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Innovative Industrial Design

Principles and Practices

*Edited by Sharad Chandra Srivastava, Rohit Raja,
Ritesh Kumar Singh and Sanjiv Kumar Tiwari*



Innovative Industrial Design - Principles and Practices

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Rohit Raja, Ritesh Kumar Singh
and Sanjiv Kumar Tiwari*

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Industrial Engineering and Management

Volume 18

Aims and Scope of the Series

Industrial Engineering and Management (IEM) is a discipline that focuses on optimizing complex processes and systems within various industries. It involves the integration of engineering, business, economics, mathematics, and behavioral sciences to improve efficiency, productivity, quality, and overall performance in organizations. Key aspects of Industrial Engineering and Management include: Process Optimization; System Analysis and Design; Quality Control and Management; Supply Chain Management; Operations Management; Human Factors and Ergonomics; Project Management; Cost Analysis and Financial Management; Decision Analysis.

Overall, Industrial Engineering and Management aims to optimize resources, improve processes, enhance productivity, and ensure the effective and efficient utilization of all elements involved in the production or delivery of goods and services. It is crucial in today's competitive business environment for organizations to stay efficient and competitive.

Production Engineering and Operational Excellence are fields of study and practices that focus on optimizing and improving the manufacturing and production processes within an organization. It combines principles from engineering, management, and operational strategies to enhance productivity, efficiency, quality, safety, and sustainability in the production of goods and services.

Here are the key components of Production Engineering and Operational Excellence: Process Optimization; Operational Excellence; Manufacturing Systems Design; Quality Management; Supply Chain Optimization; Production Planning and Scheduling; Automation and Technology Integration; Health, Safety, and Environmental Management; Cost Management; Performance Measurement and Key Performance Indicators (KPIs); Continuous Improvement and Innovation. Production Engineering and Operational Excellence are crucial for organizations aiming to stay competitive in the global market by achieving high levels of efficiency, quality, and customer satisfaction while optimizing resources and minimizing waste. It is a multidisciplinary approach that encompasses engineering principles, management strategies, and the effective use of technology to drive operational success.

Meet the Series Editor



Fausto Pedro Garcia Marquez is a Full Professor at UCLM, Spain, with accreditation since 2013. He also holds the position of Honorary Senior Research Fellow at Birmingham University, UK, and serves as a Lecturer at the Postgraduate European Institute. In addition to these roles, Fausto has experience as a Senior Manager at Accenture from 2013 to 2014. He earned his European Ph.D. with the highest distinction. Throughout his career, Fausto has received numerous awards and honors. These include the Nominate Prize (2022), Gran Maestre (2022), Grand Prize (2021), Runner Prize (2020), and Advancement Prize (2018), as well as Runner (2015), Advancement (2013), and Silver (2012) by the International Society of Management Science and Engineering Management (ISMSEM). He was also the recipient of the First International Business Ideas Competition 2017 Award. Fausto's contributions extend to academic publishing, with over 242 papers to his name. Notably, his work has been recognized in journals like "Applied Energy" (Q1, IF 9.746, Best Paper 2020) and "Renewable Energy" (Q1, IF 8.001, Best Paper 2014). His affiliations include the editorial and authorship roles in more than 50 books, with publications through respected publishers such as Elsevier, Springer, Pearson, Mc-GrawHill, IntechOpen, IGI, Marcombo, and AlfaOmega. He has authored over 100 international chapters and holds 6 patents. Fausto serves as the Editor of 5 International Journals and is a Committee Member for more than 70 International Conferences. His research portfolio encompasses being the Principal Investigator in 4 European Projects, 8 National Projects, and participating in over 150 projects involving universities and companies. His areas of expertise and research interests span Artificial Intelligence, Maintenance, Management, Renewable Energy, Transport, Advanced Analytics, and Data Science. Fausto is a recognized Expert in the European Union in AI4People (EISMD) and ESF. He also serves as the Director of www.ingeniumgroup.eu, holds the status of Senior Member at IEEE since 2021, and has been honored as an Honorary Member of the Research Council of the Indian Institute of Finance since 2021. Fausto is also the Committee Chair of The International Society for Management Science and Engineering Management (ISMSEM) since 2020.

Meet the Volume Editors



Dr. Sharad Chandra Srivastava attained his Bachelor of Engineering (B. E.) degree in the dynamic field of Industrial & Production Engineering in 1998, marking the commencement of his journey into engineering innovation. He furthered his academic prowess by earning his Master of Engineering (M. E.) degree from MNNIT Allahabad in 2002, solidifying his expertise in advanced engineering concepts. Driven by a passion for knowledge and research, Dr. Srivastava pursued his Doctor of Philosophy (Ph.D.) degree, completing his doctoral studies in 2009. This milestone marked the culmination of his dedication to scholarly exploration and his commitment to contributing groundbreaking insights to the field of engineering. Currently serving as a distinguished Professor in the dynamic field of Industrial & Production Engineering at Guru Ghasidas Vishwavidyalaya (A Central University), located in the vibrant setting of Koni, Bilaspur. Additionally, he holds the prestigious role of Dean of the School of Engineering & Technology, showcasing his expertise and leadership in academia. With a rich professional trajectory, he has previously held pivotal roles, including Head of Department and Finance Officer at GGV, demonstrating his strategic acumen and administrative prowess. Prior to his tenure at GGV, he made significant contributions to the Department of Production Engineering at B. I. T., Mesra, Ranchi, from 2002 until June 29, 2020, culminating in his esteemed position as an Associate Professor. His career is characterized by a passion for innovation, academic excellence, and visionary leadership, making him a revered figure in the field of engineering education. Dr. Sharad Chandra Srivastava's research spans various domains, including CAD/CAM, Lean Manufacturing Engineering, the Application of AI tools in manufacturing systems, sustainability, Computer-Aided Process Planning (CAPP), Computer Integrated Manufacturing (CIM), and Tool Design and Industrial Engineering. His proactive engagement in these active areas reflects his commitment to pushing the boundaries of engineering innovation and sustainability practices. As an author and co-author, Dr. Srivastava has made significant contributions to scholarly discourse, with over 40 published papers in prestigious national and international journals and conferences. His prolific output not only showcases his expertise but also underscores his dedication to sharing valuable insights and advancements within the engineering community.

He has authored four books (some of which are used as textbooks in India and other Asian countries)

1. Intelligent scheduling controller for FMS
2. Tool Design
3. Textbook of "Metrology & Measurement
4. Computer-aided Manufacturing.

Under his exceptional mentorship, numerous students have successfully obtained their Master's and Ph.D. degrees, showcasing his profound impact on academia. His prolific contributions include over five patents credited to his name, highlighting his innovative spirit and commitment to advancing knowledge. He holds esteemed memberships in various professional bodies, including being a Life Member of the ISTE, Institution of Engineers (India), as well as a Member of IIF India and a lifetime member of IIIE, underscoring his dedication to continuous learning and professional development.



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emerged as a key contributor to various emerging domains within computer science, including face recognition, digital image processing, signal processing, and computer networks. Throughout his academic career, Dr. Raja has authored and published over 100 research papers in reputable international and national journals and conference proceedings. His research work is recognized for its innovative approach and practical relevance, often focusing on real-world challenges in areas such as biometric systems, intelligent healthcare, and smart communication networks. His contributions to face recognition and identification, in particular, have found applications in surveillance systems, security architectures, and user authentication technologies. In addition to his prolific academic output, Dr. Raja has demonstrated a strong inclination toward innovation and intellectual property development. He has filed and successfully published 29 patents across various technological domains. These patents reflect his commitment to practical innovation and the application of research to solve real-world problems. His work in this area has further elevated his profile within the academic and industrial research communities. Dr. Raja is also an active participant in the global research ecosystem. He has been invited as a guest and speaker at numerous Institute of Electrical and Electronics Engineers (IEEE) conferences, where he has contributed as a session chair, keynote speaker, and panelist. These invitations underscore his growing reputation as an expert and thought leader in computer science and engineering. His academic journey is marked not only by research and innovation but also by a dedication to mentoring and capacity building. Dr. Raja has mentored numerous undergraduate and postgraduate students and continues to guide several Ph.D. scholars in their research work. His teaching is informed by his research, ensuring that students are exposed to the latest developments and practices in the field. Dr. Raja also serves on the editorial boards and reviewer panels of various peer-reviewed and refereed journals. His critical insights and academic rigor are highly valued in evaluating and improving the quality of scholarly publications in the fields of artificial intelligence, image processing, and network technologies.



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Preface

Innovative Industrial Design – Principles and Practices brings together a collection of scholarly contributions that explore the evolving landscape of industrial design, where creativity, technology, and user-centered approaches intersect to shape the products and experiences of the future. This edited volume aims to present foundational principles alongside emerging practices that define the modern design ecosystem, offering a comprehensive reference for students, researchers, practitioners, and educators in the field.

This volume is the result of dedicated efforts from a diverse group of authors and reviewers, whose expertise and commitment are gratefully acknowledged. We also extend our appreciation to the editorial and production teams whose support was invaluable throughout the preparation of this work.

We hope this volume will not only serve as a valuable academic resource but also inspire readers to think critically, act ethically, and design innovatively in shaping the world around us.

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Introductory Chapter: Principles and Paradigms in Modern Industrial Design

Rohit Raja and Sharad Chandra Srivastava

1. Introduction

Industrial design is a key multidisciplinary practice that brings together elements of engineering, art, psychology, and business to create not just functional and manufacturable products but also ones that are visually appealing and user-focused. Indeed, design has evolved from a simple form-giving for mass production to a more sophisticated, strategic, and human-centered profession, with a significant impact on product innovation, brand personality, and user experience [1]. Industrial design today is facing new and widening challenges concerning environmental sustainability, digital convergence, and cross-cultural usability. Contrary to the more conventional, manufacturing-oriented frameworks that only focused on operational efficiency and technical performance constraints, contemporary trends in industrial design now juggle multifaceted and competing considerations ranging from human behavior, market dynamics, and material resources to ecological implications [2]. This turnaround, from object-centricity toward a systemic, experience-driven, and socially responsive one, is an important change in design thinking [3]. Current designers are required to increasingly work together interdisciplinarily and to apply new tools, such as AI, the Internet of Things (IoT), or additive manufacturing, to produce intelligent, adaptive, and sustainable solutions [4]. This chapter reviews those fundamental principles, design methods, and enabling technologies that have characterized design practice today in the industry. It also accentuates the movement from the traditional to the user-centered approach and the importance of sustainability. Tables and case examples are used to illustrate the impact of these changing paradigms.

