotics, CPS, and real-time process control), and batch-level traceability (e.g., Big Data and IoT). Firm D, with its just-in-time, pull-based production system, relies on I4.0 technologies to maintain takt-time control and supply chain coordination, ensuring timely dispatch. Although its primary I4.0-driven priorities are sustainability and quality, real-time analytics and automated systems that reduce deviations and downtime contribute to consistent flow and adherence to dealership schedules. This cross-case analysis demonstrates that I4.0

technologies facilitate diverse approaches to delivery excellence, tailored to each firm’s unique production context and strategic orientation.

4.3.4 Flexibility priority

Flexibility has emerged as a central strategic priority, particularly in manufacturing environments characterized by customization demands and market volatility. Within this framework, flexibility refers to the ability to adapt production volumes, product types, and sequencing in response to customer requirements.

• Managerial Scope: Strategic practices associated with a flexibility focus on operational agility, including adaptation to customer-specific needs, responsiveness to product variety, reduced setup times, flexibility in demand priorities and order sequencing, and the ability to expand the product mix.

• Technological Scope: The I4.0 technologies supporting flexibility include:

Reconfigurable Systems and IoT-enabled Production Control: Enable digital synchronization and system reconfigurability in response to demand changes.

Collaborative Robotics: Facilitate shop floor adaptation and improve setup performance.

Additive Manufacturing: Support rapid prototyping, mass customization, on-demand production, and the creation of customized tooling or fixtures.

Empirical evidence across the case firms demonstrates that flexibility is no longer achieved through traditional buffers and lead-time margins, but through digital synchronization and system adaptability. Firms B and C, for example, implemented 3D printing to produce custom fixtures and robot grippers internally, enabling rapid adjustments for varied product configurations. Automation in assembly processes further supported line reconfiguration and responsiveness to market variation.

From a cross-case perspective (Table 3), I4.0 technologies enhance operational flexibility in diverse ways, shaped by each firm´s production context and strategic orientation. Firms A and B exhibit a strong emphasis on flexibility, aligned with their custom production models. Firm A, operating in a high-precision, low-volume setting, utilizes sensor integration and digital modelling to accommodate client-specific variations while maintaining precision or traceability. Firm B, engaged in complex automation projects, integrates IoT-enabled traceability, real-time analytics, and collaborative robotics to switch efficiently between product designs and respond rapidly to urgent customer demands in its compressor segment. Firm D demonstrates flexibility within a highly standardized lean environment. It employs modular automation and MES-based production sequencing to assemble multiple vehicle variants with minimal impact on lead time, maintaining precise takt-time control while adapting to dealership orders. In contrast, Firm C, operating within a high-volume, standardized production model, exhibits a narrower interpretation of flexibility, primarily focused on volume scaling and takt-time stability. Its evolving customization capability reflects an ongoing effort to balance mass production efficiency with emerging responsiveness. This cross-case comparison highlights how I4.0 enables varied forms of flexibility, ranging from product customization and rapid prototyping to reconfigurable systems and adaptive production sequencing, each contingent on the firm's operational structure and strategic goals.

4.3.5 Sustainability priority

Sustainability has increasingly emerged as a strategic manufacturing priority, driven by regulatory mandates, stakeholder expectations, and corporate social responsibility (CSR) commitments. Within this framework, sustainability refers to the optimization of resource utilization and the minimization of environmental impact, with a focus on embedding eco-efficiency into core operational routines.

• Managerial Scope: Strategic practices associated with sustainability aim to enhance environmental performance and resource efficiency. This includes alignment with environmental standards, reduction of emissions and material usage, and the institutionalization of sustainability within daily operations. Key objectives include advancing CSR goals, ensuring long-term viability, reducing workplace accidents, and minimizing environmental footprint through improved compliance and operational discipline.

• Technological Scope: The I4.0 technologies enabling sustainability include:

Real-time Energy Monitoring (via IoT/Sensors): Enable precise tracking of consumption and identification of optimization opportunities.

Automation: Support waste reduction through automated waste separation and systems that minimise rework and overproduction.

Environmental Performance Dashboards and Data Analytics: Facilitate eco-efficient operations by using AI and Big Data to identify inefficiencies, monitor compliance, and reduce resource consumption (e.g., energy and water).

Process Digitalization: Reduce material waste, such as paper usage, by transitioning to digital workflows.

In the proposed framework, sustainability is supported by a combination of sensor-based monitoring systems, automated environmental controls, and real-time analytics. These technologies enable firms to reduce waste, optimize energy use, and monitor compliance. The Gioia analysis (Table 2) captured Sustainability as an emergent aggregate dimension, supported by second-order themes such as Systematic Sustainability Initiatives and Resource Monitoring and Optimization. Empirical evidence across the case firms illustrates the gradual institutionalisation of sustainability as a strategic manufacturing objective. Firm A reported efforts to reduce paper usage and digitalize workflows, aligning operational practices with long-term environmental goals. Firm B deployed energy monitoring systems to detect and reduce energy waste, supporting resource efficiency. These initiatives reflect a growing maturity in embedding sustainability into day-to-day operations and strategic planning.

From a cross-case perspective (Table 3), sustainability is increasingly integrated into operations, though with varying degrees of strategic emphasis. Firm D stands out for its deliberate and structured approach to environmental performance, leveraging IoT for real-time energy tracking and predictive control systems to manage emissions. These practices reinforce lean principles while enabling the firm to meet environmental targets. Firm C also reports sustainability, often linked to efficiency and cost reduction. Technologies that minimize rework, eliminate overproduction, and optimize energy consumption indirectly contribute to resource conservation and a reduced environmental impact. Firm A aligns its digitalization efforts with sustainability goals, using precision sensors and analytics to minimise material waste. While Firm B places less explicit emphasis on sustainability, it acknowledges the potential of traceability systems and automation to deliver environmental benefits, particularly through energy monitoring systems and waste reduction. This cross-case analysis demonstrates that I4.0 technologies empower firms to pursue sustainability through real-time monitoring, automation, and data analytics. These tools facilitate the integration of environmental considerations into strategic operations, reflecting a growing maturity in aligning digital transformation with sustainability objectives.

4.3.6 Innovativeness priority

Innovativeness represents a strategic frontier in manufacturing, where digital technologies enable new forms of value creation, differentiation, and market responsiveness. Moving beyond operational enhancement, innovativeness reflects a commitment to strategic renewal through continuous adaptation, process evolution, and expansion of value propositions.

• Managerial Scope: Strategic practices associated with innovativeness focus on leveraging technological advancements to accelerate design cycles, test new concepts, embed innovation into daily operations (e.g., continuous improvement, process innovation, knowledge management practices), and market differentiation through co-creation with clients. Firms also pursue smart solutions that extend traditional offerings and enhance competitive positioning.

• Technological Scope: The I4.0 technologies enabling innovativeness include:

Additive Manufacturing (AM): Supports virtual prototyping and accelerates design cycles.

Artificial Intelligence (AI): Facilitates evaluation of new product configurations, process optimization, and continuous improvement.

Cloud Computing: Provides collaborative digital infrastructures and centralizes data streams to accelerate design cycles and embed innovation into daily operations.

Big Data Analytics: Generates insights for new product and process development.

IoT: Enables data collection for co-creation with clients and supports the new product development with innovative features.

In the conceptual framework, innovativeness is supported by technologies that enable virtual prototyping, advanced analytics, and collaborative infrastructures. Across the case firms, digitalization efforts were primarily oriented toward process innovation, though product innovation and strategic renewal were also evident. Firm D, for example, employed AI-driven camera systems to detect quality deviations, illustrating how technology augment lean practices. Firm A emphasized the role of digital dashboards enabled agile decision-making. The establishment of dedicated innovation departments in Firms A and B reflects the organizational structuring of digital transformation initiatives.

From a cross-case perspective (Table 3), innovativeness is increasingly integrated into daily operations through I4.0 technologies, though the emphasis varies by firm. Firm A, while centralizing product development at its headquarters, demonstrates innovativeness through process improvements, using specialist information systems for real-time data analysis to identify production bottlenecks and support performance metrics. The firm also has an 'Innovation Department' and a program named ‘Inova Projects’ that signal a formalized approach to digital transformation. Firm B, whose strategic priorities include flexibility and delivery as central priorities, actively pursues innovation by integrating cloud-based platforms and remote monitoring systems into its offerings. These initiatives expand its value proposition toward smart solutions and are supported by strategic partnerships with government institutions and startups, providing access to technical expertise and accelerating adoption. Firm D applies Artificial Intelligence (AI) for supply chain planning, enabling continuous improvement and operational agility. Its use of AI-enhanced camera systems for microscopic defect detection reflects a readiness for future innovation expansion. Firm C, operating in a mass-production environment, adopts a more incremental approach to innovation, focusing on process refinement and balancing standardization with emerging customization capabilities. This analysis underscores that I4.0 technologies support diverse pathways to innovativeness, from digital process improvement and capability building to new value creation and market differentiation. These approaches are contingent on each firm’s strategic intent, organizational structure, and production environment.

4.3.7 Servitization priority

Servitization reflects a strategic transformation in manufacturing, wherein firms evolve from product-centric entities into solution providers. This shift expands the business model to include digitally enabled services such as predictive maintenance, diagnostics, and remote support, extending the customer relationship beyond the point of sale and opening new avenues for value capture through service integration.

• Managerial Scope: Strategic practices associated with servitization focus on transitioning toward solution-oriented business models. This includes the integration of advanced technical support, predictive maintenance, and remote diagnostics into the value proposition, as well as revenue diversification through service offerings. Key objectives involve enhancing customer accessibility to digital documentation and order status, deepening remote monitoring capabilities, and enabling customer-product interaction via AI-driven diagnostics.

• Technological Scope: The I4.0 technologies enabling servitization include:

IoT: Facilitates data collection from connected products, enabling remote monitoring and service delivery.

Cloud Computing: Supports decentralized data processing for faster insights and centralized infrastructures for collaborative service platforms.

Digital Twins: Create virtual representations of physical assets; allow predictive diagnostic and service interventions before critical failures.

Artificial Intelligence (AI): Enables advanced data analysis and customer interaction in service contexts.

Information Systems Integration**:** Provides customers with real-time access to diagnostics, documentation, and operational updates.

In the conceptual framework, servitization is supported by technologies that enable real-time connectivity, condition-based services, and digital co-creation. While not always explicitly labelled as “servitization” by interviewees, the Gioia analysis (Table 2) captured this dimension through themes such as smart services and digital value extension. For example, Firm B articulated its intent to implement Digital Twins and remote monitoring systems for compressors, aiming to offer predictive maintenance and overhaul services before failure. A first-order quote, *“With the new technologies developed, we will make a single trip where sensors and the necessary electronics will be installed… Digital Twins will be implemented on the field machine and at the firm´s base…”*, illustrates a clear trajectory toward service-oriented transformation.