2. Definition and scope of industrial design

Industrial design is a formal professional activity, the aim of which is the generation of ideas and specifications to optimize the function, value, and appearance of products and systems for the mutual benefit of both user and manufacturer [1]. It is the beautiful collision of art, engineering, simplicity, upholstery, and thought. Good industrial design not only secures the way for production but also adds value and improves human factors, strongly related to business goals and market differentiation. Industrial design covers a lot of fields, such as consumer electronics, furniture,

Criteria	Traditional design approach	User-centered design approach
Focus	Product features and manufacturing	User needs and experience
Process flow	Linear, top-down	Iterative, co-creative
User involvement	Minimal	Continuous throughout the process
Evaluation	Technical testing	Usability testing and feedback loops
Outcome	Technically sound product	Intuitive, user-aligned product

Table 1.
Comparative analysis of user-centered and traditional design models.

household appliances, medical devices, transportation systems, and smart wearables [2]. In an era of connected and smart products on the rise, designers are now required to stretch beyond their traditional limits and take into account issues such as user instructiveness, sustainability, and long-term value creation [3]. This is the work of collaboration. Industrial designers often work with engineers, manufacturers, marketers, and others to turn ideas into finished products. Thereby, they strategically contribute to increasing product usability, reinforcing brand image, and building customer loyalty in competitive globalized markets [1, 5]. **Table 1** Shifting of focus from product-dominated to user-centric strategies in contemporary industrial design.

3. Evolution and relevance of industrial design

Industrial design became a separate discipline as part of the Industrial Revolution, which presented the challenge of humanizing mass production and bringing individuality to standardized production [1]. As products became mass-produced, the need for functional designs to be esthetically pleasing and emotionally appealing gained prominence. This philosophy was subsequently further developed by the Bauhaus artistic movement in early twentieth-century Germany, which combined art with usefulness in what today forms the basis of modern design (i.e., minimalism and utility in esthetics) [2]. After World War II, industrial design grew on an enormous scale and spread to new industries under newly wealthy consumers and to the use of products in the world, such as consumer electronics, vehicles, and household appliances. This development was facilitated by advances in materials, manufacturing processes, and an increasing awareness of design in everyday life [3]. The arrival of plastics, lightweight metals, and automation technologies gave designers the freedom to reimagine the form and function of products. Today, industrial design has transformed into an engine of innovation strategy. International companies like Apple, IKEA, and Tesla are examples of how design serves as more than a design-differentiated element, applying it as a competitive means to solve complex issues, to better user experiences, and to create brand value that endures [5]. Today, industrial design represents a company's values and makes statements on sustainability and technology ambitions, which represent future-proofness and user fit in varied markets.

4. Design process and methodology

The industrial design process tends to be solidified into isolated but cyclical phases of research, ideation, sketching and modeling, prototyping, testing, and production. Studies offer insights into user pain points and market needs, which are transferred to

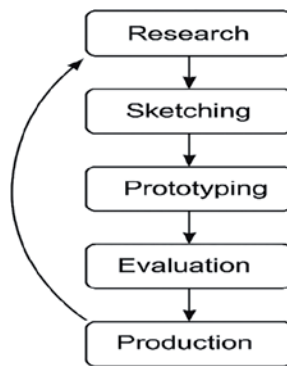


Figure 1.
Design process and methodology flowchart.

concepting and visual development. Sketches and drafts developed out of prototypes are able to be tested and proven. There is an iterative process of adjustment, spool reviews, and final designs that happens.

Figure 1 illustrates how each stage leads to the next, and the final output is an integrated, user-informed collection. Nowadays, tools like Computer-Aided Design (CAD) and Computer-Aided Industrial Design (CAID) offer possibilities of precision, simulation, and visualization, and technologies such as 3D printing facilitate quick and inexpensive physical prototyping [4]. As examples, AI tools enable generative design and customization, and the Internet of Things (IoT) supports smart, connected products that learn from user interaction and can adapt themselves [3].

5. Embracing sustainability and innovation

Sustainability can no longer be an optional factor in the design discipline. Today, design must take into account cradle-to-cradle lifespans, material sources, energy consumed, and breakdown at end-of-life [2, 5]. Methods like Design for Disassembly (DfD), modularity, and usage of environmentally friendly materials are already in use in industrial design [2]. Examples such as IKEA and bamboo-based products now come in the form of flat-pack design and pay rich dividends for having such sustainable values. Moreover, new tendencies such as inclusive design [3], the integration of a circular economy, and data-driven solutions for personalization are playing a big role in the new scene of industrial design. Designers of today must be able to produce products that are not only “functional” and “esthetic” but also “ethical,” “socially inclusive,” and “context-aware” to different cultural and environmental conditions [1, 2].

6. Conclusion

Industrial design has evolved from an esthetic proposition to an integral part of the product development and innovation process. It is a mix of looks, comfort, plausibility, and emotional connection. Thus, it serves as the connection between user demand, technological development, and market profit. Through the adoption of new practices, sustainable and user-centered values, industrial design has the opportunity to shape the future of responsible innovation in multiple sectors.

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IDEA COACH: Using Generative AI and Mind Genomics Thinking to Drive Questions and Answers in Industrial Design

Howard R. Moskowitz, Stephen D. Rappaport and Sharon Wingert

Abstract

Designers used to brainstorm product ideas from their own ingenuity and experiences. Today's generative AI uses algorithms to create unique, cutting-edge designs, revolutionizing the design process. With generative AI, designers may enter criteria and limitations into algorithms to generate a variety of design possibilities. These ideas may combine old principles with new ones that the designer may not have previously considered. This paper presents a simple design issue at the earliest stages: a device which sits on the forehead and, upon demand, instantly translates text written in a foreign language either to speech or to text in one's own language. Through this worked example, strictly using generative AI coupled with Mind Genomics thinking, the paper shows the range of what might be done in the very early design stages where the issue is conceptual, not physical.

Keywords: design thinking, generative AI, simulation, Mind Genomics thinking, worked examples

1. Introduction

Generative AI (hence just AI alone) possesses an extraordinary ability to generate thought-provoking questions and solutions to those questions by analyzing data, recognizing patterns, and predicting outcomes. AI technologies possess the capacity to generate thought-provoking inquiries that may not typically be taken into account in conventional design processes, leading to groundbreaking solutions and novel viewpoints. The result is that AI has the power to significantly enhance the design process by inspiring designers to think creatively and venture into uncharted territories. By posing thought-provoking questions, generative AI has the ability to challenge conventional wisdom, spark creativity, and ultimately produce design solutions that are both impactful and efficient.

A newly available paper on the Internet elegantly summarized the history and promise of AI in “design thinking” [1]. The paragraph is cited in full, except for references, which are left out.

“With the rapid progress of technology and societal changes, design thinking has become essential for developing 21st-century skills. It is a commonly used innovation method that affects company culture, customer involvement, and the driving principles of the innovation process. Design thinking was developed as a result of a collaboration between Stanford University and IDEO, with the main goals of laying the groundwork for creative approaches to be in line with corporate goals and helping managers understand designers' thought processes ... Artificial intelligence (AI) mimics human cognitive processes. It offers a variety of skills, including perception, logic, learning, problem-solving, and creativity, to complete various challenging tasks ... Because of its adaptability and usefulness across numerous industries, AI boosts output, effectiveness, and problem-solving in diverse contexts ... The importance of AI in fostering digital transformation cannot be overstated ... It alters how firms run and promotes innovative methods. As it affects the future of design thinking and the interaction of creativity, it is essential to understand how AI contributes to digital transformation, particularly in recognizing which design thinking stages benefit the most from AI solutions. Design thinking, which encourages innovation by challenging presumptions and coming up with fresh ideas, can work in harmony with AI's ability to process massive amounts of data and identify patterns to provide creative solutions to problems facing the digital revolution.”

AI excels in the realm of exploring various design options and producing multiple solutions for a single design problem. By employing targeted inquiries, designers can effectively generate a variety of design options and evaluate them based on their unique features and potential impact. By employing an iterative process, one may well unearth groundbreaking design solutions which push the boundaries of what is possible. Consider the scenario of a designer who is currently working on a brand-new chair design. Using AI, the designer can effortlessly explore multiple facets such as structural integrity, esthetic appeal, comfort level, and material selection, all in a single endeavor. The “magic” of thought-provoking questions merges through meticulous analysis of data, recognizing patterns, and predicting outcomes. By posing insightful questions, AI challenges conventional wisdom, sparks creativity, and produces impactful and efficient design solutions. This technology has the power to significantly enhance the design process by inspiring designers to think creatively and venture into uncharted territories. Strategic questioning driven by AI uncover valuable insights. Combining rigorous analysis with creative flair empowers designers to “turbocharge” knowledge acquisition, technical talent, and decision making, crafting products which elegantly represent a blend of esthetics, practicality, and cost-effectiveness [1–6].

Finally, AI revolutionizes the design process by allowing designers to ask targeted questions which lead to highly creative and personalized product solutions. This groundbreaking technology allows for unparalleled levels of innovation, productivity, and accuracy. By combining the analytical rigor of academia with the persuasive flair of a copywriter, designers can explore a wide range of possibilities and discover creative solutions that might have gone unnoticed. When AI is configured to be an iterative process, it may well become even stronger as the AI generates questions, examines alternative answers, synthesizes a point of view, and uses that point of view to create the next question to be answered in the same fashion. An iterative process using only AI may create new capabilities in the early steps of design.

2. A short retrospective on AI-driven design

In the year 2000, the concept of using artificial intelligence to support designers in creating product features was a groundbreaking and forward-thinking notion. Considering the limitations of the technology at that time, AI had the ability to provide valuable insights and recommendations by analyzing data and recognizing patterns. Designers may have felt a combination of doubt and admiration when confronted with the idea of a machine determining which features to prioritize. There are varying viewpoints when it comes to this concept. There are those who viewed it as a valuable resource for enhancing productivity, whereas others perceived it as a potential constraint on their artistic expression.

At the time of this writing, summer, 2024, there has been a notable shift in people's attitudes towards embracing AI-generated features in product design. It has become a crucial component of the design process. Designers are starting to realize the immense value of AI in their creative process. By harnessing the power of data-driven insights, AI can help generate groundbreaking ideas and optimize product features. The relationship between designers and AI has evolved into a powerful partnership, with designers leveraging the capabilities of AI to enhance their creative abilities and enhance their decision-making capabilities.

Looking ahead to 2030, designers can anticipate a further evolution and seamless integration of generative AI as a valuable coach throughout the design process. Designers have the ability to harness the power of AI for a variety of tasks. This includes generating valuable feature suggestions, accurately predicting market trends, thoroughly analyzing consumer preferences, and efficiently optimizing product performance. The partnership between designers and AI is anticipated to be seamless, with AI acting as a dependable advisor that enhances the designer's abilities and efficiency.

Designers may find themselves experiencing a wide array of emotions when reflecting on their collaboration with generative AI. Some individuals appreciate the efficiency and innovation that AI brings to the design process, whereas others may have concerns about technology replacing their creative intuition. Collaborating with AI as a design coach is an experience both intellectually stimulating and creatively innovative. It motivates individuals to venture beyond their familiar territory and discover a world of potential that they could not have imagined on their own. Successfully navigating the dynamic world of technology calls for designers to fully embrace the convergence of human creativity and artificial intelligence in product design. Thriving in this dynamic field requires overcoming unique challenges and embracing exciting opportunities.