From a cross-case perspective (Table 3), Firm B has taken concrete steps towards servitization, deploying IoT and remote diagnostics to support smart services. Its strategic partnerships with government institutions and startups further reinforce its ambition to expand service capabilities. Firm D also demonstrates potential for servitization, leveraging AI and remote connectivity to track operational parameters and support defect diagnostics. Its use of AI-driven car diagnostics signals a future orientation toward service-based value creation. Firm A shows intent to enhance customer accessibility through digital dashboards and documentation, aligning with servitization by extending digital value into the customer relationship. While Firm C does not explicitly prioritize servitization, its advanced process control and real-time monitoring systems could serve as a foundation for future service offerings.

These findings suggest that servitization, though still emerging, represents a meaningful trajectory for manufacturing firms seeking to reposition themselves in the digital era. I4.0 technologies provide the backbone for this transition, enabling real-time connectivity, predictive services, and value co-creation beyond the factory floor. The strategic integration of these technologies supports the evolution of manufacturing firms into holistic solution providers, capable of delivering sustained value across the product lifecycle.

5 Discussion

5.1 Alignment with existing research

The findings of this study provide robust empirical support for the proposition advanced by Enrique et al. (2022), namely that the adoption of I4.0 enabling technologies should not follow a standardized implementation path, but rather be tailored to specific performance objectives and operational contexts. While prior research, such as Enrique et al. (2022), established the general principle of contingent I4.0 adoption, our multiple-case study further refines this understanding by detailing how distinct production logics strategically configure technological solutions to align with differentiated competitive priorities, ranging from highly customized, low-volume operations (Firm A) to standardized, high-volume settings (Firm C), and hybrid or lean-integrated models (Firms B and D). For example, our cases reveal how digital tools are leveraged to enhance traceability and delivery responsiveness (Firms A and B), improve energy efficiency in pursuit of sustainability goals (Firms C and D), and support operational flexibility through additive manufacturing (Firms A and B). This context-specific deployment is particularly salient in developing economies, where adoption patterns may differ from those in developed countries, a nuance highlighted by Reis and Camargo Júnior (2024). Our in-depth qualitative insights thus underscore that the effectiveness of I4.0 technologies is profoundly contingent upon their strategic alignment with production goals, demanding purposeful orchestration to generate meaningful performance outcomes.

Moreover, the findings of this study reinforce existing literature, which positions I4.0 implementation not merely as a technological upgrade but as a strategic transformation demanding significant managerial and organizational adaptation (Elnadi and Abdallah, 2024). The establishment of dedicated innovation departments in Firms A and B exemplifies how organizational structures are evolving to support digital transformation initiatives.

The empirical findings of this study significantly advance the theoretical discourse by demonstrating that digital adoption is inherently contingent upon firm-level strategic orientation. This context-specific deployment of technologies substantiates Enrique et al.'s (2022) assertion that gains in flexibility, quality, and productivity do not solely depend on the presence of digital tools, but on their purposeful orchestration in alignment with strategic goals. The cross-case analysis reveals that while foundational technologies such as vertical integration and cyber-physical systems (e.g., in Firm C) support multiple performance dimensions, more specialized configurations such as digital twins and cloud platforms are selectively employed to address targeted priorities like servitization (e.g., Firm B) and innovativeness. Our inductive Gioia methodology allowed us to uncover and richly contextualize the emergence of Sustainability, Innovativeness, and Servitization as core strategic imperatives, moving beyond the traditionally emphasized dimensions of Cost, Quality, Delivery, and Flexibility. This expansion is not merely an addition but a re-conceptualization of competitiveness in the digital age. For instance, the drive towards Servitization, often overlooked in traditional manufacturing, is vividly illustrated by Firm B's intent to implement Digital Twins for predictive maintenance and overhaul services. As Firm B's manager articulated, *"With the new technologies, we will make a single trip where sensors and the necessary electronics will be installed… Digital Twins will be implemented on the field machine and at the firm´s base…"*. This aligns with Paiola et al. (2024), who emphasize how digital servitization strategies are closely associated with business model innovation and frequently supported by knowledge-intensive business services (KIBS). Our qualitative data provides direct empirical grounding for this global phenomenon in a Brazilian context, showing how firms are fundamentally restructuring their value propositions to offer intelligent, data-driven services. Similarly, the integration of Sustainability is not merely compliance but a strategic driver, as seen in Firm D's use of IoT for real-time energy tracking to reinforce lean principles and meet environmental targets. These insights move beyond merely reinforcing prior work to offer a refined and context-specific understanding of how I4.0 reshapes manufacturing strategy, particularly in developing economies where resource and institutional contexts may present unique challenges and opportunities.

5.2 Theoretical contributions

This study makes three primary theoretical contributions to the manufacturing strategy and Industry 4.0 literature, expanding on the core arguments outlined in our introduction.

Our primary theoretical contribution is the expansion of the traditional competitive priorities framework. While classic dimensions like cost, quality, delivery, and flexibility remain relevant, our findings empirically establish Sustainability, Innovativeness, and Servitization as distinct, first-order competitive priorities in the I4.0 era. We demonstrate that technologies like IoT-based energy monitoring elevate sustainability beyond a mere cost-saving activity to a strategic imperative for resource optimization and environmental management (Firms D and B). Similarly, we show that innovativeness becomes embedded in strategy through digital process improvements and dedicated organizational structures (Firms A and B), enabled by technologies such as AI and Digital Twins. Lastly, we identify Servitization as a profound strategic transformation, where firms leverage IoT, Digital Twins, and AI to evolve from product manufacturers to solution providers, a shift often supported by knowledge-intensive business services (KIBS) that facilitate business model innovation.

Our second contribution directly addresses the theoretical clarity lacking in the integration mechanisms that translate technological potential into competitive outcomes. The study proposes that the realization of competitive advantage is structured along a dual perspective—the Technological Scope and the Managerial Scope. We provide robust evidence that I4.0 adoption is not uniform but strategically contingent. Crucially, we identify the Managerial Scope as the empirically grounded integration mechanism that explains how this contingency is operationalized. By articulating this dual finding, the framework demonstrates that I4.0 performance outcomes are realized not solely through technological adoption but through the purposeful alignment of these technologies with organizational intent and production logic. This alignment refines prior work by Enrique et al. (2022), which established the principle of contingency, by offering granular empirical detail on *how* this contingency unfolds across distinct production logics and strategic intent. Our multiple-case analysis illustrates how digital tools are leveraged for different strategic objectives: enhancing traceability for delivery responsiveness (Firms A and C), improving energy efficiency for sustainability goals (Firms C and D), and supporting operational flexibility through additive manufacturing (Firms B and C).

In closing, this study highlights the essential role of managerial and organizational enablers in facilitating this digital transformation. Our findings show that digital transformation is accelerated by external collaborations and internal capabilities. Strategic partnerships with government institutions, startups, and KIBS provide access to technical expertise and mitigate financial risks. Internally, the creation of dedicated innovation departments, as observed in Firms A and B, reflects a deliberate organizational structuring to drive and manage the integration of I4.0, underscoring that technological implementation must be accompanied by strategic and structural adaptation.

By explicitly integrating these expanded dimensions and underscoring the role of the Managerial Scope in orchestrating the strategic contingency of I4.0 enabling technologies implementation, this study provides a more comprehensive framework for evaluating I4.0 adoption and elevates the theoretical understanding of manufacturing strategy in the digital era.

5.3 Managerial implications

Manufacturing managers navigating the complexities of the adoption of I4.0 and strategic competitive alignment can derive several actionable insights from this study. These implications are crucial for effectively leveraging I4.0 technologies to achieve operational excellence and secure long-term competitive advantage in dynamic markets.

Firstly, managers should proactively cultivate strategic alliances and engage in innovation ecosystems. Collaborations with research institutions, technology providers, and *startups* offer critical access to cutting-edge technical expertise, financial incentives, and opportunities for collaborative co-creation. This approach is particularly vital for Small and Medium-sized Enterprises (SMEs), which can mitigate resource limitations and capacity gaps by engaging with specialized Knowledge-Intensive Business Services (KIBS). KIBS act as knowledge brokers, providing both technological and managerial contributions that help firms design and implement their innovation journeys, especially in digital servitization. Government initiatives also play a significant role in fostering and financing I4.0 projects, demonstrating the importance of external support. Furthermore, managers should recognize that supply chain relationships can act as "communicating vessels" for I4.0 technology learning and diffusion, especially between large and medium-sized enterprises, presenting strategic opportunities for SMEs to improve performance and competitiveness.

Secondly, investment in and operationalization of real-time data collection and advanced analytics capabilities are paramount for fostering proactive decision-making and operational agility. Technologies such as the Internet of Things, Big Data, Artificial Intelligence, and machine learning enable a critical shift from reactive problem-solving to predictive insights. These technologies allow for the optimization of production processes, significant enhancement of traceability, robust support for predictive maintenance, and improved responsiveness in dynamic operational environments. For example, firms can utilize IoT sensors and AI for real-time quality monitoring and defect detection, transforming quality assurance into a preventive function, and deploy predictive analytics to minimize waste and unplanned downtime, reinforcing cost efficiency. Similarly, real-time data integration through Cyber-Physical Systems and the Internet of Things enhances delivery performance through dynamic scheduling and rapid adjustments.

Thirdly, managers must recognize and strategically position sustainability as an intrinsic driver of competitive advantage, moving beyond its traditional role as a mere compliance or cost-reduction objective. I4.0 technologies, such as IoT-based energy monitoring, automated waste separation systems, and predictive control systems, should be deliberately deployed to optimize resource utilization, minimize environmental impact, and reinforce corporate social responsibility. These initiatives contribute significantly to long-term viability, bolster stakeholder trust, and enhance brand reputation. Integrating sustainability deeply into the operational fabric, as demonstrated by Firm D, not only meets environmental targets but also reinforces lean principles and efficiency.

Finally, to effectively evaluate the impact of I4.0 adoption, managers are strongly advised to adopt a holistic performance measurement framework. This expanded framework should extend beyond traditional metrics—such as cost, quality, delivery, and flexibility—to explicitly include Innovativeness, Servitization, and Sustainability as key performance indicators. Such a comprehensive view ensures a more accurate and profound assessment of digital transformation's influence on strategic competitive priorities and value creation in contemporary manufacturing environments, reflecting the redefinition of competitiveness in the digital era. This means evaluating how I4.0 enables product development acceleration and design flexibility for innovativeness, and how it facilitates the evolution into solution providers through services like predictive maintenance and remote diagnostics for Servitization.