3. Specifying a hypothetical problem: The “forehead” translator

With this all too short introduction, let us explore the way that a design team might use generative AI to create a new product, or more correctly, to ask questions about the product leading to a good design. The problem dealt with in this chapter—one which allows us to explore different ways of developing ideas—comes from a problem increasingly faced by people who travel. Many people struggle with the local languages when traveling or living in different places. Let us see how AI might become a coach to the designer, guiding them to ask questions, even answering some of the questions and making recommendations. In doing so, AI may be a coach, indeed, an IDEA COACH.

4. Task 1: Instructing AI to create a “focused” set of questions on a topic

One of the advantages of clearly stating the design problem and using generative AI to inquire is the enhanced efficiency and speed of the process. Through a careful examination of the subject matter, the AI has the ability to generate precise and relevant questions that effectively tackle the issue at hand. By implementing this approach, the design process can be optimized, resulting in more targeted and efficient discussions. In addition, the AI’s capacity to pose pertinent and thought-provoking inquiries can help to uncover solutions or considerations not immediately evident to the designers.

It is important to consider the drawbacks of this approach, such as the AI’s limitations in understanding complex concepts and asking detailed questions. Although the AI has the capacity to generate a substantial quantity of questions, it may fall short in terms of the ingenuity and analytical abilities possessed by a human designer. There is a possibility that the questioning process could be somewhat limited and repetitive, potentially missing out on fully exploring all possible angles of the design issue. Furthermore, the AI’s questioning may lack emotional intelligence and empathy, potentially impeding the problem-solving process.

Understanding the problem at hand is essential for developing effective solutions for design issues. By clearly defining the design problem and using AI to inquire further, designers can tackle the underlying issue rather than merely addressing surface-level symptoms. By combining the expertise of academia with the persuasive skills of a copywriter, we can create design solutions that not only meet the needs of the end users, but also leave a lasting impact and inspire innovation.

With the foregoing considerations in mind, let us look at the first exercise, specifically, questions about the feature of the “forehead translator.” **Table 1** shows this approach in action, using the Mind Genomics platform, BimiLeap.com. The designers (or any other users) simply type in the request, and any relevant background. The request and background appear in bold type at the top of **Table 1**. At the bottom of **Table 1** are the 15 questions and the AI-generated reasons for the importance of the question.

By focusing on a specific design issue and using AI to inquire about relevant aspects, the designer ends up with enhanced comprehension of the problem. Through a careful analysis of the problem, dissecting it into smaller parts and approaching it from various perspectives using AI-generated questions, there may emerge intricate details and subtleties which may have eluded us at first glance.

Questions regarding design issues may foster creativity and spur innovation. AI raises thought-provoking questions which ignite fresh ideas and perspectives, pushing the designer to explore innovative solutions beyond traditional boundaries. Through the exploration of different possibilities and the experimentation with various solutions, the designer ends up pushing the boundaries of design thinking, leading to the possibility of novel concepts that may have otherwise gone unexplored.

5. Task 2: Can generative AI learn from its own questions to create better questions?

In the realm of industrial design, the process of brainstorming and discussing ideas at the early stages is crucial for the success of a project. Traditionally, this process

Instructions given to the AI to generate 15 focused questions and description of “importance”
Give me 15 questions that I need to ask for using AI to generate a new product, which is a forehead translator. These questions have to deal with the different actions that the product will do, so the questions have to lead to specifications of product features. Make sure the questions are focused on specific features of design and physical use. Make the question length between 10 and 20 words. Make the questions focus on design ONLY, design from the point of view of the user, a traveler.

When you give me the questions, follow it immediately by a paragraph explaining why that question is important to the industrial design. Start the paragraph with one word, **IMPORTANCE** (all capitals). Then write a paragraph explaining why this particular question is important, how it will guide the designer, why it will be important for manufacturing, for sales, etc.

The 15 questions generated by AI

QUESTION 1: Can the head translator be comfortably worn for extended periods of time?

IMPORTANCE: Comfort is crucial for user satisfaction and ensuring the product is functional throughout a traveler's journey.

QUESTION 2: Will the head translator have adjustable straps to fit different head sizes?

IMPORTANCE: Adjustable straps accommodate various users, enhancing the product's accessibility and usability.

QUESTION 3: Is the head translator lightweight and portable for easy travel?

IMPORTANCE: Portability is key for travelers, making it essential for the product to be compact and easy to carry.

QUESTION 4: Does the head translator have noise canceling technology for clear audio translation?

IMPORTANCE: Clear audio translation is essential for effective communication in diverse environments, making noise cancelation a critical feature.

QUESTION 5: Will the head translator have a long battery life to support extended use during trips?

IMPORTANCE: Long battery life ensures the product remains functional for the duration of a traveler's journey, enhancing user experience.

QUESTION 6: Does the head translator have a user-friendly interface for intuitive operation?

IMPORTANCE: An intuitive interface simplifies the user experience, making it easy for travelers to navigate and utilize the product effectively.

QUESTION 7: Will the head translator be compatible with various languages to cater to global travelers?

IMPORTANCE: Language compatibility is crucial for a versatile product that can effectively translate across different regions, ensuring its usefulness for a wide range of users.

QUESTION 8: Is the head translator designed with high quality materials for durability and longevity?

IMPORTANCE: Durable materials enhance the product's lifespan, making it a reliable companion for frequent travelers in various conditions.

QUESTION 9: Does the head translator have a sleek and modern design for a stylish appearance?

IMPORTANCE: Esthetic appeal contributes to the product's attractiveness to users, enhancing its desirability and marketability.

QUESTION 10: Will the head translator have a built-in microphone for accurate voice recognition?

IMPORTANCE: Accurate voice recognition is essential for precise translation, improving the overall performance and functionality of the product.

QUESTION 11: Is the head translator equipped with real time translation capabilities for seamless communication?

IMPORTANCE: Real time translation enhances the product's efficiency, allowing for immediate and fluid exchanges between users speaking different languages.

QUESTION 12: Does the head translator offer multi person translation for group conversations?
IMPORTANCE: Multi person translation functionality expands the product's utility, making it suitable for group interactions and social settings during travel.
QUESTION 13: Will the head translator feature an adjustable display for easy viewing of translated text?
IMPORTANCE: An adjustable display improves visibility and readability, ensuring users can easily access and understand translated information.
QUESTION 14: Is the head translator designed with ergonomic ear cups for comfortable listening?
IMPORTANCE: Ergonomic ear cups enhance comfort during extended listening sessions, making the product more user friendly and enjoyable to use.
QUESTION 15: Does the head translator have a compact and foldable design for convenient storage in travel bags?
IMPORTANCE: A compact and foldable design enhances the product's portability and storage options, making it easy for travelers to carry and pack the device on their journeys.

Table 1.
AI-generated focused questions and analyses of “importance”.

involved human experts and stakeholders coming together to hash out ideas and requirements. However, with the advent of AI, there is an opportunity to enhance this process and bring a new level of innovation to industrial design.

Table 1 showed the outcome of instructing AI to generate relevant questions for the topic of the forehead translator. Are these the best questions to ask? How can we make AI more “self-critical” in the questions it generates?

Table 2 shows what happens when the AI is instructed to act as a coach for or is critical of the 15 questions. For the first set of questions generated by AI in **Table 2**, evaluation of the quality of these questions was positive, but was followed immediately by the presentation of a new set of 15 questions. The implicit statement is that the questions could have been better. This new second set of 15 questions was in turn presented to the AI with the same instructions, namely, to evaluate the quality of the questions. This time AI did not suggest a new set of 15 questions. The failure to provide a new set of 15 questions for this second run of AI suggests that the second set of questions were qualitatively better, and that a third set of questions was not needed. This finding has important implications for how we can effectively integrate generative AI into the design process. It emphasizes the significance of incorporating AI as a valuable tool to enhance human expertise, rather than completely replacing it. By harnessing the combined power of AI and human expertise, we can elevate the creative and problem-solving prowess of the design process.

Curiously, the process abruptly stops after the second set of 15 questions generated by the AI. It appears that the AI might have some limitations when it comes to generating an infinite number of fresh questions. Can the AI generate top-notch questions that span various pertinent subjects in only two iterations?

A potential drawback of this approach is that the AI may automatically or even randomly stop generating new questions after a certain number of iterations. One might wonder about the AI's effectiveness and limitations in generating thought-provoking and pertinent discussion questions. On the other hand, it might suggest that the AI has already furnished a thorough collection of questions and insights to steer the design process.

From a careful analysis, it becomes evident that the AI possesses the ability to generate exceptional questions and valuable insights when given the opportunity. This

After reading all the questions, and being a professional in the design field, please tell me what you think of these questions as a whole. Are they good? Are they useful? A complete, detailed paragraph about you as a design teacher would say to this group about their efforts.

Here are the questions that you should read as a group, and then write your evaluation.

First set of 15 questions, the AI evaluation, and the AI recommendation of 15 new questions

1. Can the head translator be comfortably worn for extended periods of time?
2. Will the head translator have adjustable straps to fit different head sizes?
3. Is the head translator lightweight and portable for easy travel?
4. Does the head translator have noise canceling technology for clear audio translation?
5. Will the head translator have a long battery life to support extended use during trips?
6. Does the head translator have a user-friendly interface for intuitive operation?
7. Will the head translator be compatible with various languages to cater to global travelers?
8. Is the head translator designed with high quality materials for durability and longevity?
9. Does the head translator have a sleek and modern design for a stylish appearance?
10. Will the head translator have a built-in microphone for accurate voice recognition?
11. Is the head translator equipped with real time translation capabilities for seamless communication?
12. Does the head translator offer multi person translation for group conversations?
13. Will the head translator feature an adjustable display for easy viewing of translated text?
14. Is the head translator designed with ergonomic ear cups for comfortable listening?
15. Does the head translator have a compact and foldable design for convenient storage in travel bags?

As a design teacher, I would say that this set of questions is quite comprehensive and well thought out. They cover a wide range of important factors that should be considered when designing a head translator, from comfort and portability to functionality and esthetics. The questions demonstrate a good understanding of the needs and preferences of potential users, such as global travelers who value clear communication and convenience. Overall, this group has put in a lot of effort in formulating these questions and should be commended for their thoroughness in addressing key aspects of the design process.

Second set of 15 questions, the AI evaluation, and the AI recommendation of “stop here” (because no new questions are recommended)

Here are 15 additional questions that could be considered based on the initial idea. By including these additional questions, the design process can be further refined and tailored to meet the needs and expectations of a diverse range of users.