5.4 Limitations and future research

This study, while offering valuable insights into I4.0 implementation within manufacturing firms, is subject to certain limitations stemming from its research design and scope. These limitations, alongside opportunities for deeper understanding, also pave the way for several promising avenues for future research.

The study's qualitative design and contextual scope are inherent limitations. The findings are derived from a small sample size of manufacturing firms operating exclusively in Brazil. This approach means the generalizability of the results is constrained beyond the specific context examined. The reliance on managerial perceptions, which are dynamic and subject to evolution, further impacts the generalizability of the findings. Concerns have also been highlighted by related literature regarding the challenges of extrapolating insights from Brazil’s industrial landscape due to its unique cultural dynamics.

To address these limitations and further advance the understanding of I4.0 adoption, several avenues for future research are suggested:

Firstly, expanding the scope and conducting comparative studies would be highly beneficial. Future research should aim to include a larger and more diverse sample of firms across multiple industrial sectors or engage in cross-country comparisons. Such studies could explore how varying regulatory environments, market maturities, and institutional conditions shape the adoption of I4.0 and its impact on competitive priorities, thereby enhancing both generalizability and contextual richness.

Secondly, while this study employed qualitative methods to develop a conceptual framework, future research could apply quantitative approaches to validate and extend these insights. This would involve survey-based studies and statistical modeling to quantify the impact of I4.0 technologies on specific competitive priorities and to explore the relationships between I4.0 enabling technologies, competitive priorities, and performance outcomes at scale.

Finally, longitudinal research tracking firms over time would offer a deeper understanding of the sustained effects of I4.0 adoption. Such studies could illuminate how competitive priorities evolve, how innovation capabilities mature, and how digital transformation influences long-term financial performance. Capturing these dynamics would provide a more comprehensive understanding of the strategic trajectory of digital transformation within manufacturing firms.

6 Conclusion

This study rigorously explored how Industry 4.0 (I4.0) enabling technologies shape the configuration of competitive priorities in manufacturing. By integrating a multiple-case study approach with the Gioia methodology, this research offered a structured and systematic analysis that captures both organizational perspectives and theoretical advancements in the domain of digitally driven manufacturing strategy.

Grounded on inductive theorization, the findings reveal that I4.0 adoption is not standardized but strategically contingent. Firms align digital technologies with their unique production realities and competitive intent, deploying them in differentiated ways to support distinct combinations of classic priorities — such as cost, quality, flexibility, and delivery—and emerging ones, including Sustainability, Innovativeness, and Servitization. This nuanced understanding positions I4.0 enabling technologies not merely as operational tools, but as strategic enablers conditioned by organizational context and market dynamics. The collective evidence suggests that I4.0 technologies strengthen firms' capacity to meet traditional manufacturing priorities while simultaneously enabling the pursuit of new strategic objectives that reflect evolving societal and market expectations. Digital transformation, therefore, is not simply a matter of technological adoption but represents a redefinition of competitiveness, shifting emphasis from efficiency alone to agility, service integration, sustainability, and innovation-driven differentiation.

The conceptual framework proposed herein contributes to theory by extending traditional models of manufacturing strategy to account for digitally induced evolution in competitive priorities. By explicitly incorporating Sustainability, Innovativeness, and Servitization, the study offers a more comprehensive lens through which to evaluate alignment in the digital era. Crucially, the framework articulates the strategic realization of competitive advantage through a dual perspective—the Technological Scope and the Managerial Scope. This empirical duality, acting as the integration mechanism, demonstrates that performance outcomes are realized not solely through technological adoption but through the purposeful alignment of these technologies with organizational intent and production logic. This finding addresses a key theoretical gap by clarifying the mechanisms through which technological potential is translated into strategic performance.

For practitioners, the findings emphasize the importance of aligning digital initiatives with broader strategic goals and highlight the critical role of managerial capabilities, organizational structures, and strategic partnerships in sustaining transformation. This underscores the need for managers to move beyond technological investment to ensure the strategic orchestration of technologies, people, and processes to create resilient and differentiated paths to competitiveness.

While the study is limited in scope and generalizability due to its qualitative design and contextual focus, it provides a valuable conceptual foundation for future research. Subsequent investigations may build on these findings by employing quantitative methods, conducting cross-country comparisons, or exploring the longitudinal dynamics of digital strategy formation. Ultimately, thriving in the digital era will require more than adopting advanced technologies; it will demand the strategic orchestration of technologies, people, and processes to create resilient and differentiated paths to competitiveness.

References

Abdullah, F.M., Saleh, M., Al-Ahmari, A.M., Anwar, S., 2022. The impact of Industry 4.0 technologies on manufacturing strategies: Proposition of technology-integrated selection. IEEE Access, 10, 21574–21589. https://doi.org/10.1109/ACCESS.2022.3151898

Abdullah, F.M., Al-Ahmari, A.M., Anwar, S., 2023. An integrated fuzzy DEMATEL and fuzzy TOPSIS method for analyzing smart manufacturing technologies. Processes, 11, 906. https://doi.org/10.3390/pr11030906

Achouch, M., Dimitrova, M., Ziane, K., Sattarpanah Karganroudi, S., Dhouib, R., Ibrahim, H., Adda, M., 2022. On predictive maintenance in Industry 4.0: Overview, models, and challenges. Appl. Sci. 12 (16), 8081. https://doi.org/10.3390/app12168081

Arcidiacono, F., Ancarani, A., Di Mauro, C., Schupp, F., 2023. What drives I4.0 adoption? Establishing the importance of strategy. IEEE Eng. Manag. Rev. 51 (3), 33–41. https://doi.org/10.1109/EMR.2023.3281549

Bhatia, M.S., Kumar, S., 2020. Critical success factors of Industry 4.0 in automotive manufacturing industry. IEEE Trans. Eng. Manag. 69 (5), 2439–2453. https://doi.org/10.1109/TEM.2020.3017004

Chiarini, A., Kumar, M., 2021. Lean Six Sigma and Industry 4.0 integration for operational excellence: Evidence from Italian manufacturing companies. Prod. Plan. Control, 32 (13), 1084–1101. https://doi.org/10.1080/09537287.2020.1784485

Dohale, V., Gunasekaran, A., Akarte, M., Verma, P., 2022. 52 years of manufacturing strategy: An evolutionary review of literature (1969–2021). Int. J. Prod. Res. 60 (2), 569–594. https://doi.org/10.1080/00207543.2021.1971788

Dohale, V., Verma, P., Gunasekaran, A., Akarte, M., 2023. Manufacturing strategy 4.0: A framework to usher towards Industry 4.0 implementation for digital transformation. Ind. Manag. Data Syst. 123 (1), 10–40. https://doi.org/10.1108/IMDS-12-2021-0790

Eisenhardt, K.M., 1989. Building theories from case study research. Acad. Manag. Rev. 14 (4), 532–550. https://doi.org/10.2307/258557

Elnadi, M., Abdallah, Y.O., 2024. Industry 4.0: Critical investigations and synthesis of key findings. Manag. Rev. Q. 74, 711–744. https://doi.org/10.1007/s11301-022-00314-4

Enrique, D.V., Marodin, G.A., Santos, F.B.C., Frank, A.G., 2022. Implementing Industry 4.0 for flexibility, quality, and productivity improvement: Technology arrangements for different purposes. Int. J. Prod. Res. 61 (20), 7001–7026. https://doi.org/10.1080/00207543.2022.2142689

Frank, A.G., Dalenogare, L.S., Ayala, N.F., 2019. Industry 4.0 technologies: Implementation patterns in manufacturing companies. Int. J. Prod. Econ. 210, 15–26. https://doi.org/10.1016/j.ijpe.2019.01.004

Gaiardelli, P., Pezzotta, G., Rondini, A., Romero, D., Jarrahi, F., Bertoni, M., Wiesner, S., Wuest, T., Larsson, T., Zaki, M., Jussen, P., Boucher, X., Bigdeli, A.Z., Cavalieri, S., 2021. Product-service systems evolution in the era of Industry 4.0. Serv. Bus. 15 (2), 177–207. https://doi.org/10.1007/s11628-021-00438-9

Gioia, D.A., Corley, K.G., Hamilton, A.L., 2013. Seeking qualitative rigor in inductive research: Notes on the Gioia methodology. Organ. Res. Methods, 16 (1), 15–31. https://doi.org/10.1177/1094428112452151

Götz, M., Jankowska, B., 2020. Adoption of Industry 4.0 technologies and company competitiveness: Case studies from a post-transition economy. Foresight STI Gov. 14 (4), 61–78. https://doi.org/10.17323/2500-2597.2020.4.61.78

Hermann, M., Pentek, T., Otto, B., 2016. Design principles for Industry 4.0 scenarios. Proc. Hawaii Int. Conf. Syst. Sci. 49, 3928–3937. https://doi.org/10.1109/HICSS.2016.488

Johanesa, A.T.V., Equeter, L., Mahmoudi, S.A., 2024. Survey on AI applications for product quality control and predictive maintenance in Industry 4.0. Electronics, 13, 976. https://doi.org/10.3390/electronics13050976

Lattanzi, L., Raffaeli, R., Peruzzini, M., Pellicciari, M., 2021. Digital twin for smart manufacturing: A review of concepts towards a practical industrial implementation. Int. J. Comput. Integr. Manuf. 34 (6), 567–597. https://doi.org/10.1080/0951192X.2021.1911003

Machado, C.G., Winroth, M., Ribeiro da Silva, E., 2020. Sustainable manufacturing in Industry 4.0: An emerging research agenda. Int. J. Prod. Res. 58 (5), 1462–1484. https://doi.org/10.1080/00207543.2019.1652777

Maretto, L., Faccio, M., Battini, D., 2023. The adoption of digital technologies in the manufacturing world and their evaluation: A systematic review of real-life case studies and future research agenda. J. Manuf. Syst. 68, 576–600. https://doi.org/10.1016/j.jmsy.2023.05.009

Moeuf, A., Lamouri, S., Pellerin, R., Tamayo-Giraldo, S., Tobon-Valencia, E., Eburdy, R., 2020. Identification of critical success factors, risks and opportunities of Industry 4.0 in SMEs. Int. J. Prod. Res. 58 (5), 1384–1400. https://doi.org/10.1080/00207543.2019.1636323

Paiola, M., Grandinetti, R., Kowalkowski, C., Rapaccini, M., 2024. Digital servitization strategies and business model innovation: The role of knowledge-intensive business services. J. Eng. Technol. Manag. 74, 101846. https://doi.org/10.1016/j.jengtecman.2024.101846

Prabhu, M., Nambirajan, T., Abdullah, N.N., 2020. Analytical review on competitive priorities for operations under manufacturing firms. J. Ind. Eng. Manag. 13 (1), 38–55. https://doi.org/10.3926/jiem.2876

Ramesh, P.G., Dutta, S.J., Neog, S.S., Baishya, P., Bezbaruah, I., 2020. Implementation of predictive maintenance systems in remotely located process plants under Industry 4.0 scenario. In: Karanki, D., Vinod, G., Ajit, S. (Eds.), Advances in RAMS Engineering. Springer Series in Reliability Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-36518-9_12

Reis, F.B. dos, Camargo Júnior, A.S.C., 2024. Industry 4.0: An investigation of benefits and barriers with managers of Brazilian manufacturers adopters. J. Eng. Technol. Manag. 71, 101786. https://doi.org/10.1016/j.jengtecman.2023.101786

Sousa, T.B., Guerrini, F.M., Oliveira, M.R., Cantorani, J.R.H., 2025. Industry 4.0 and collaborative networks: A goals- and rules-oriented approach using the 4EM method. Platforms, 3 (3), 14. https://doi.org/10.3390/platforms3030014

Tedaldi, G., Miragliotta, G., 2023. Early adopters of Manufacturing-as-a-Service (MaaS): State-of-the-art and deployment models. J. Manuf. Technol. Manag. 34 (4), 580–600. https://doi.org/10.1108/JMTM-01-2022-0052

Wan, J., Li, X., Dai, H.-N., Kusiak, A., Martínez-García, M., Li, D., 2021. Artificial-intelligence-driven customized manufacturing factory: Key technologies, applications, and challenges. Proc. IEEE, 109 (4), 377–398. https://doi.org/10.1109/JPROC.2020.3034808

Yilmaz, A., Dora, M., Hezarkhani, B., Kumar, M., 2022. Lean and Industry 4.0: Mapping determinants and barriers from a social, environmental, and operational perspective. Technol. Forecast. Soc. Change, 175, 121320. https://doi.org/10.1016/j.techfore.2021.121320

Appendix A

Interview Protocol: Strategic Alignment of Industry 4.0 Technologies and Manufacturing Priorities

Research Objective	Interview Question
Identify the existence of strategic policies for manufacturing and how they are formulated	1. How are strategic policies for the manufacturing area defined?
Identify competitive priorities, their ranking, and practices for achieving them	2. Please rank the competitive priorities (dimensions) for the manufacturing area in order of importance (1 = most important). You may add others if relevant. 3. What actions or policies has the company implemented to achieve these manufacturing competitive priorities?
Detect the application of Industry 4.0 technologies and the motivation behind their implementation	4. Which tools/technologies associated with Industry 4.0 has the company implemented? Feel free to include technologies not listed in Table 1 if applicable. 5. What motivated the company to start implementing Industry 4.0 technologies? 6. When did the implementation of these tools/technologies begin?
Examine the alignment between current I4.0 technologies and manufacturing priorities	7. How do the Industry 4.0 technologies already in use relate to the achievement of the company's targeted manufacturing competitive priorities (as per question 2)?
Verify alignment between planned I4.0 technologies and future manufacturing priorities	8. Which Industry 4.0 tools/technologies does the company plan to adopt within the next five years? 9. How are these planned Industry 4.0 technologies expected to contribute to the achievement of the company's future manufacturing competitive priorities?

8 ARTIGO 3 - A DELPHI STUDY ON THE EXTENDED MANUFACTURING COMPETITIVE PRIORITIES FRAMEWORK IN THE INDUSTRY 4.0 SCENARIO

Abstract

The domain of Industry 4.0 (I4.0) is currently marked by conceptual immaturity and a lack of widely accepted definitions. This necessitates external validation to ensure the robustness and practical applicability of strategic conceptual frameworks. To address this, our study employed the rigorous Delphi method to validate and refine an extended conceptual framework. This framework maps the relationship between I4.0 enabling technologies and manufacturing competitive priorities through consensus achieved among qualified academic and professional experts. The proposed framework employs a Dual Perspective (Technological Scope and Managerial Scope) and integrates the four traditional competitive priorities with three empirically established first-order strategic imperatives: Sustainability, Innovativeness, and Servitization. The Delphi process successfully achieved a high level of expert consensus, confirmed by a strong internal consistency metrics. Crucially, this process mandated key conceptual adjustments that significantly refined the Managerial Scope of the model. The resulting final validated model expands manufacturing strategy by legitimizing these three emerging priorities. It confirms that achieving strategic performance is dependent on the intentional alignment of technologies with production logic and organizational intent, thereby providing a robust strategic reference for decision-making and strengthening both the theoretical consistency and managerial applicability in real-world manufacturing contexts.

Keywords: Technological Scope, Managerial Scope, Manufacturing Strategy, Expert Panel.

1. Introduction

Recent advances in digital technologies are profoundly reshaping the foundations of manufacturing, introducing new paradigms that challenge established production models and strategic assumptions. This transformation is embodied by Industry 4.0 (I4.0), often described as the Fourth Industrial Revolution, which encompasses core enabling technologies such as the Internet of Things, Cloud Computing, and Cyber-Physical Systems, which collectively drive profound organizational and operational transformations (Alcácer & Cruz-Machado, 2019; Fatorachian & Kazemi, 2018; Lasi et al., 2014). These technological drivers are propelled by increasingly dynamic market environments, characterized by heightened global competition and rapidly evolving customer demands (Bibby & Dehe, 2018; Weking et al., 2020).

Successfully leveraging I4.0 requires substantial strategic and managerial adaptation, extending beyond the technical deployment of new tools (Frank et al., 2019; Müller et al., 2018). While advanced technologies are central, they cannot be understood merely as isolated components; organizational and managerial structures act as critical enablers for navigating the complexity of this transition (Kiel et al., 2017; Schneider, 2018). Integrating technological and managerial dimensions is therefore essential to achieve core manufacturing objectives such as flexibility, quality, and productivity (Schuh et al., 2020).

Nevertheless, the I4.0 domain continues to be characterized by conceptual immaturity and the absence of widely accepted definitions among scholars (Fettermann et al., 2018; Fratocchi & Di Stefano, 2020; Lu, 2017). Given this uncertainty, conceptual frameworks designed to guide strategic implementation requires rigorous external validation to ensure their robustness, relevance, and applicability in real manufacturing contexts (Elnadi & Abdallah, 2023; Kritzinger et al., 2018; Müller et al., 2018). The Delphi method is particularly well-suited for this purpose, as it synthesizes expert perspectives to build consensus on emerging topics where established theory remains incomplete (Elnadi & Abdallah, 2023).

Against this background, the guiding research question is: To what extent do expert perspectives validate the extended framework for manufacturing competitive priorities in Industry 4.0, and what conceptual and managerial refinements are necessary to achieve a robust and applicable final model?

Accordingly, the objective of this study is to validate an extended conceptual framework, which maps Industry 4.0 adoption and manufacturing competitive priorities through consensus-building among a panel of qualified academic and professional experts. Meeting this objective ensures that the resulting model is both theoretically consistent and practically relevant for strategic decision-making in manufacturing organizations. The Delphi method, chosen for this purpose, is well suited to achieving consensus on complex issues characterized by uncertainty and incomplete theory. Meeting this objective ensures that the final model is both theoretically robust and practically relevant for manufacturing organizations.

The Introduction establishes the need to validate the conceptual model derived from empirical research. Section 2, Conceptual Framework, presents the initial model that served as input for the Delphi study. The following section, Methodology, details the selection and application of the Delphi Method, explicitly addressing statistical rigor and the purposive sampling strategy. The Results section presents the quantitative findings (consensus/agreement) and the qualitative adjustments mandated by the expert panel. In Section 5, Discussion, analyses the validation of the model´s Dual Perspective and Strategic Contingency, alongside the contributions to theory and managerial practice. Finally, the Conclusion section summarizes the main findings and reaffirms the achievement of the article’s objective.

2 Conceptual Framework: Input for the Delphi Study

This section presents the foundational conceptual framework, which served as the primary input for the subsequent Delphi validation study. This model was developed through an inductive, empirical investigation grounded in multiple case studies, aiming to systematically map the relationship between digital technologies and strategic outcomes in manufacturing.

The framework articulates seven distinct competitive priorities: the four traditional dimensions (Cost, Quality, Delivery, and Flexibility) and three emerging priorities - Sustainability, Innovativeness, and Servitization - which were empirically established as critical, first-order strategic imperatives in the Industry 4.0 era.

- Sustainability: Defined as optimizing resource utilization and minimizing environmental impact (Silva et al. 2009).
- Innovativeness: Focused on strategic renewal, continuous adaptation, and expansion of value propositions, often involving technology-assisted design and experimentation (Abdullah et al. 2022).
- Servitization: Described as the transformation from product-centric to solution-oriented business models, enabled by digital services such as predictive maintenance and remote diagnostics (Vivares et al. 2022).

A core principle embedded in the framework is the Dual Perspective, which structures the strategic realization of competitive advantage along two interconnected mechanisms: the Technological Scope and the Managerial Scope.

The Technological Scope represents the cluster of I4.0 enabling technologies (e.g., IoT, AI, Robotics) deployed to support a given competitive priority. The Managerial Scope operates as the critical mediating mechanism, translating technological potential into measurable performance outcomes through purposeful organizational intent and production logic. This distinction is crucial, as performance gains are realized not solely through technology adoption but through the strategic orchestration of technologies and managerial intent.

The framework models the I4.0 influence by detailing the Managerial Scope and Technological Scope for each priority, as summarized in Table 1. This comprehensive framework details how technology and management practices intersect to drive competitive advantage in the I4.0 environment.

3 Methodology: Delphi Method and Panel Profile

This study employed the Delphi method to conduct external validation and refinement of the extended conceptual framework. The Delphi method is a well-established exploratory research technique, selected for its suitability in synthesizing expert opinion and achieving consensus on complex or emerging issues characterized by uncertainty and incomplete theory (Elnadi & Abdallah, 2023; Hsu & Sandford, 2007). It is particularly appropriate for strengthening the theoretical consistency and managerial applicability of conceptual models derived from prior exploratory work (Torrecilla-Salinas et al., 2017; Okoli & Pawlowski, 2004).