1. Will the head translator offer offline translation capabilities for use in areas with limited internet connectivity?
 2. Is the head translator compatible with popular translation apps for seamless integration with existing tools?
 3. Does the head translator have a secure connection to prevent data breaches or leaks during use?
 4. Will the head translator come with a warranty or customer support for troubleshooting issues?
 5. Is the head translator water-resistant or waterproof for use in different weather conditions?
 6. Does the head translator have a voice activation feature for hands-free operation?
 7. Will the head translator come with customizable language settings for personalized translation experiences?
 8. Is the head translator designed with sustainability in mind, using eco-friendly materials or packaging?
 9. Does the head translator have a companion mobile app for additional features or updates?
 10. Will the head translator support simultaneous translation of multiple languages for complex conversations?
 11. Is the head translator designed ergonomically to minimize strain on the wearer's neck or head?
 12. Does the head translator have a customizable display screen for personalized settings or preferences?
 13. Will the head translator be equipped with biometric security features for user authentication?
 14. Is the head translator compatible with smart home devices for seamless integration into daily routines?
 15. Does the head translator have a community forum or platform for users to share feedback and suggestions for improvement?
-

As a design teacher, I would say that these questions are well-thought-out and address a variety of important aspects when designing a head translator. The questions cover functionality, compatibility, security, user experience, sustainability, and innovation, which are all crucial factors to consider in product design. However, I would recommend that the group also consider factors such as affordability, battery life, ease of maintenance, and overall user interface design in their evaluation. Additionally, they could benefit from brainstorming questions that focus on potential market demand, target audience needs, and potential competitors in the field to ensure their design is competitive and meets consumer expectations. Overall, this group has made a good effort in creating thoughtful questions but could further enhance their evaluation by considering a broader range of factors in their design process.

Note: The AI did not provide a third set of questions, suggesting that the user had done sufficiently good with the second set of question.

Table 2.

Two successive sets of questions by AI, and their evaluation by AI as a “judge” or “coach”.

emphasizes how AI can significantly contribute to improving the initial phases of industrial design and fostering innovation in the field. Through the utilization of generative AI in the design process, designers can tap into a wealth of creative possibilities and push the limits of what can be achieved in industrial design.

6. Task 3: Using AI to simulate a design team iterating better design ideas

This third task now begins to put AI “through its paces.” The objective here is to simulate the interactions of members of the design team, presented with ideas generated by AI, with AI simulating discussion. Emerging from those discussions should be rapid, simple analyses such as a short discussion, analysis of the impact of the discussion, and surfacing of weak points and strong points. At the end of this analysis, the program is requested to provide a new “best” question. Whether the question provided is the best or not cannot easily be answered. What is important at this early stage of development is to request the program to provide the question. One can always evaluate the strength and importance of the question in an intermediate or in a parallel step. **Table 3** presents the instructions to the AI (top), and then a sequence of five iterations, in which the AI explores one question in depth, and afterwards generates the “new best question” emerging from the AI exploration.

7. Task 4: Using AI to create a set of questions and answers, and then more deeply analyze the information

Our final use of AI instructs it to do two rounds of generating/analyzing. The first round is to answer a question or a request with that which we wanted. The second round is to return later with a series of post-event analyses. The objective is to make AI more of a co-worker, wherein it provides more useful contribution. The post-event analyses are a standard feature of the Mind Genomics technology, specifically the “Idea Book” returned to the user after the study has been set up, and ready to run in the “field.” **Table 4** shows the sequence of materials. For ease of presentation, we list the steps in the sequence.

Section A is the background to the project and request to the AI to provide questions, analyses, and answers. The AI, not the designer, provided the questions,

Instructions given to the AI

We are designing a camera to be worn on the forehead, which reads foreign languages, and translates them immediately. It is a dash cam which feeds the translation to either earbuds, or to a watch. Everything in the discussion, the questions, the answers, have to do with the FEATURES AND CUSTOMER USE of this dash cam, the technology of this dash cam, and the specific use of this dash cam by a person, and nothing else.

The team consists of four people:

The LEAD designer

The CAMERA designer

The TRANSLATION designer

The USER INTERFACE designer

1. QUESTION: What is the most important question about the specific design features that we need to ask as we move to the middle of the project? Begin the sentence with the word QUESTION.
2. PROBLEM: What is the problem that we are focusing on, and why is that problem appropriate for this sequence of questions and answers? Begin the sentence with the word PROBLEM.
3. LEAD Designer: What is the point of view of the LEAD designer, and why does the LEAD designer think that way? Begin the answer with the words LEAD Designer.
4. CAMERA Designer: What is the answer of the CAMERA Designer and why does the CAMERA designer think that way? Begin the answer with the words CAMERA Designer.
5. TRANSLATION Designer: What is the answer of the TRANSLATION designer and why does the TRANSLATION designer think that way? Begin the answer with the words TRANSLATION designer.
6. INTERFACE Designer: What is the answer of the INTERFACE designer and why does the INTERFACE designer think that way? Begin the answer with the words INTERFACE Designer.
7. SHORT DISCUSSION: Summarize their short discussions with each other leading to a new question. Make that summary four sentences long. Begin the answer with the words SHORT DISCUSSION.
8. IMPACT: Summarize the impact on the design project of their discussion. Begin the answer with the word IMPACT.
9. WEAK POINTS: What potential issues may arise in integrating the various answers from the four team members to this specific problem? Begin the answer with the words WEAK POINTS.
10. STRONG POINTS: What potential advantages and benefits may arise in integrating the various answers from the four team members to this specific problem? Begin the answer with the words STRONG POINTS.
11. BEST NEW QUESTION: Based upon the discussion among the different designers, pick the best question to ask, keeping the SAME general focus. Begin the answer with the words BEST NEW QUESTION.

Five sequential iterations, in which the AI analyzes the question and then comes up with the best new question. It is the best new question which becomes the question for the next iteration.

ITERATION 1

QUESTION: What specific design features are crucial for ensuring accurate and fast language translation on the camera?

PROBLEM: Optimize the design features of the camera to provide a seamless translation experience for the user.

LEAD Designer: Prioritizing ease of use and accuracy in translation technology is essential for the success of the project.

CAMERA Designer: Incorporate high-quality lenses and sensors to capture clear images of text in various languages.

TRANSLATION Designer: Use advanced machine learning algorithms to improve language recognition and translation accuracy.

INTERFACE Designer: User-friendly interface which allows the user to easily access and control translation features.

SHORT DISCUSSION: Potential challenges of integrating complex translation technology with camera hardware and user interface design, leading to a focus on optimizing system performance.

IMPACT: Streamlined approach to integrating translation technology with camera features, ultimately improving the user experience.

WEAK POINTS: Potential issues may arise in ensuring seamless communication and cooperation among the different design elements, leading to inconsistencies in the overall functionality.

STRONG POINTS: The integration of diverse expertise in camera technology, translation algorithms, and user interface design can result in a comprehensive and innovative product which effectively meets user's needs.

BEST NEW QUESTION: How can we effectively balance the technical requirements of translation technology with the user interface design to create a seamless and intuitive user experience?

ITERATION 2

QUESTION: How can we effectively balance the technical requirements of translation technology with the user interface design to create a seamless and intuitive user experience?

PROBLEM: The problem we are focusing on is ensuring the seamless integration of translation technology with the user interface design for a smooth user experience.

LEAD Designer: The key to success lies in creating a user-friendly interface that allows for easy access to the translation features, prioritizing simplicity and functionality.

CAMERA Designer: Emphasizes the importance of optimizing the camera's hardware technology to accurately capture and interpret foreign languages for translation.

TRANSLATION Designer: Suggests focusing on developing advanced algorithms and machine learning capabilities to enhance the accuracy and speed of language translation.

INTERFACE Designer: Highlights the significance of designing a visually appealing and intuitive interface that simplifies the user's interaction with the translation features.

SHORT DISCUSSION: The team discussed the need to ensure a balance between the hardware and software components of the camera, as well as the importance of seamless integration between the translation technology and user interface design to enhance user experience. They also explored potential challenges in implementing advanced algorithms for language translation and identified the need for continuous user feedback to improve the interface design. This led to a new question about the implementation of user feedback in the design process.

IMPACT: The discussion underscores the need for a collaborative approach to design that prioritizes both technical innovation and user experience, setting the stage for a more cohesive and effective design process.

WEAK POINTS: Potential issues may arise in integrating the various answers from the team members if there are conflicting perspectives on the prioritization of technical features versus user interface design elements.

STRONG POINTS: The integration of various perspectives from the team members may lead to a more comprehensive and well-rounded design approach that combines advanced technology with user-friendly interface design, resulting in a superior product for customers.

BEST NEW QUESTION: How can user feedback be effectively integrated into the design process to optimize the balance between technical requirements and user interface design for the translation camera?

ITERATION 3

QUESTION: How can user feedback be effectively integrated into the design process to optimize the balance between technical requirements and user interface design for the translation camera?

PROBLEM: The focus is on designing a camera that reads and translates foreign languages in real-time, requiring a balance between technical functionality and user-friendly interface design to ensure optimal usability.

LEAD Designer: Believes that user feedback is crucial in determining the functionality and design of the translation camera, as it will ensure that the final product meets the needs and preferences of the target users.

CAMERA Designer: Emphasizes the importance of technical specifications and capabilities in the design process to ensure accurate language recognition and translation.

TRANSLATION designer: The TRANSLATION designer emphasizes the need for advanced language processing algorithms to accurately translate foreign languages in real-time.

INTERFACE Designer: Focuses on creating a user-friendly interface that allows for seamless communication and interaction with the translation camera.

SHORT DISCUSSION: The team members discuss the importance of balancing technical requirements with user interface design to create an effective translation camera that meets both functional and usability needs. They explore ways to gather and incorporate user feedback into the design process. The team agrees on the importance of combining advanced technology with user-friendly interfaces to optimize the performance of the translation camera. They discuss potential challenges in integrating various design elements and seek solutions to address them.

IMPACT: The discussion among the design team helps to align their perspectives and goals, leading to a more cohesive approach to designing the translation camera. By considering both technical requirements and user interface design, the team can create a product that meets the needs and expectations of users.

WEAK POINTS: Potential issues may arise in integrating the different perspectives and ideas of the team members, leading to conflicts in prioritizing technical functionality over user interface design or vice versa.

STRONG POINTS: Integrating the various answers from the team members can lead to a comprehensive design that combines advanced technology with user-friendly features for an optimal user experience.

BEST NEW QUESTION: How can we ensure that the translation camera seamlessly integrates advanced language processing algorithms with a user-friendly interface to provide accurate and convenient translations in real-time?

ITERATION 4

QUESTION: How can we ensure that the translation camera seamlessly integrates advanced language processing algorithms with a user-friendly interface to provide accurate and convenient translations in real-time?

PROBLEM: What is the problem that we are focusing on, and why is that problem appropriate for this sequence of questions and answers?

LEAD Designer: Prioritizing accuracy and user-friendliness is crucial in order to ensure that the translation camera meets the needs of the user effectively.

CAMERA Designer: Suggests incorporating high-quality lenses and sensors to capture clear images of foreign language text for accurate translation.