Table 1 – Conceptual model content

Competitive Priority	**Managerial Scope (MS)**	**Technological Scope (TS)**	**I4.0 Enables (Systemic Implementation - SI)**
Cost	Reduction of production costs, optimization of energy consumption.	Process automation, IoT, AI, and robotics for real-time monitoring and predictive analytics.	Cost reduction in several manufacturing areas, from factory location to inventory policies.
Quality	Improved communication and collaboration between areas, integration of quality management systems.	Smart sensors, IoT, and CPS for real-time monitoring, defect detection, and prevention.	Quality management systems and real-time monitoring of production processes integrated; Better quality of the final product and compliance with customer requirements.
Delivery	Optimization of logistics management, greater visibility, and traceability of the supply chain.	Automation of logistics processes, real-time inventory management, and route optimization.	Logistics management enhanced; Delivery process more efficient and responsive to customer demands.
Flexibility	Quick adaptation to changes in demand, product customization, lean production.	Process flexibility, ability to produce smaller and customized batches, rapid prototyping.	More flexible production and more rapid response to market fluctuations; Easier adaptation to the individualized customer's needs.
Sustainability	Strategic focus on resource efficiency, waste reduction, and environmental compliance to enhance long-term sustainability.	Use of real-time monitoring, automated controls, and data analytics to support eco-efficient operations.	Improved visibility into resource use, enabling predictive waste control, and supporting regulatory compliance through transparent and traceable operations.

Innovativeness	Acceleration of design cycles, integration of innovation into everyday routines, data-informed decision-making, and collaborative solution development with customers.	Advanced data analytics for product and process innovation, digital platforms to speed up prototyping and testing, and AI to support creativity and market differentiation.	Innovativeness through the integration of real-time data, AI-assisted development, and digital tools that allow agile experimentation and customer-driven innovation.
Servitization	Transformation from product-centric to solution-oriented business models. Expansion of value proposition through service integration and revenue diversification.	Embedded sensors, remote monitoring, digital platforms for predictive services, and system integration to offer real-time diagnostics, updates, and post-sales services.	Servitization by transforming physical products into connected platforms that deliver added value through continuous services and real-time interactions with end-users.

The core principles of the Delphi methodology applied in this study included: 1. Anonymity; 2. Iteration; 3. Controlled Feedback; and 4. Statistical Group Response (Dalkey & Helmer, 1963; von der Gracht, 2012). The study was conducted in two rounds (R1 and R2).

3.1 Panel Selection and Profile

A rigorous purposive sampling strategy was implemented to select a panel of domain experts (Hsu & Sandford, 2007). The selection prioritized individuals from both the academic and professional sectors to capture perspectives informed by theory as well as practice.

The final panel consisted of six highly qualified experts (N=6). All participating experts held the highest academic degrees (Ph.D. or Postdoctoral), and included positions such as University Professors, a Chief Executive Officer (CEO), and a Manufacturing Director. The experts demonstrated substantial depth of experience: their total professional experience ranged from 11 to 38 years, with specialized expertise in Industry 4.0 or Advanced Manufacturing ranging from 6 to 25 years.

3.2 Rounds and Convergence Criteria

The study utilized two rounds (R1 and R2). The first round of the Delphi study was conducted over approximately three weeks, beginning in September 2025 and ending in October 2025. The process was executed sequentially: the experts received the instrument (likely via email or an online platform, judging by the timestamps) and submitted their independent evaluations.

The validation instrument at the first round consisted of 23 structured statements derived directly from the conceptual framework, covering:

1. General Framework Structure: Assessing the overall presentation and contribution of I4.0 technologies to the achievement of CPs.

2. Specific Competitive Priorities (CPs): Evaluating the relevance and definition of the Managerial Scope (MS), the appropriateness of the Technological Scope (TS), and the feasibility of systemic implementation for seven CPs: Cost, Quality, Delivery, Flexibility, Sustainability, Innovativeness, and Servitization.

Experts were asked to rate their level of agreement with each statement using a five-point Likert scale (Likert, 1932), with anchors defined as follows: 5 = Totally Agree, 4 = Partially Agree, 3 = Neutral / Undecided, 2 = Partially Disagree, 1 = Totally Disagree. In addition to numerical ratings, the experts provided qualitative comments to justify their assessments or suggest conceptual refinements.

The data collected via this scale were analyzed using descriptive statistics to determine the level of consensus within the panel. Consensus was formally defined as the percentage of experts who indicated positive agreement, meaning they provided a score of 4 (Partially Agree) or 5 (Totally Agree) on the scale. For a statement to be considered highly validated, a predetermined threshold of consensus was sought. Items that did not reach the minimum consensus threshold, or those receiving significant conflicting qualitative feedback, were prioritized for discussion and reevaluation in subsequent Delphi rounds.

4 Results

This section reports on the validation results, highlighting both the consensus achieved and the specific conceptual adjustments made.

4.1 Instrument and Content

The primary goal of Round 1 was to evaluate the foundational validity of the conceptual framework, which articulates the relationship between I4.0 enabling technologies and competitive priorities. Table 2 describes statements, ratings, and consensus level.

The resulting data from R1 provided an initial measure of consensus (e.g., 100% consensus was achieved for the Managerial Scope of Cost and Flexibility, while also highlighting areas requiring discussion such as specific statements that required adjustment due to a consensus level below the 75% threshold stipulated by the research protocol or because they received disagreement (a score of 1 or 2), prompting refinement for Round 2. Four statements fell below the required quantitative rigor or received explicit disagreement:

i. 2.3.1 Delivery – Technological Scope: With consensus at 67%, the Round 2 adjustment required further discussion and refinement to improve the statement's precision. The revision emphasized the specific technologies and processes necessary to enhance efficiency, responsiveness, and overall effectiveness in logistics management.

ii. 2.7.1 Servitization – Managerial Scope: Although consensus reached 83%, partial disagreement and qualitative feedback indicated the need for adjustment. The refinement incorporated an explicit caveat, clarifying that positive outcomes depend on the existence of viable business models in which such transformation can be realistically applied.

iii. 2.7.2 Servitization – Technological Scope: This statement received an explicit score of 2 (Partially Disagree) from at least one expert. In response, the adjustment formally included Artificial Intelligence (AI) as a key enabling technology, reinforcing its role in supporting predictive services under this competitive priority.

iv. 2.7.3 Servitization – Systemic Implementation: Despite achieving an overall consensus of 83%, one expert rated the statement as 2 (Partially Disagree). The Round 2 adjustment integrated a critical caveat into the managerial scope definition of servitization, emphasizing that positive results depend on application within business models and products where such transformation is viable.

Additionally, some statements with high quantitative consensus (≥83%) still received critical feedback. The qualitative comments provided specific feedback, such as questions about the cost of implementation, and suggestions for incorporating principles like transparency and collaboration into the framework. The qualitative inputs were fundamental for structuring the subsequent Delphi rounds and refining the model. Table 3 presents the consensus rate after R2.

Table 2 - Delphi Round 1: Items, Ratings, and Consensus

Item	Expert Ratings (N=6)	Consensus Level (%)
1.1. The proposed framework presents the relationships among enabling technologies of Industry 4.0 and the classical competitive priorities.	5, 4, 5, 3, 5, 4	83%
1.2. The enabling technologies of Industry 4.0, as defined in the framework, are strategically relevant to manufacturing operations.	5, 5, 5, 4, 5, 4	100%
2.1.1. Managerial Scope: Reduction of production costs and optimization of energy consumption. The managerial scope related to “Cost” is relevant and well defined in the context of Industry 4.0.	5, 4, 4, 4, 5, 4	100%
2.1.2. Technological Scope: Process automation, IoT, Artificial Intelligence (AI), and robotics for real-time monitoring and predictive analytics. The technological scope associated with “Cost” is appropriate to support cost reduction through Industry 4.0.	5, 4, 3, 4, 5, 4	83%
2.1.3. Industry 4.0 Enabling Technologies: IoT, Cyber-Physical Systems (CPS), Industrial Automation and Robotics, Modeling and Simulation, Artificial Intelligence, and Big Data. The enabling technologies of Industry 4.0, when implemented jointly and systemically, effectively enable cost reduction across multiple areas of manufacturing, such as plant location and inventory policies, for example.	5, 4, 3, 4, 5, 5	83%
2.2.1. Managerial Scope: Improvement of communication and collaboration across departments, and integration of quality management systems. The managerial scope for “Quality” is relevant and well defined in the context of Industry 4.0.	5, 4, 4, 4, 5, 4	100%
2.2.2. Technological Scope: Smart sensors, IoT, and Cyber-Physical Systems (CPS) for real-time monitoring, defect detection, and prevention. The technological scope for “Quality” is appropriate to achieve quality improvements through Industry 4.0.	5, 4, 4, 4, 5, 4	100%
2.2.3. Industry 4.0 Enabling Technologies: IoT, CPS, Industrial Automation and Robotics, Technology Integration, and Big Data.	5, 4, 4, 5, 5, 4	100%

Item	Expert Ratings (N=6)	Consensus Level (%)
The enabling technologies of Industry 4.0, when implemented jointly and systemically, enable quality management systems and real-time monitoring of integrated production processes, resulting in improved final product quality and compliance with customer requirements.		
2.3.1. Managerial Scope: Optimization of logistics management, with greater visibility and traceability of the supply chain. The managerial scope for “Delivery” is relevant and well defined in the context of Industry 4.0.	5, 3, 4, 3, 5, 5	**67%**
2.3.2. Technological Scope: Automation of logistics processes, real-time inventory management, and route optimization. The technological scope for “Delivery” is appropriate to make delivery processes more efficient and responsive.	5, 4, 4, 3, 5, 4	83%
2.3.3. Industry 4.0 Enabling Technologies: IoT, Cyber-Physical Systems (CPS), Industrial Automation and Robotics, and Big Data. The enabling technologies of Industry 4.0, when implemented jointly and systemically, enhance logistics management and make the delivery process more efficient and responsive to customer demands.	5, 4, 4, 4, 5, 4	100%
2.4.1. Managerial Scope: Rapid adaptation to changes in demand, product customization, and lean production. The managerial scope for “Flexibility” is relevant and well defined in the context of Industry 4.0.	5, 4, 4, 4, 5, 4	100%
2.4.2. Technological Scope: Process flexibility, capability to produce smaller and customized batches, and rapid prototyping. The technological scope for “Flexibility” is appropriate to enable more flexible and adaptable production in the era of Industry 4.0.	5, 4, 4, 5, 5, 5	100%
2.4.3. Industry 4.0 Enabling Technologies: IoT, Cyber-Physical Systems (CPS), Industrial Automation and Robotics, Additive Manufacturing, and Information Systems Integration.	5, 4, 5, 3, 5, 4	83%