TRANSLATION Designer: Recommends implementing machine learning algorithms to continuously improve the accuracy of translations over time.

INTERFACE Designer: Proposes creating a simple and intuitive interface that allows users to easily navigate and customize settings for a personalized experience.

SHORT DISCUSSION: The team discussed the importance of balancing technical complexity with user-friendly design to create a seamless experience for the user. They also touched upon the need for continuous improvement in translation accuracy and the importance of clear, high-quality image capture.

IMPACT: The discussion helped the team gain a deeper understanding of the key components necessary for the successful integration of technology and design in the translation camera project.

WEAK POINTS: Potential issues may arise in coordinating the different design elements to ensure cohesive functionality and user experience. Communication and collaboration between team members will be crucial to address any potential conflicts or inconsistencies.

STRONG POINTS: By integrating the expertise and perspectives of the different team members, the translation camera project stands to benefit from a comprehensive approach that addresses both technical and user-centered aspects. The diverse skills and knowledge of the team members can lead to innovative solutions and a more refined final product.

BEST NEW QUESTION: How can we effectively balance technical complexity with user-friendly design in the development of the translation camera to ensure optimal functionality and ease of use?

ITERATION 5

QUESTION: How can we effectively balance technical complexity with user-friendly design in the development of the translation camera to ensure optimal functionality and ease of use?

PROBLEM: What is the problem that we are focusing on, and why is that problem appropriate for this sequence of questions and answers?

LEAD Designer: Prioritize functionality and efficiency in the design to ensure the translation camera meets the needs of the user.

CAMERA Designer: Believes in optimizing image quality and stability in the design of the camera to enhance translation accuracy.

TRANSLATION Designer: Focuses on developing advanced language recognition software that can accurately translate a variety of foreign languages in real-time.

INTERFACE Designer: Create a user-friendly interface that allows for easy navigation and customization of settings for the translation camera.

SHORT DISCUSSION: The team discussed the importance of seamless integration between the camera, translation software, and user interface to create a cohesive and efficient product. They also highlighted the need for regular user testing to gather feedback and improve the design.

IMPACT: The discussion helped the team identify key areas of improvement and potential challenges in the design process, ultimately leading to a more streamlined and user-focused product.

WEAK POINTS: Potential issues may arise in integrating the various answers from the team members if there is a lack of communication and alignment on design goals and priorities.

STRONG POINTS: Potential advantages of integrating the various answers include a holistic approach to design that considers all aspects of the translation camera's functionality and user experience.

BEST NEW QUESTION: How can the team ensure consistency and cohesion in the design process to create a seamless and user-friendly translation camera?

Table 3.

Sequence of five iterations, with the AI creating a question, evaluating it, and then recommending the "new best question".

A. Background to the project and instructions given to AI

I am a traveler in Europe and the Middle East. I am not a good student of languages. I want to develop a camera like device, somewhat like a dashcam on a car, which sits on my forehead, looks at the world, and has a way of translating what I am looking at into my own language, either as a translated text I can look at with a phone like device that I am holding, or sends me a translation into my earbuds.

What are recommended questions about that design that I should surface with the designer who has just been hired? Assume that the designer is just out of school, and is learning, as I am.

Give me 8 questions to ask, all related to the features. For each question, give me both the question itself, as well as why the question is being asked, and four types of answers that I might get from the designer. Finally, for that question, synthesize what I have learned.

B. Answers delivered immediately by AI

QUESTION 1: Can the camera device accurately capture and translate text from various languages in real time?

WHY ASKED? This is important to ensure the device will be able to effectively translate language in different environments.

POSSIBLE ANSWERS: Yes, the device uses advanced OCR technology / No, the device may struggle with handwritten or poorly lit text / Somewhat, the device can accurately translate printed text but may have difficulty with certain fonts / The device may require internet connectivity to translate text accurately.

SYNTHESIS: By asking this question, you will gain insight into the device's capabilities in translating text, which is crucial for language understanding.

QUESTION 2: Can the device differentiate between different languages spoken in the environment?

WHY ASKED? It is important to know if the device can accurately identify and translate multiple languages simultaneously.

POSSIBLE ANSWERS: Yes, the device can detect and translate multiple languages simultaneously/No, the device may only be able to translate one language at a time/The device can switch between pre-selected languages for translation/The device may struggle with detecting lesser-known languages.

SYNTHESIS: Understanding how the device handles multiple languages will impact its usability in diverse linguistic environments.

QUESTION 3: How does the device handle regional accents and dialects?

WHY ASKED? Regional accents and dialects can significantly impact translation accuracy, so it is essential to know how the device copes with these variations.

POSSIBLE ANSWERS: The device is trained to recognize and adjust for regional accents/The device may struggle with certain accents/Users can input specific accent settings for better accuracy/The device provides general translations irrespective of accents.

SYNTHESIS: Knowing the device's capabilities with accents can help determine its effectiveness in different regions.

QUESTION 4: Can the translation feature be customized or adjusted based on user preferences?

WHY ASKED? Customizing the translation settings can enhance user experience and accuracy to meet individual needs.

POSSIBLE ANSWERS: Yes, users can customize language settings and preferences/No, the device has fixed translation settings/Some customization options are available, such as accent adjustments/Customization features may require additional software updates.

SYNTHESIS: Understanding the device's customization options will inform how well it can adapt to the user's specific language needs.

QUESTION 5: Does the device have the ability to provide real time translations, or does it require processing time?

WHY ASKED? Real time translation can be crucial for immediate language understanding in dynamic environments.

POSSIBLE ANSWERS: The device offers instant translations without delay/The device may have a slight processing delay for translations/Real time translation is possible with a stable internet connection/Translation speed can vary depending on the language complexity.

SYNTHESIS: Knowing the device's translation speed will determine its efficiency in providing immediate language assistance.

QUESTION 6: How does the device handle translating complex phrases or idiomatic expressions?

WHY ASKED? Language nuances such as idioms and colloquialisms can pose challenges for translation accuracy.

POSSIBLE ANSWERS: The device can accurately translate complex phrases and idiomatic expressions/Some idioms may be lost in translation/Users can access explanations for translated idioms/The device may struggle with interpreting slang or cultural references.

SYNTHESIS: Understanding how the device interprets complex language constructs will impact its ability to convey meaning accurately.

QUESTION 7: Can the device store translated text for offline access?

WHY ASKED? Offline access to translated text can be crucial in areas with limited internet connectivity.

POSSIBLE ANSWERS: Yes, the device can store translated text for offline use/No, the device requires an internet connection for translations/Offline storage is available for a limited number of translations/Users can manually save translations for offline access.

SYNTHESIS: Knowing if the device supports offline translation storage will determine its usability in various connectivity conditions.

QUESTION 8: How does the device handle privacy and data security concerns with captured translations?

WHY ASKED? Data security and privacy are essential considerations, especially when handling sensitive language information.

POSSIBLE ANSWERS: The device ensures secure storage and encryption of translated data/User data is anonymized and not stored on the device/Users can opt in for data sharing for improving translation accuracy/The device might have potential privacy vulnerabilities that need to be addressed.

SYNTHESIS: Understanding the device's approach to privacy and data security will inform users about the safety of their translated information.

C. AI analysis of the pattern of questions

C1. Key ideas

1. The device's ability to accurately capture and translate text in real time across various languages.
2. The device's capability to differentiate between multiple languages spoken in the environment.
3. How the device handles regional accents and dialects in translation.
4. The availability of customization options for user preferences in translation settings.
5. The device's speed in providing real time translations.
6. How the device translates complex phrases or idiomatic expressions.
7. The device's ability to store translated text for offline access.
8. Privacy and data security considerations regarding captured translations.

C2. Themes

1. Translation Accuracy and Real time Capabilities
 - The device's ability to accurately capture and translate text in real time across various languages.
 - The device's speed in providing real time translations.
 - How the device translates complex phrases or idiomatic expressions.
 2. Language Differentiation and Regional Considerations
 - The device's capability to differentiate between multiple languages spoken in the environment.
 - How the device handles regional accents and dialects in translation.
-

3. Customization and User Preferences

- Availability of customization options for user preferences in translation settings.

4. Storage and Accessibility

- The device's ability to store translated text for offline access.

5. Privacy and Data Security

- Privacy and data security considerations regarding captured translations.

C3. Perspectives

Translation accuracy and real time capabilities

- Plus: The device accurately captures and translates text in real time, allowing for seamless communication across languages.
- Minus: The device may struggle with accurately translating complex phrases or idiomatic expressions.
- Interesting: The speed at which the device provides real time translations can greatly impact its effectiveness in various scenarios.

Language differentiation and regional considerations

- Plus: The device can differentiate between multiple languages spoken in the environment, accommodating a diverse range of users.
- Minus: The device may struggle with handling regional accents and dialects, potentially resulting in inaccurate translations.
- Interesting: How the device adjusts its translations based on regional variations can provide insight into its adaptability and effectiveness.

Customization and user preferences

- Plus: The device offers customization options for user preferences, allowing for a personalized translation experience.
- Minus: Limited customization options may restrict users from fully optimizing their translation experience.
- Interesting: The impact of user preferences on the device's translation accuracy and effectiveness can reveal the importance of personalization in language translation technology.

Storage and accessibility

- Plus: The device can store translated text for offline access, ensuring that users can access translations even without an internet connection.
- Minus: Limited storage capacity may restrict the amount of translated text that can be saved for offline access.
- Interesting: The device's approach to storing and accessing translated text offline can provide insights into its usability and convenience for users in various settings

Privacy and data security

- Plus: The device prioritizes privacy and data security considerations regarding captured translations, safeguarding user information.
- Minus: Potential privacy breaches or data security vulnerabilities could compromise user trust in the device.
- Interesting: The measures taken to ensure privacy and data security in translation technology can inform users of the device's commitment to protecting their sensitive information.

C4. What is missing

QUESTION: How accurate is the device's translation in comparison to human translation?

WHY ASKED? Understanding the accuracy of the device's translation compared to human translation can provide insight into its reliability.

POSSIBLE ANSWERS: The device's translation is comparable to human translation/The device's translation may have some inaccuracies compared to human translation/The device's translation is generally reliable but may struggle with nuanced language nuances/Users may need to review and edit translations for accuracy.

SYNTHESIS: Knowing the device's accuracy in translation compared to human proficiency can help users gauge its reliability in language understanding.

QUESTION: What features or tools does the device offer to enhance language learning or understanding?

WHY ASKED? Language learning tools can be valuable for users looking to improve their language skills or deepen their understanding of different languages.

POSSIBLE ANSWERS: The device offers language learning exercises or quizzes/Users can access language grammar and vocabulary resources/The device provides pronunciation guides and practice tools/Users can receive cultural insights and language usage tips.

SYNTHESIS: Exploring the device's language learning features can provide additional value for users beyond simple translation capabilities.

C5. Alternative viewpoints

1. Some users may prefer a device that prioritizes speed over accuracy in translation, whereas others may prioritize accuracy even if it means slightly longer processing times.
2. There may be users who are concerned about the device's reliance on internet connectivity for translations, whereas others may not mind as long as the translations are accurate.
3. Users may have varying opinions on the level of customization they require from the device, with some preferring a more user-friendly interface and others wanting more advanced customization options.
4. Some users may prioritize the device's ability to handle regional accents and dialects, whereas others may prioritize its ability to handle complex phrases and idiomatic expressions.
5. Users may have differing perspectives on the importance of offline access for translated text, with some prioritizing this feature for travel purposes and others not seeing it as necessary.
6. There may be users who are more concerned about data security and privacy in translation devices than others, with some willing to sacrifice privacy for improved functionality.

C6. Interested audiences

1. Travelers: Travelers who frequently visit countries with different languages will be interested in the topic questions as they rely on translation devices to communicate effectively in foreign environments.
2. Language learners: Individuals studying or learning new languages would find the topic questions relevant as they may use translation devices to aid their language acquisition process.
3. Business professionals: Business professionals who conduct international dealings or communicate with clients in various languages will be interested in the topic questions to ensure accurate and efficient communication.
4. Tour guides: Tour guides who interact with tourists from different linguistic backgrounds may find the topic questions helpful in understanding how translation devices can assist in their work.
5. Language service providers: Companies or individuals providing translation services may be interested in the topic questions to assess the capabilities of translation devices in comparison to human translation services.
6. Educational institutions: Schools and language programs could benefit from the topic questions to evaluate the potential use of translation devices in language classes or educational settings.
7. Linguists and language researchers: Professionals in the field of linguistics may be interested in the topic questions to explore how technology is advancing language translation and understanding capabilities.

C7. Opposing audiences

1. Language professionals and translators: Language professionals and translators may oppose the development of a camera device that can accurately translate text in real time as it could potentially threaten their job security. These professionals rely on their expertise and experience to provide accurate and nuanced translations, and they may view the automated translation technology as a threat to their livelihood.
2. Privacy advocates: Privacy advocates may oppose the development of a camera device that captures and translates text in real time due to concerns about data security and privacy. They may be worried about the potential for sensitive information to be captured, stored, or shared without the user's consent, leading to privacy violations.
3. Linguists and language educators: Linguists and language educators may oppose the reliance on automated translation technology like a camera device as they believe it could hinder language learning and comprehension. They may argue that relying on technology for translation could limit users' ability to understand and appreciate the nuances of different languages, leading to a decline in language proficiency.
4. Cultural preservationists: Cultural preservationists may oppose the development of a camera device that can translate text in real time as they may see it as a threat to the preservation of indigenous languages and cultures. They may be concerned that the widespread use of automated translation technology could lead to the erosion of unique linguistic and cultural identities.

C8. Innovations

1. A real time translation earpiece that can accurately translate conversations in multiple languages, with a focus on capturing and translating complex phrases or idiomatic expressions.
 2. A language recognition software that can differentiate between various languages spoken in an environment, including handling regional accents and dialects.
 3. A translation app with customizable settings for user preferences, allowing users to choose specific languages, accents, or dialects for translation.
 4. A handheld translation device with offline storage capabilities, allowing users to access previously translated text without needing an internet connection.
 5. A translation service that prioritizes privacy and data security, implementing strict protocols to protect user data and translations from unauthorized access.
-

Table 4.

Using AI to create eight questions and analyses, followed by a deeper set of analyses done after the study has been set up.

although there is no reason to limit the questions to those provided by AI. Any source and any number of questions will do, up to approximately 15. The number 15 is the limit of information returned by ChatGPT 3.5.

Section B has the eight questions and additional analyses based upon those questions. The request was to provide three things for each, namely why asked, possible answers, and synthesis of the possible answers.

Section C is where the secondary analyses are done. The important thing at this juncture is that already we are “ahead of the game.” AI has done the questions itself and has given the answers and has done some of the thinking for it.

C1 are the key ideas, the three types of questions.

C2 is the AI’s attempt to specify the themes embedded in these questions. In other terms, if we were to talk about the main ideas across this set of eight questions what would we say?

C3 are the perspectives, the different ways of looking at the information. What are the positive and negative aspects of what is being said?

C4 asks about what is missing.

C5 are alternative viewpoints, different ways of looking at the issue of design, other ways that customers might wish, or users might wish.

C6 presents the interested audiences, those who might be interested in the product from a marketing point of view.

C7 presents the opposed audience. Surprisingly, it is possible to create an audience who might be opposed to this entire effort.

C8 are potential innovations hinted at but not defined in the original effort.

8. Conclusion

AI has revolutionized various industries by mimicking human creativity and intuition, leading to new fields of art, music, and literature. Generative AI, a tool that can enhance human creativity by providing suggestions, generating innovative ideas, and offering constructive feedback, has the potential to revolutionize the design process. By generating precise questions and examining multiple facets of a design challenge simultaneously, AI can lead to innovative and efficient product solutions.

In industrial design, generative AI has gained traction by serving as a valuable tool during the initial phases of the design process. By generating sets of questions and

evaluating them with expert-level precision, AI can provide valuable insights and guidance. However, it is crucial to balance AI with human expertise to create cutting-edge solutions that cater to user and consumer demands.

Generative AI can streamline the brainstorming process, extracting valuable insights from vast amounts of data, and generate innovative solutions. By blending perspectives, new and innovative design concepts can be discovered. By incorporating AI in the initial phases of industrial design, designers can gain advantages from a broader spectrum of ideas and perspectives, resulting in a more efficient and innovative future. The potential for incorporating generative AI into industrial design is immense, promising a future filled with innovation and efficiency.

Generative AI has the potential to revolutionize the design process by generating thought-provoking questions and enhancing efficiency. This approach allows designers to explore new possibilities, identify potential pitfalls, and inspire deeper exploration. AI's data processing and information analysis capabilities lead to groundbreaking solutions. However, challenges include ensuring AI is trained on relevant data, upholding ethical standards, and overcoming inherent biases. Despite these challenges, AI can enhance creativity, productivity, and a broader spectrum of possibilities. However, it also requires careful consideration of human input, heavy reliance on technology, and potential overlooking of crucial factors. Ultimately, integrating AI into the design process requires balancing human ingenuity with technology's potential.

The bottom line here is that with simple requests (prompts), a generative AI can become an extremely strong, powerful help which does some of the thinking of the designer. This ability of AI does not replace the need for the designer, but rather demonstrates that AI is a new partner to the design process. It is the task of the designer to make the best use of this capability. But the capability is here. It is demonstrable. It exists and can easily be accessed today at a very low cost on the Mind Genomics platform, BimiLeap.com. In fact, as noted above, all of these studies, all of these demonstrations were developed in a matter of a few hours showing how powerful the new AI can be under the guidance of a professional.

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Political and Institutional Determinants of Industrialization in Africa

Dieudonné Mignamissi, Bernard Nguekeng and Philémon NSi Ella

Abstract

The aim of this chapter is to assess the contribution of political-institutional factors to industrialization in Africa over the period 1996–2022. To this end, we adopt a model of industrialization that takes into account the specificities of African economies. Because of the potential endogeneity bias between industrialization and its main determinants, we apply the Instrumental Variable Two-Stage Least Squares estimator to a panel of 52 African countries. After estimation, we arrive at three main results: (i) weak democratization of political regimes is an obstacle to industrialization in Africa. In other words, the predominance of autocratic political regimes in Africa is a major factor in deindustrialization; (ii) in the absence of good governance, political fragility is a brake on industrialization in Africa; and (iii) good institutional quality stimulates industrialization in Africa. All things being equal, countries that improve their institutional framework benefit from an industrial dividend. This includes low levels of corruption, effective government, a stable political environment, inclusive laws and good-quality regulation, as well as increased political accountability. However, several future avenues would be important to further bridge the gap in the intrinsic analysis of industrialization in Africa. These could include the role of transmission channels, the mobilization of historical factors and legal origins.

Keywords: institutions, governance, fragility, industrialization, IV-2SLS

1. Introduction

According to United Nations Conference on Trade and Development (UNCTAD) [1] (2018), economic growth in Africa's gross domestic product (GDP) has seen significant increases in recent years. It averaged 4.87% between 1995 and 2016, compared with 1.28% between 1980 and 1994, the highest rate (7.49%) achieved in 2007 and the lowest (1.76%) in 2016. Due to its high volatility and unsustainable nature, this growth is marked by significant disparities between different sectors. For example, agriculture's value added as a percentage of GDP was 14.78% in 2015, services 53.52% and industry 29.61% [2]. These disparities can also be observed at sub-regional level, with a sizeable growth gap between East Africa (5.52%) and Southern Africa

(2.90%). At national level, countries, such as Equatorial Guinea (15.09% average), Angola (6.65%) and Nigeria (7.28%), are the best performers, with Madagascar, Mali and Sierra Leone recording the lowest scores.

Industrialization is the process by which primary products are transformed into high value-added products [3]. On a factual level, recent work shows that industrialization is a factor in job creation, productivity growth, access to capital, learning and innovation [4, 5]. Africa's recent growth performance could only be sustainable if the continent implements a genuine industrialization strategy [6]. With this in mind, the African Development Bank's global strategy for transforming Africa includes industrialization as one of the five pillars of its development strategy for the continent.

The relevance of analyzing industrialization in Africa is part of the rationale for the scope of the five key priorities set out by the African Development Bank (AfDB) to sustainably transform African economies: (i) lighting and powering Africa, (ii) feeding Africa, (iii) industrializing Africa, (iv) integrating Africa, and (v) improving the quality of life of Africans. Specifically, the industrialization priority aims to increase industry's contribution to GDP by 130%, support 35 industrial clusters, and strengthen 30 public-private partnerships. Thus, undertaking to study industrialization in Africa by focusing on the political-industrial determinants presents a great opportunity.

Today's interest in industrialization stems from the paradox illustrated by the case of Africa, marked by structural deindustrialization in certain sub-regions, while the continent is lagging far behind in structural transformation. For example, Jalilian and Weiss [7] have shown that 7 of the 16 African countries¹ in their sample experienced deindustrialization during the period 1975–1993. A study by United Nations Industrial Development Organization (UNIDO) [8] notes disparate performances in terms of industrial development in Africa over the period 1980 to 2009: the contribution of manufacturing to GDP increased slightly in North Africa, from 12.6% to 13.6%, while it declined in the rest of the continent, from 16.6% to 11.7%.

Faced with this downward trend in industrialization, several national, regional and continental strategies have been adopted to curb deindustrialization in Africa. On a national level, the emergence programs designed in several countries have given a large part to industrialization strategies as a driver of development. At regional level, CEMAC's (Central African Economic and Monetary Community) emergence trajectory, for example, is calculated on the basis of two main variables: energy intensity and the rate of manufacturing industrialization. On a continental scale, the African Union, through the definition of Agenda 2063, has placed industrialization at the heart of its priorities (Objective 4 of Aspiration 1).