Item	Expert Ratings (N=6)	Consensus Level (%)
The enabling technologies of Industry 4.0, when implemented jointly and systemically, allow flexible production and rapid response to market fluctuations, facilitating adaptation to individualized customer needs.		
2.5.1. Managerial Scope: Strategic focus on resource efficiency, waste reduction, and environmental compliance to enhance long-term sustainability. The managerial scope for “Sustainability” is relevant and well defined in the context of Industry 4.0.	5, 5, 4, 4, 4, 4	100%
2.5.2. Technological Scope: Use of real-time monitoring, automated controls, and data analytics to support eco-efficient operations. The technological scope for “Sustainability” is appropriate to support more eco-efficient and compliant operations.	5, 5, 4, 5, 5, 4	100%
2.5.3. Industry 4.0 Enabling Technologies: Industrial Automation and Robotics, Artificial Intelligence, Information Systems Integration, and Big Data. The enabling technologies of Industry 4.0, when implemented jointly and systemically, provide enhanced visibility of resource utilization, predictive waste control, and support for regulatory compliance through transparent and traceable operations.	5, 4, 4, 4, 5, 5	100%
2.6.1. Managerial Scope: Acceleration of design cycles, integration of innovation into daily routines, data-driven decision-making, and collaborative development of solutions with customers. The managerial scope for “Innovativeness” is relevant and well defined in the context of Industry 4.0.	5, 4, 4, 4, 3, 4	83%
2.6.2. Technological Scope: Advanced data analytics for product and process innovation, digital platforms to accelerate prototyping and testing, and Artificial Intelligence (AI) to support creativity and market differentiation. he technological scope for “Innovativeness” is appropriate to foster innovation in products, processes, and business models.	5, 4, 4, 4, 4, 4	100%
2.6.3. Industry 4.0 Enabling Technologies: Cloud Computing, Big Data, Additive Manufacturing, Artificial Intelligence, and IoT.	5, 4, 5, 4, 4, 5	100%

Item	Expert Ratings (N=6)	Consensus Level (%)
The enabling technologies of Industry 4.0, when implemented jointly and systemically, enable innovativeness through real-time data integration, AI-assisted development, and digital tools that allow agile experimentation and customer-driven innovation.		
2.7.1. Managerial Scope: Transformation of business models from product-centered to solution-oriented; expansion of the value proposition through service integration and revenue diversification. The managerial scope for "Servitization" is relevant and well defined in the context of Industry 4.0.	5, 4, 4, **2**, 5, 5	83%
2.7.2. Technological Scope: Embedded sensors, remote monitoring, digital platforms for predictive services, and system integration to provide real-time diagnostics, updates, and after-sales services. The technological scope for "Servitization" is appropriate to facilitate the transition from product-based offerings to solution-oriented offerings that may include products, services, digitalized services, and service platforms.	5, 4, 4, **2**, 5, 5	83%
2.7.3. Industry 4.0 Enabling Technologies: Cloud Computing, Digital Twins, Information Systems Integration, and IoT. The enabling technologies of Industry 4.0, when implemented jointly and systemically, enable servitization by transforming physical products into connected platforms that deliver added value through continuous services and real-time interactions with end users.	5, 4, 4, **2**, 5, 5	83%

Table 3 - Delphi Round 2: Revised statements, Ratings, and Consensus

Item	Expert Ratings (N=6)	Consensus Level (%)
2.3.1. Managerial scope for “Delivery”: Optimization of logistics management, with improved predictability, accuracy, and responsiveness to demand, as well as greater visibility and traceability of the supply chain, applicable to both “intra” and “inter” organizational relationships. *The managerial scope for “Delivery” is relevant and well defined for the context of Industry 4.0.*	5, 4, 5, 5, 3, 5	**83%**
2.7.1. Managerial scope for “Servitization”: Transformation of business models from product-centered to solution-oriented. *Expansion of the value proposition through the integration of services and revenue diversification. Positive outcomes depend on application in business models and products where such a transformation is viable.* *In this context, the managerial scope for “Servitization” is relevant and well defined for Industry 4.0.*	5, 3, 4, 4, **2**, 5	**67%**
2.7.2. Technological scope for “Servitization”: Embedded sensors, remote monitoring, digital platforms for predictive services, and system integration to provide real-time diagnostics, updates, and after-sales services. *The technological scope for “Servitization” is appropriate to support the transition from product-based offerings to solution-oriented offerings, which may include products, services, digitalized services, and service platforms.*	5, 3, 5, 5, 5, 5	**83%**
2.7.3. Enabling technologies of Industry 4.0 for “Servitization”: Cloud Computing, Digital Twins, Information Systems Integration, Artificial Intelligence, and IoT. *When implemented in an integrated and systemic manner, these technologies enable servitization by converting physical products into connected digital platforms capable of delivering added value through continuous services and real-time interactions with end users.*	5, 3, 5, 5, 4, 5	**83%**

4.2 Specific Conceptual Adjustments and Refinements

The Delphi process led to crucial adjustments, ensuring conceptual clarity and addressing instances of perceived over-generalization. Accordingly, the extended model represents the refined version of the conceptual framework following the critical feedback and validation from the Delphi Round 1, particularly addressing areas of low consensus and conceptual uncertainty. The adjustments primarily enhanced the precision and breadth of the Managerial Scope (MS) and the expected results of Systemic Implementation (SI) on section “I4.0 Enables” - Table 4 details refinements in the extended model, presented in Figure 1.

4.3 General Validation and Consensus

The panel generally agreed that the proposed framework is "very well structured". The concept that I4.0 enabling technologies contribute to the transformation and achievement of competitive priorities was strongly supported, with experts noting these technologies are "essential" to achieving competitive levels.

The Cronbach’s Alpha value for internal consistency in the Delphi study, using the 23 statements, is approximately 0.88. This result indicates a level of internal consistency classified as “good” to “very good,” significantly exceeding the threshold of 0.7 established for instrument reliability (George & Mallery, 2003). This suggests that the questionnaire items are cohesively measuring the underlying construct, namely the validity of the conceptual framework.

5 Discussion and Contributions

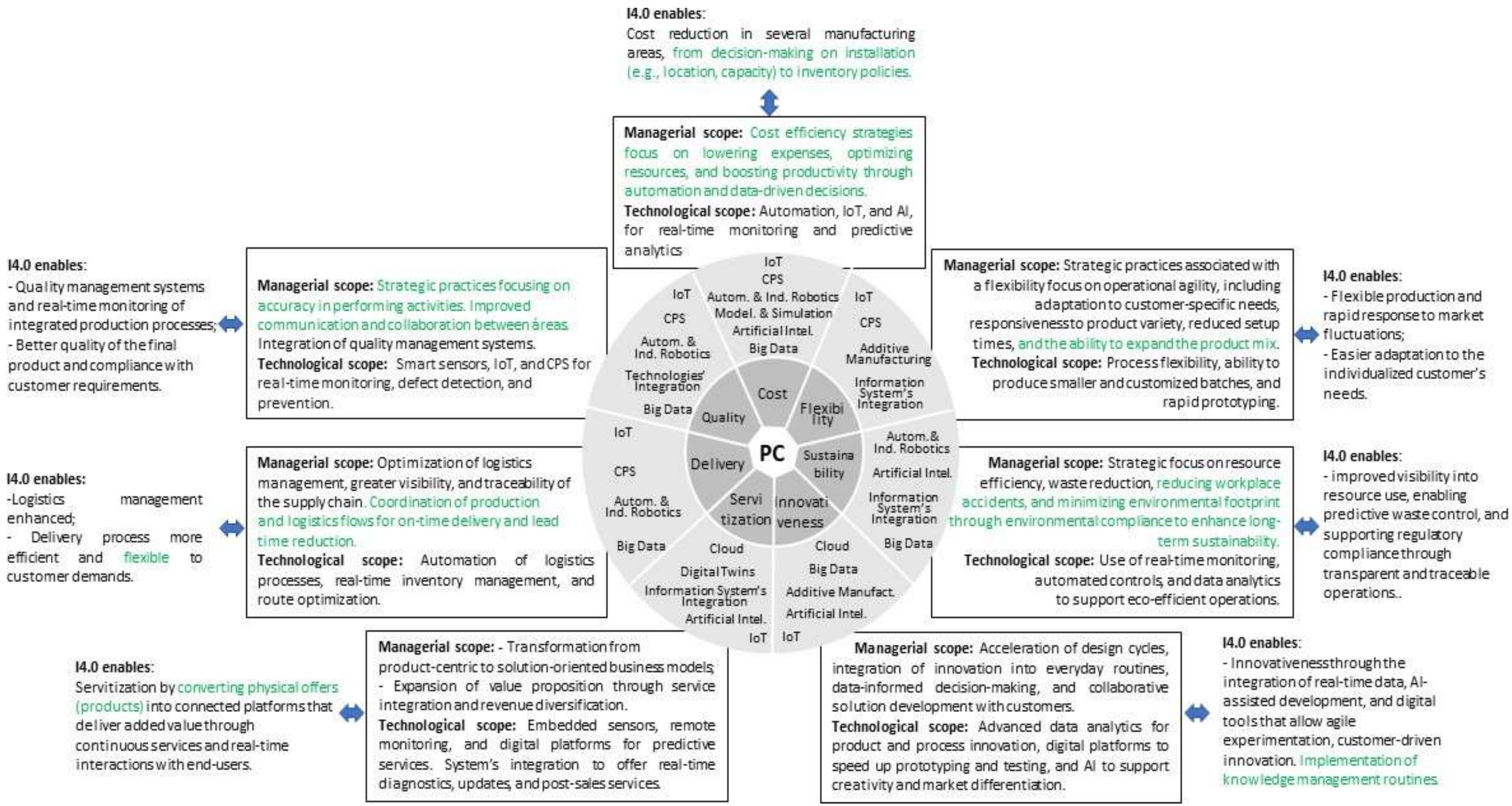
The results of our study demonstrate that the Expert Panel achieved a high level of convergence and consensus, thereby validating the robustness of the framework’s core structure while simultaneously requiring refinements to critical conceptual details. Experts emphasized that the framework is well structured and serves as a conceptual foundation for investigating the relationships between Industry 4.0 and competitive priorities, rather than presenting definitive causal links. They also agreed that the enabling technologies of Industry 4.0 are not only contributory but essential for achieving manufacturing competitiveness.