Efforts to design and implement industrialization policies have met with varying success. Recent data from the World Bank (2021) reveal two situations. The first is illustrated by regions that have experienced continuous deindustrialization since 2010. This is the case in Central Africa, where the industrialization rate has fallen from 36.36% in 2010 to 28.69% in 2020, and in Northern Africa (33.57% in 2010 and 27.19% in 2020). The same situation can be observed in Southern Africa (28.51% in 2010 and 25.86% in 2020), with South Africa's weight unable to absorb the low level of industrialization observed in the other countries. The second situation is observed in West Africa, where the industrialization rate rose from 19.79% to 22.38%, and in East Africa, where the industrialization rate rose from 19.19% to 21.62%. As a result of these mixed performances, Sub-Saharan Africa has seen an oscillating evolution, from 23.04% in 2010, to 25.18% in 2015 and 27.80% in 2020. The main lesson to be drawn from these trends is that deindustrialization seems to be accelerating faster than industrialization, which justifies the difficulties of economic transformation in Africa.

The low level of industrialization merits in-depth economic investigation, as it may be due to a number of factors. Rowthorn and Coutts [9] identify three main ones: (1) specialization: Due to the outsourcing of certain activities to various service providers, the manufacturing sector seems to be shrinking, as this value-added sector is now being reclassified in other sectors; (2) consumption: Contrary to Engel's law, which establishes a positive relationship between increased income and the consumption of manufactured goods, Bell [10], in his theory of post-industrial society, shows that this increase could eventually curve in favor of the demand for services; and (3) productivity: given that labor productivity is equal to the growth in output net of that in employment, a dynamic sector (the industrial sector) would result in a decrease in employment, which translates into a fall in its contribution to the economy. This analysis is a generalization of the historical causes of deindustrialization already identified by Rowthorn [11], who puts forward three theses: the "maturity" thesis, the "specialization" thesis and the "failure" thesis.

Other, no less important factors explaining deindustrialization are identified in the unconventional literature. They are historical [12], political [13] and institutional [14]. In particular, the role of political-institutional factors is poorly documented in the literature. Thanks to the work of the new institutional economics, economic development has been explained, particularly since the 1980s, by institutions, interpreted as rules, constraints, instruments of governance or even a balance of payments. They can be formal or informal, hierarchical according to their frequency of change, fundamental or not to legitimize and regulate the economy, inclusive or extractive. North [15] shows that differences in the level of development between countries cannot be understood independently of the incentive mechanisms embedded in the institutions.

The aim of this chapter is to assess the contribution of politico-institutional factors to industrialization in Africa, a region of the world lagging the furthest behind in terms of industrialization coupled with a low-incentive institutional context. In this respect, it goes beyond recent work on the subject [14, 16–18], the latter remaining focused on the economic determinants of industrialization or the moderating effects of institutions. Furthermore, in our robustness tests, we extend the analysis to the dimension of the continent's main sub-regions.

The main contribution of this chapter is to show empirically that the industrialization process is not only important for the structural transformation of an economy, but is also dependent on several forces. Beyond natural, economic and financial conditions, it is essential to focus on the institutional forces capable of driving the industrialization process. Indeed, since the work of the New Institutional School [15], institutions have made it possible to capture development gaps between countries. Analyzing this concern on an African scale is a significant contribution. Furthermore, we mobilize several institutional indicators and several industrialization proxies, and analyze the heterogeneity of the relationship studied across Africa's 5 geographical zones, namely North Africa, West Africa, Central Africa, East Africa and Southern Africa. This distinction makes it possible to understand the differences in development between these regions, based on their institutional performance.

Our main measure of industrialization is industrial value added. Similarly, the main political-institutional variables used are political fragility, political regime and World Bank governance indicators. The International Country Risk Guide (ICRG) political risk indicators are used for robustness. Because of the endogeneity bias between industrialization and some of its fundamentals, we mainly apply double least squares on a panel of 54 African countries observed between 1995 and 2019. Our

results show that the continent's low level of industrial development is due to a poor institutional environment.

The rest of the chapter is organized as follows. The second section presents a brief review of the literature. The empirical strategy is presented in the third section. The fourth section analyzes the results. The fifth tests their robustness and the sixth concludes.

2. Selective literature review

Unlike standard neoclassical theory, for which institutions are exogenous, the New Institutional School emphasizes their effectiveness. Since the work of North [15] in particular, good-quality institutions have been a key factor in economic development. This conclusion, reinforced by Barro [19], is the subject of ongoing renewal [20, 21]. This chapter is based on Gerschenkron's [22] "relative gap" theory, which explains the industrialization gaps between countries at different levels of development, and Kaldor's [23] theory, which outlines the possible links between industrialization and economic growth. Against this backdrop, we place particular emphasis on institutions.

Gerschenkron's [22] theory of the relative gap, a critique of the stages of growth initially proposed by Rostow [24], underlines the impossibility of thinking in terms of a uniform pattern of industrialization in all countries. For Gerschenkron [22], countries that experienced a late industrial take-off benefited from the existence of three main factors: the preponderance of the role of the State as a catch-up factor, the massive development of exports following the protection of the domestic market, and the possibility of benefiting from technology transfer through learning by exporting. This theory, which indirectly highlights the role of institutions in industrialization through the state and market protection mechanisms, explains the development gap between industrialized and developing countries today.

Kaldor's [23] theory is based on three laws: (i) the first law postulates a positive relationship between the growth rate of the economy and the growth rate of manufacturing output; (ii) the second law, akin to Verdoorn's law, relates productivity growth in the manufacturing sector to the growth rate of manufacturing output; and (iii) the third law combines elements of the first two and essentially postulates a positive relationship between the growth of overall productivity in the economy and the growth rate of manufacturing output.

Empirically studies specifically assessing the effects of institutions on industrialization take several approaches. For example, Asiedu [25] across 22 sub-Saharan African countries that effective institutions, political and economic stability and low levels of corruption encourage private capital inflows, which are favorable to the installation of processing structures. Globerman and Shapiro [26] find that good governance has an ambivalent impact on industrialization. The positive effect is observed when these institutions encourage the inflow of capital conducive to industries, and the negative effect follows the outflow of capital. What's more, they argue that good institutions can have a positive impact because they create favorable conditions for multinational companies to emerge and invest abroad.

Daude and Stein [27] find that political instability and violence, government effectiveness, regulatory burden, rule of law and corruption have a significant effect on the industrialization process. However, political representation and accountability are not significant.

On the other hand, some works point to the evidence that institutions do not influence industrialization [28]. Specifically, non-institutional factors mainly explain income variations between agrarian countries, while institutional factors largely explain income differences between industrialized economies. Furthermore, Luo and Wen [28] provide evidence of a developmental trap in which non-institutional forces explain a country's lack of industrialization, while institutions do not. This controversy rekindles the interest of this chapter.

3. Methodology

3.1 Empirical model

The industrialization process has been studied by Jalilian and Weiss [7] in both absolute and relative terms. However, their approach ignores the influence of factors, such as fragility, political regime, governance and political risk. To this end, the model used in this chapter is as follows:

$$IND_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 Pop_{it} + \beta_3 Scol_{it} + \beta_4 GFCF_{it} + \beta_5 FDI_{it} + \beta_6 Op_{it} + \beta_7 Fra_{it} + \beta_8 PR_{it} + \beta_9 Gov_{it} + \mu_i + \lambda_t + \nu_{it} \quad (1)$$

IND is the measure of industrialization. Here, we focus on industrial value added, which captures the capacity to transform natural resources into final goods [29]. For the sake of robustness, we also use several absolute and relative indicators of industrialization. *GDP* is real gross domestic product per capita, with its level and squared values included in the specification in order to test the non-linearity with respect to industrialization postulated by Clark [30]. Moreover, the choice of this variable is justified for testing the big push theory of industrialization [31, 32]. *Pop* refers to total population. This variable is used to assess the influence of the local market on the industrialization rate. *Scol* captures the school enrollment rate. This rate is calculated in net terms for primary and secondary levels. The net enrollment rate is the ratio of children of official school age enrolled in school to the corresponding official school-age population. *GFCF* stands for gross fixed capital formation. It is a measure of investment as a percentage of GDP at constant prices. This variable, along with population and school enrollment, serves as proxy for urbanization. *FDI* measures the effect of net capital flows on the industrialization process. This variable measures whether the FDI balance has contributed to the industrialization of the African continent. *Op* stands for trade openness, understood as the share of total trade in GDP. This variable generalizes the Rowthorn et al. [33] model to an open economy [34].

Fra is a measure of the fragility index, understood as a country's capacity to manage conflict, develop and implement public policies, essential services and systemic resilience in maintaining systemic coherence, cohesion and quality of life, responding effectively to challenges and crises and supporting progressive development. The Fragility Matrix rates each country on effectiveness and legitimacy in four performance dimensions: security, political, economic and social. Each of the matrix indicators is assessed on a 4-point fragility scale: 0 "no fragility", (1) "low fragility", (2) "medium fragility", and (3) "high fragility", with the exception of the economic efficiency indicator, which is assessed on a 5-point fragility scale (including 4 "extreme fragility"). The state fragility index then combines scores on all eight

indicators, ranging from 0 “no fragility” to 25 “extreme fragility”. *PR* is a measure of political system, based on scores calculated by the Center for Systemic Peace’s Polity IV Project. This variable measures competition and openness in executive recruitment, constraint on the executive, regulation and competition in political participation. It is codified in an interval defining a continuum of regimes ranging from -10 (purely autocratic regime) to $+10$ (purely democratic regime). The political regime is described as “autocratic” when the annual Polity2 score is between -10 and -6 , “anocratic” when the score is between -5 and $+5$, and “democratic” when the score is between $+6$ and $+10$. *Gov* is the average governance index constructed using the World Bank’s six governance indicators: voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law and control of corruption. All the above indicators range from -2.5 (poor quality of governance) to $+2.5$ (good quality of governance).

The β are parameters to be estimated. μ_i is the country-specific effect, λ_t the time effect and ν_{it} the random term.

3.2 Estimation strategy

There are several econometric approaches to modeling the determinants of industrialization. A first approach may lead to classical estimation methods, such as ordinary least squares. However, these methods ignore the existence of an endogeneity bias, which remains highly probable due to measurement errors, the omission of relevant variables or reverse causality. As for reverse causality, industrialization and production growth influence each other: high growth can be the source of high industrial value added, which in turn can be sustained by growth. This analysis can be generalized to institutional variables. To overcome this bias, most authors use the instrumental variables (IV) technique, which has two competing estimators, namely the two-stage least squares (2SLS) estimator and the generalized method of moments (GMM) estimator. However, because of the predominance of measurement errors on institutional variables in the African context, we choose the IV-2SLS method, with Hansen’s overidentification test used for instruments’ validity. The instruments are chosen according to an internal strategy in the sense put forth by Lewbel [35]. Indeed, according to this author, when there is no consensus on the choice of a good instrument, lags or differences in suspected endogenous variables are better instruments. In addition, to ensure robustness, we will use the GMM estimator, making sure that the conditions laid down by Roodman [36, 37] regarding proportionality between the study period and the number of countries Roodman [36], as well as controlling the proliferation of instruments Roodman [37], are met.