Table 4 - Comparative Conceptual Model and Extended Model

Competitive Priority	Framework Component	Conceptual Model (Baseline)	Extended Model (Refined)	Key Difference/Refinement
Cost	Managerial Scope	Reduction of production costs, optimization of energy consumption.	Cost efficiency strategies focus on lowering expenses, optimizing resources, and **boosting productivity through automation and data-driven decisions**.	Sharpened focus on "Cost efficiency strategies" and the active role of data/automation in boosting productivity.
	I4.0 Enables	Cost reduction in several manufacturing areas, from **factory location** to inventory policies.	Cost reduction in several manufacturing areas, from **decision-making on installation (e.g., location, capacity)** to inventory policies.	Language adjusted to focus on the **decision-making** process regarding installation and capacity.
Quality	Managerial Scope	Improved communication and collaboration between areas, integration of quality management systems.	**Strategic practices focusing on accuracy in performing activities.** Improved communication and collaboration between areas. Integration of quality management systems.	Explicitly includes a strategic focus on **"accuracy in performing activities,"** reflecting refinement based on expert feedback.
Delivery	Managerial Scope	Optimization of logistics management, greater visibility, and traceability of the supply chain.	Optimization of logistics management, greater visibility, and traceability of the supply chain. **Coordination of production and logistics flows for on-time delivery and lead time reduction**.	Significantly expanded scope to emphasize **coordination of flows** and specific metrics like **on-time delivery and lead time reduction**, addressing R1 uncertainty.
	I4.0 Enables	Delivery process more efficient and **responsive** to customer demands.	Delivery process more efficient and **flexible** to customer demands.	Semantic shift from "responsive" to "flexible".
Flexibility	Managerial Scope	Quick adaptation to changes in demand, product customization, lean production.	**Strategic practices associated with a flexibility focus on operational agility, including adaptation to customer-specific needs, responsiveness to product variety, reduced setup times, and the ability to expand the product mix**.	Significantly enhanced detail, providing a comprehensive definition of "operational agility" by listing key practices (setup times, product mix expansion).

Sustainability	Managerial Scope	Strategic focus on resource efficiency, waste reduction, and environmental compliance to enhance long-term sustainability.	Strategic focus on resource efficiency, waste reduction, **reducing workplace accidents**, and minimizing environmental footprint through environmental compliance to enhance long-term sustainability.	Scope expanded to include a social dimension, explicitly adding the goal of **"reducing workplace accidents"**.
Innovativeness	I4.0 Enables	Innovativeness through the integration of real-time data, AI-assisted development, and digital tools that allow agile experimentation and customer-driven innovation.	Innovativeness through the integration of real-time data, AI-assisted development, and digital tools that allow agile experimentation, customer-driven innovation. **Implementation of knowledge management routines**.	Added the explicit operationalization of innovation through the **"Implementation of knowledge management routines"**.
Servitization	I4.0 Enables	Servitisation by **transforming physical products** into connected platforms that deliver added value through continuous services and real-time interactions with end-users.	Servitization by **converting physical offers (products)** into connected platforms that deliver added value through continuous services and real-time interactions with end-users.	Semantic adjustment from "transforming physical products" to "**converting physical offers (products)**".

Figure 1 – Extended Model



The external validation confirmed both the Dual Perspective and the strategically contingent nature of I4.0. Refinements to the Managerial Scope underscored its role as the critical integration mechanism, demonstrating that strategic performance is not achieved solely through technological adoption but through the intentional alignment of technologies with production logic and organizational intent. This finding highlights the importance of managerial orchestration in translating technological potential into strategic outcomes.

One of the most critical points emerging from the Delphi validation concerns the Servitization dimension. The recurrence of partial disagreement across all three servitization-related items indicates that this dimension remains the most contested among the panel. Although consensus was achieved at the 83 percent level, with most experts assigning ratings of 4 or 5, the dissent underscores a perceived gap between the theoretical promise of Servitization and its practical realization in Industry 4.0 contexts. This divergence points to the need for further refinement of the Servitization dimension in the conceptual framework, particularly by clarifying the technological enablers most directly associated with service-oriented strategies and by addressing the maturity level of Servitization practices in manufacturing.

From a theoretical perspective, the validated framework expands the content of manufacturing strategy by incorporating new competitive priorities into the core agenda of Industry 4.0. In addition to the traditional priorities of Cost, Quality, Delivery, and Flexibility, the study legitimizes sustainability, innovativeness, and Servitization as first-order priorities in the digital era. From a managerial standpoint, the consensus achieved and the refinements incorporated enhance the framework’s applicability in real manufacturing contexts, offering a strategic reference for decision-making and guiding investments in enabling technologies aligned with competitive objectives.

The achievement of consensus and the incorporation of conceptual refinements validate the framework as the final proposal of the dissertation. The model explicitly demonstrates how the implementation of I4.0 enabling technologies influences and shapes the strategic reorganization of manufacturing, thereby strengthening both its theoretical consistency and managerial relevance.

6. Conclusion

The Delphi study successfully achieved its objective by obtaining high consensus and incorporating detailed refinements from the panel of experts, resulting in a conceptual framework that is both theoretically consistent and practically applicable. This process confirms the strategic legitimacy of the expanded competitive priorities - Sustainability, Innovativeness, and Servitization - and validates the framework's core principles, including the Dual Perspective and Strategic Contingency.

The research question guiding this work was comprehensively answered through the external validation process: the expert panel provided the final, authoritative certification for the model. Quantitatively, the framework achieved a Cronbach’s Alpha value of approximately 0.88 for internal consistency, indicating a "good" to "very good" level of instrument reliability, significantly exceeding the established 0.7 threshold. Experts strongly agreed that the proposed framework is "very well structured" and affirmed that I4.0 enabling technologies are essential for achieving manufacturing competitiveness. Conceptually, the Delphi process led to crucial adjustments, ensuring conceptual clarity and addressing areas of low consensus and uncertainty. The refinements underscored that strategic performance is realized not solely through technological adoption but through the intentional alignment of technologies with production logic and organizational intent. The achievement of consensus and the incorporation of these conceptual refinements validate the framework as the final proposal of the dissertation.

The finalized model offers two critical contributions. Theoretically, the validated framework expands the scope of manufacturing strategy by empirically establishing and legitimizing Sustainability, Innovativeness, and Servitization as first-order competitive priorities in the I4.0 era, placing them alongside the traditional dimensions of Cost, Quality, Delivery, and Flexibility. Managerially, the consensus achieved and the resulting refinements enhance the framework’s applicability, offering a strategic reference for decision-making that guides investments in enabling technologies to ensure strict alignment with competitive objectives in real manufacturing contexts. The final model explicitly demonstrates how the implementation of I4.0 technologies influences and shapes the strategic reorganization of manufacturing, strengthening its managerial relevance.

A limitation of the study concerns the Servitization dimension, which emerged as a contested issue among the expert panel. While consensus was reached on 83 percent across all related statements in the first round and subsequent refinement efforts were undertaken, the recurrence of partial disagreement revealed a persistent divergence. This outcome points to a perceived gap between the theoretical potential of Servitization and its practical realization within Industry 4.0 contexts. Given this ongoing conceptual uncertainty, further research is required to consolidate the dimension. Future investigations should prioritize clarifying the technological enablers most directly linked to service-oriented strategies and conducting empirical studies to evaluate both the maturity level and the implementation patterns of Servitization practices in advanced manufacturing environments.

REFERENCES

Abdullah, F. M., Al-Ahmari, A. M., & Anwar, S. (2022). The impact of Industry 4.0 technologies on manufacturing strategies: Proposition of technology-integrated selection. *IEEE Access*, *10*, 21574–21583. https://doi.org/10.1109/ACCESS.2022.3151898

Alcácer, V., & Cruz-Machado, V. (2019). Scanning the Industry 4.0: A literature review on technologies for manufacturing systems. *Engineering Science and Technology, an International Journal*, *22*(3), 899–919. https://doi.org/10.1016/j.jestch.2019.01.006

Bibby, L., & Dehe, B. (2018). Defining and assessing Industry 4.0 maturity levels–case of the defence sector. *Production Planning & Control*, *29*(12), 1030–1043. https://doi.org/10.1080/09537287.2018.1503355

Dalkey, N., & Helmer, O. (1963). An experimental application of the Delphi method to the use of experts. *Management science*, *9*(3), 458-467.

Elnadi, M., & Abdallah, Y. O. (2023). Industry 4.0: Critical investigations and synthesis of key findings. *Management Review Quarterly*, *74*, 711–744. https://doi.org/10.1007/s11301-022-00314-4

Fatorachian, H., & Kazemi, H. (2018). A critical investigation of Industry 4.0 in manufacturing: Theoretical operationalisation framework. *Production Planning & Control*, *29*(8), 633–644. https://doi.org/10.1080/09537287.2018.1424960

Fettermann, D. C., Cavalcante, C. G. S., de Almeida, T. D., & Tortorella, G. L. (2018). How does Industry 4.0 contribute to operations management? *Journal of Industrial and Production Engineering*, *35*(4), 255–268. https://doi.org/10.1080/21681015.2018.1462863

Frank, A. G., Dalenogare, L. S., & Ayala, N. F. (2019). Industry 4.0 technologies: Implementation patterns in manufacturing companies. *International Journal of Production Economics*, *210*, 15–26. https://doi.org/10.1016/j.ijpe.2019.01.004

Fratocchi, L., & Di Stefano, C. (2020). Industry 4.0 technologies and manufacturing back-shoring: A European perspective. *Acta IMEKO*, *9*(4), 13–20. https://doi.org/10.21014/acta_imeko.v9i4.721

George, D., & Mallery, P. (2024). *IBM SPSS statistics 29 step by step: A simple guide and reference*. Routledge.

Hsu, C. C., & Sandford, B. A. (2007). The Delphi technique: making sense of consensus.*Practical assessment, research, and evaluation*,*12*(1).

Kiel, D., Müller, J. M., Arnold, C., & Voigt, K. I. (2017). Sustainable industrial value creation: Benefits and challenges of Industry 4.0. *International Journal of Innovation Management*, *21*(8), 1–22. https://doi.org/10.1142/S1363919617400151

Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine*, *51*(11), 1016–1022. https://doi.org/10.1016/j.ifacol.2018.08.474

Lasi, H., Fettke, P., Kemper, H. G., Feld, T., & Hoffmann, M. (2014). Industry 4.0. *Business and Information Systems Engineering*, *6*(4), 239–242. https://doi.org/10.1007/s12599-014-0334-4

Likert, R. (1932). A technique for the measurement of attitudes. *Archives of psychology*.

Lu, Y. (2017). Industry 4.0: A survey on technologies, applications and open research issues. *Journal of Industrial Information Integration*, *6*, 1–10. https://doi.org/10.1016/j.jii.2017.04.005

Müller, J. M., Kiel, D., & Voigt, K. I. (2018). What drives the implementation of Industry 4.0? The role of opportunities and challenges in the context of sustainability. *Sustainability (Switzerland)*, *10*(1), 247–271. https://doi.org/10.3390/su10010247

Schneider, P. (2018). Managerial challenges of Industry 4.0: An empirically backed research agenda for a nascent field. *Review of Management Science*, *12*(55), 1–32. https://doi.org/10.1007/s11846-018-0283-2

Schuh, G., Anderl, R., Dumitrescu, R., Krüger, A., & ten Hompel, M. (2020). *Industrie 4.0 Maturity Index: Managing the digital transformation of companies (Update 2020).* acatech – National Academy of Science and Engineering.

Silva, E. M., Jabbour, C. J. C., & Santos, F. C. A. (2009). Integrating environmental management and manufacturing strategy: An emerging competitive priority. *International Journal of Environmental Technology and Management*, *10*, 397–411. https://doi.org/10.1504/IJETM.2009.023742

Torrecilla-Salinas, C. J., De Troyer, O., Escalona, M. J., & Mejías, M. (2017). Una aplicación práctica del método Delphi para la validación de una propuesta de Ingeniería Web. *XXII Jornadas de Ingeniería del Software y Bases de Datos. La Laguna, Tenerife, España: JISBD*.

Vivares, J. A., Avella, L., & Sarache, W. (2022). Trends and challenges in operations strategy research: Findings from a systematic literature review. *Cuadernos de Gestión*, *22*, 81–96. https://doi.org/10.5295/cdg.211543ja

Von Der Gracht, H. A. (2012). Consensus measurement in Delphi studies: review and implications for future quality assurance. *Technological forecasting and social change*, *79*(8), 1525-1536.

Weking, J., Stöcker, M., Kowalkiewicz, M., Böhm, M., & Krcmar, H. (2020). Leveraging Industry 4.0 – A business model pattern framework. *International Journal of Production Economics*. https://doi.org/10.1016/j.ijpe.2019.107588

ANEXO A – PARECER DE COMISSÃO DE ÉTICA E PESQUISA

UNIVERSIDADE PAULISTA - UNIP

PARECER CONSUBSTANCIADO DO CEP

DADOS DO PROJETO DE PESQUISA

Título da Pesquisa: Tecnologias Habilitadoras da Indústria 4.0 e Prioridades Competitivas da Manufatura em Ambientes Produtivos MTS e MTO

Pesquisador: ANDREA CRISTINA ELIAS RIBEIRO

Área Temática:

Versão: 1

CAAE: 78506424.3.0000.5512

Instituição Proponente: ASSOCIACAO UNIFICADA PAULISTA DE ENSINO RENOVADO OBJETIVO-

Patrocinador Principal: Financiamento Próprio

DADOS DO PARECER

Número do Parecer: 6.789.593

Apresentação do Projeto:

Resumo:

O conceito de Indústria 4.0 tem se destacado recentemente no cenário da gestão empresarial trazendo consigo expectativas no sentido de incremento do desempenho competitivo organizacional. Apesar do avanço existente até o momento na literatura sobre o assunto, há mais a ser estudado para o aprofundamento tanto do entendimento teórico (THOBEN et al., 2017), quanto empírico sobre o tema. Considerando ainda que se trata de um campo de estudo emergente e que as tecnologias associadas à I4.0 estão em constante evolução (ENRIQUE et al., 2022), são oportunos trabalhos que abordem a prática empresarial quanto à aplicação das tecnologias que habilitam a implantação deste novo modelo industrial e seus desdobramentos para as diferentes áreas organizacionais, para organizações como um todo, para mercados concorrenciais e para ambientes de negócio.

Indicativos quanto à contribuição desta pesquisa tanto no campo acadêmico quanto em termos de incremento da compreensão da realidade organizacional podem ser relacionados:

i. Ensaios no sentido de elaborar um quadro de análise que contemple as tecnologias relacionadas à Indústria 4.0 e como estas se relacionam com a estratégia competitiva das organizações são escassos;

ii. Mais especificamente no que diz respeito à estratégia de manufatura, há carência de pesquisas que tracem possíveis inter-relações entre as tecnologias emergentes das I4.0 e a

performance da função produção (DOHALE et al., 2022);
iii. Maior ainda é a exiguidade de trabalhos que tragam considerações práticas na forma de estudos empíricos (DOHALE e KUMAR, 2018; ABDULLAH et al., 2023) quanto às possíveis relações entre as prioridades competitivas da manufatura e as tecnologias habilitadoras da Indústria
4.0 em ambientes produtivos específicos, como é o caso do presente trabalho.

Objetivo da Pesquisa:

Objetivo Primário:

O intuito do trabalho é analisar as relações (implicações gerenciais) entre: (1) a implantação de tecnologias habilitadoras da Indústria 4.0 (Techs I4.0), (2) o gerenciamento das prioridades competitivas (Competitive Priorities - CP) da estratégia da área de operações e; (3) contextos de
manufatura do tipo produção para pronta entrega (MTS ¿ Make to Stock) e produção sob encomenda (MTO ¿ Make to Order).

Objetivo Secundário:

O foco da pesquisa pode ser sintetizado da seguinte forma: i. Como a implementação de tecnologias habilitadoras da indústria 4.0 possibilita a reorganização estratégica e competitividade das empresas em termos de prioridades competitivas operacionais? ii. Mais especificamente, quais
configurações de tecnologias habilitadoras da I4.0 e prioridades competitivas da manufatura ocorrem em ambientes de produção MTS e MTO?

Avaliação dos Riscos e Benefícios:

Riscos:

- Não ter acesso às pessoas adequadas, com conhecimento das informações desejadas;
- Problemas com a escolha do vocabulário apropriado ao tema e de conhecimento dos/as entrevistados/as;
- Dificuldade na formulação (redação) das questões, de modo a obter as informações desejadas;
- Não ter acesso às informações devido ao fato de tratar-se de assunto estratégico (e talvez confidencial) para as empresas.

Benefícios:

Endereço: Rua Dr. Bacelar, 1212 4º andar
Bairro: Vila Clementino **CEP:** 04.026-002
UF: SP **Município:** SAO PAULO
Telefone: (11)5586-4086 **E-mail:** cep@unip.br

Serão elaborados dois tipos de relatórios:

¿ Um sumário executivo do estudo de cada caso a ser disponibilizado para as respectivas empresas objeto de estudo;

¿ Um relatório completo com análise de cada um dos casos individualmente, contendo avaliação intra caso. O mesmo relatório incluirá também comentários e comparações entre o que foi observado em cada uma das organizações estudadas, permitindo uma análise entre casos.

Comentários e Considerações sobre a Pesquisa:

Projeto de pesquisa com desenho transversal, descritivo e analítico, com dados qualitativos. Pesquisa proposta para elaboração de tese de doutorado.

Centro único. Financiamento próprio.

Pretende-se entrevistar 20 pessoas.

Considerações sobre os Termos de apresentação obrigatória:

Adequado

Recomendações:

não há

Conclusões ou Pendências e Lista de Inadequações:

Projeto de pesquisa sem óbices éticos.

Considerações Finais a critério do CEP:

Diante do exposto, o CEP-UNIP, de acordo com as atribuições definidas na Resolução CNS n.° 466, de 2012, manifesta-se por confirmar o parecer do projeto de pesquisa como APROVADO, nos termos em que está proposto. Ressalta-se que cabe ao pesquisador responsável encaminhar os relatórios parciais e finais da pesquisa, por meio da Plataforma Brasil, via notificação do tipo ¿relatório¿ para que sejam devidamente apreciadas pelo CEP, conforme Norma Operacional CNS nr 001/12, item XI.2.d.

Este parecer foi elaborado baseado nos documentos abaixo relacionados:

Tipo Documento	Arquivo	Postagem	Autor	Situação
Informações Básicas do Projeto	PB_INFORMAÇÕES_BÁSICAS_DO_PROJETO_2263789.pdf	26/03/2024 18:51:36		Aceito
Outros	frm_intencao_de_pesquisa_Andrea_	26/03/2024	ANDREA CRISTINA	Aceito

Outros	Ribeiro_assinado.pdf	18:50:17	ELIAS RIBEIRO	Aceito
TCLE / Termos de Assentimento / Justificativa de Ausência	formulario_termo_de_consentimento_TCLE_Andrea_Ribeiro.docx	20/03/2024 12:42:59	ANDREA CRISTINA ELIAS RIBEIRO	Aceito
Projeto Detalhado / Brochura Investigador	Projeto_protocolo_de_pesquisa_Andrea_Ribeiro.docx	20/03/2024 12:41:33	ANDREA CRISTINA ELIAS RIBEIRO	Aceito
Informações Básicas do Projeto	PB_INFORMAÇÕES_BÁSICAS_DO_PROJETO_2263789.pdf	20/03/2024 02:23:39		Aceito
Projeto Detalhado / Brochura Investigador	Projeto_protocolo_pesquisa_Andrea_Ribeiro.pdf	20/03/2024 02:22:34	ANDREA CRISTINA ELIAS RIBEIRO	Aceito
Projeto Detalhado / Brochura Investigador	Projeto_protocolo_pesquisa_Andrea_Ribeiro.pdf	20/03/2024 02:22:34	ANDREA CRISTINA ELIAS RIBEIRO	Recusado
Outros	frm_intencao_de_pesquisa_Andrea_Ribeiro_assinado.pdf	20/03/2024 02:15:07	ANDREA CRISTINA ELIAS RIBEIRO	Aceito
Outros	frm_intencao_de_pesquisa_Andrea_Ribeiro_assinado.pdf	20/03/2024 02:15:07	ANDREA CRISTINA ELIAS RIBEIRO	Recusado
Outros	frm_termo_de_compromisso_do_pesquisador_Andrea_Ribeiro_assinado.pdf	20/03/2024 02:14:32	ANDREA CRISTINA ELIAS RIBEIRO	Aceito
Orçamento	frm_orcamento_de_projeto_de_pesquisa_Andrea_Ribeiro_assinado.pdf	20/03/2024 02:13:46	ANDREA CRISTINA ELIAS RIBEIRO	Aceito
Outros	Carta_Apresentacao_projeto_Andrea_assinado.pdf	20/03/2024 02:13:27	ANDREA CRISTINA ELIAS RIBEIRO	Aceito
TCLE / Termos de Assentimento / Justificativa de Ausência	formulario_termo_de_consentimento_TCLE_Andrea_Ribeiro_assinado.pdf	20/03/2024 02:12:35	ANDREA CRISTINA ELIAS RIBEIRO	Aceito
TCLE / Termos de Assentimento / Justificativa de Ausência	formulario_termo_de_consentimento_TCLE_Andrea_Ribeiro_assinado.pdf	20/03/2024 02:12:35	ANDREA CRISTINA ELIAS RIBEIRO	Recusado
Folha de Rosto	Folha1_rosto_Andrea_assinado.pdf	19/03/2024 20:55:51	ANDREA CRISTINA ELIAS RIBEIRO	Aceito

Situação do Parecer:
Aprovado

Necessita Apreciação da CONEP:
Não

UNIVERSIDADE PAULISTA - UNIP

Continuação do Parecer: 6.789.593

SAO PAULO, 26 de Abril de 2024

Assinado por:
Bettina Gerken Brasil
(Coordenador(a))

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