3.3 Sample and data characteristics

The data used cover the period 1996–2022. Industrialization and control variables are taken from the World Development Indicators. Governance indicators are taken from Worldwide Governance Indicators. The political regime variable and the fragility index are taken from the Center for Systemic Peace. The political risk indicators used for robustness are taken from the International Country Risk Guide (ICRG). The model is estimated from a sample of 52 African countries (see Appendix 1).

Careful observation of the data shows a certain harmonization of the scale of variation with regard to their means and ranges. This characteristic suggests fairly consistent and robust results. In addition, two types of variables emerge, according to

Variable	Obs	Mean	Std. Dev.	Min	Max
Industrial VA (ln)	1097	21.59423	1.886883	16.72659	25.43108
Real GDP (ln)	1213	23.04816	1.576282	18.61715	26.89112
Real GDP squared (ln)	1213	533.7002	72.94633	346.5983	723.1324
Polity2	1040	1.666346	5.109882	−7	10
Fragility	1083	14.7627	5.206282	0	25
Population (ln)	1288	15.79809	1.579327	11.24396	19.11864
GFCF (% GDP)	1095	21.36014	9.049571	−2.42	81.05
FDI (% GDP)	1241	4.313102	9.001379	−11.62	161.82
Education	1001	97.71039	23.66574	23.36	151.79
Trade openness	1146	72.66638	39.74855	16.14	348
Control of corruption	1281	−0.625098	0.618382	−1.87	1.22
Gov. effectiveness	1279	−0.738718	0.636365	−2.48	1.06
Political stability	1280	−0.562648	0.927811	−3.31	1.28
Regulation quality	1280	−0.705602	0.638704	−2.65	1.13
Rule of law	1280	−0.698687	0.665274	−2.61	1.08
Voice and accountability	1280	−0.650094	0.739238	−2.23	1.01
Governance index	1281	−0.663380	0.627152	−2.45	0.88

Source: Authors.

Table 1.
Variable characteristics.

the criterion of proportionality between the first two moments (mean and standard deviation) of their distributions. On this basis, the political score indicator (Polity2), inward FDI (% GDP) and governance indicators are relatively dispersed variables, their means being lower than their standard deviations. For the rest, we are dealing with variables that show a weak dispersion, relative to the proportionality between their means and standard deviations (**Table 1**). Also, correlations are relatively average, which does not suggest the existence of an apparent multicollinearity bias, while noting that industrial value added remains positively connected to most governance indicators (**Table 2**).

4. Main findings

4.1 Basic model results

Table 3 presents the results of the effect of institutions on industrialization. We have adopted a reduced model that consists of apprehending the marginal effect of each governance indicator. The results reveal that the weakening of democratic regimes in African countries does not allow them to transform their economies through industrialization. This result is consistent with those of some recent studies. For Bresser-Pereira [38], no country has completed its industrial and capitalist

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
Industrial VA (ln)	(1)	1.0000															
Real GDP (ln)	(2)	0.0102	1.0000														
Real GDP_sq (ln)	(3)	−0.0010	0.9993	1.0000													
Polity2	(4)	−0.1467	−0.0536	−0.0443	1.0000												
Fragility	(5)	−0.0984	−0.2089	−0.2038	−0.2458	1.0000											
Population (ln)	(6)	−0.0278	0.7079	0.7053	−0.1337	0.2848	1.0000										
GFCF (% GDP)	(7)	0.2737	0.2934	0.2836	−0.0461	−0.2729	0.1576	1.0000									
FDI (% GDP)	(8)	0.0324	−0.1796	−0.1807	0.1744	−0.0219	−0.0737	0.2021	1.0000								
Education	(9)	0.2582	0.1427	0.1429	0.0824	−0.4661	−0.1005	0.2694	0.1479	1.0000							
Trade openness	(10)	0.1291	−0.1610	−0.1603	0.2205	−0.4984	−0.4837	0.2408	0.3323	0.4135	1.0000						
Control of corr.	(11)	0.0640	0.0680	0.0659	0.4305	−0.7398	−0.3777	0.1641	−0.0160	0.2258	0.3218	1.0000					
Gov. effectiveness	(12)	0.1029	0.3158	0.3117	0.2758	−0.6864	−0.1613	0.2144	−0.1003	0.2464	0.1832	0.8723	1.0000				
Political stability	(13)	0.0076	−0.2371	−0.2402	0.2999	−0.6177	−0.5467	0.0800	0.0348	0.1902	0.3345	0.6872	0.6005	1.0000			
Regulation quality	(14)	0.1302	0.0993	0.0967	0.3582	−0.5961	−0.2186	0.1222	−0.0475	0.2034	0.1346	0.8356	0.8690	0.6496	1.0000		
Rule of law	(15)	0.1394	0.1206	0.1152	0.3666	−0.7308	−0.2783	0.1861	−0.0497	0.2233	0.2276	0.8903	0.8792	0.7248	0.8875	1.0000	
Voice and acc.	(16)	0.0382	−0.0078	−0.0040	0.7659	−0.5155	−0.2181	0.0562	0.0762	0.1245	0.2033	0.7538	0.6512	0.6241	0.7600	0.7658	1.0000
Governance index	(17)	0.0827	0.0426	0.0402	0.4679	−0.7238	−0.3555	0.1477	−0.0126	0.2252	0.2715	0.9308	0.8929	0.8245	0.9204	0.9519	0.8491 1.0000

Source: Authors.

Table 2.
Correlation matrix.

Dependent variable: Real industrial value added (Log)								
Ln(GDP)	5.660***	5.490***	5.261***	5.514***	4.754***	4.040***	4.215***	4.148***
	(1.149)	(1.136)	(1.184)	(1.170)	(1.195)	(1.141)	(1.193)	(1.182)
Ln(GDP) squared	−0.118***	−0.114***	−0.111***	−0.116***	−0.0995***	−0.0852***	−0.0891***	−0.0872***
	(0.0250)	(0.0249)	(0.0258)	(0.0254)	(0.0261)	(0.0249)	(0.0260)	(0.0258)
Political regime	−0.0639***	−0.0826***	−0.0735***	−0.0687***	−0.0847***	−0.109***	−0.211***	−0.118***
	(0.0116)	(0.0112)	(0.0118)	(0.0117)	(0.0124)	(0.0126)	(0.0194)	(0.0129)
Fragility index	−0.0296**	0.0264*	0.00663	−0.0361**	0.00607	0.0559***	0.0326**	0.0533***
	(0.0132)	(0.0150)	(0.0149)	(0.0172)	(0.0147)	(0.0165)	(0.0144)	(0.0160)
Control of corr.		0.793***						
		(0.115)						
Gov. effectiveness			0.537***					
			(0.117)					
Political stability				−0.0733				
				(0.108)				
Regulation quality					0.647***			
					(0.130)			
Rule of law						1.052***		
						(0.131)		
Voice and accountability							1.319***	
							(0.151)	
Governance index								1.088***
								(0.141)

Dependent variable: Real industrial value added (Log)								
Constant	−45.17***	−43.83***	−40.29***	−43.12***	−34.45**	−26.54**	−27.91**	−27.93**
	(13.16)	(12.92)	(13.52)	(13.37)	(13.65)	(13.02)	(13.65)	(13.49)
Observations	800	800	800	800	800	800	800	800
R-squared	0.102	0.141	0.121	0.110	0.129	0.159	0.172	0.152
Hansen p-val.	0.4435	0.1321	0.0379	0.3023	0.0628	0.1245	0.1443	0.0794
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed effects	No	No	No	Yes	No	Yes	Yes	Yes
Source: Authors. Robust standard deviations in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.								

Table 3.
Institutions and industrialization (basic model).

revolution within the framework of minimal democracy. Moreover, pre-industrial countries are extremely difficult to govern because they generally lack a strong nation. For de Schweinitz [39], on the other hand, the level of industrialization of an economy is in no way influenced by the political regime, since, according to the author, the consumption demand of the working class generates a capital flight effect, which is necessary to finance economic development.

One of the debates between democracy and industrialization is the meaning of causality. According to Paunet [40], the nature of political regimes is determined by the conditions in which industrialization takes place. The author goes on to assert that modern democracies were originally influenced by the advent of the industrial age. Industrialization would then be one of the key conditions for the take-off of Third World economies. The causality between the two notions is also part of the general issue of development. Narayan et al. [41] confirm the three main hypotheses concerning the link between democracy and long-term economic development for 30 sub-Saharan African countries. These are: (i) the Lipset hypothesis [42], which postulates the existence of causality between the level of economic development and democracy, the link between the two being positive; (ii) the complementarity hypothesis, which postulates the existence of causality between democracy and the level of economic development, the link between the two being positive; and (iii) the conflict hypothesis, which states that democracy causes real income, but the increase in democratic scores is accompanied by the decrease in income. However, the results of Narayan et al. [41] are sensitive to the democracy indicators selected.

In terms of fragility, it should be noted that the majority of poor countries at risk of fragility are in Africa. Fragility, which is a measure of institutional weakness or dysfunction [43], is characterized by the inability to provide basic services and meet vital needs, unstable and weak governance, a persistent condition of extreme poverty, lack of territorial control and a high propensity for conflict and civil war. Our results show that taken at the margin, fragility is a significant impediment to industrial development, one of the main channels being the decline in development aid [44]. On the other hand, in the presence of better governance, states would be less and less fragile and therefore able to sustain their industrial dynamics, as our results illustrate.

Overall, good-quality institutions are positively linked to industrialization, although the link between institutions and industrialization is assessed differently in the literature. In the specific case of corruption, according to Moran [45], the debate has shifted from one position to another over the decades. During the 1960s, the school of thought associated with modernization theory argued that corruption was often positively correlated with economic growth [46, 47]. Subsequently, corruption was seen as hostile to growth by undermining the basis for stable, rational public policy and market allocation [48, 49]. Moran [45] also argues that East Asian countries are important case studies of the role of corruption in industrialization. Focusing specifically on the case of South Korea, he establishes two main findings: (i) first, corruption coexists with development; and (ii) second, corruption in South Korea is plural, i.e. it can take several forms: functional, detrimental, irrelevant and relevant, but always present during rapid industrialization.

However, contrary to Sachs [50], it is clear that in many cases, poor governance is detrimental to growth, as it generates political instability [51] and reinforces the choice of bad policies [52]. In the case of Africa, apart from political stability, the other governance indicators are favorable to industrialization (**Table 1**). The results reinforce those of Asongu and Odhiambo [14], who establish on the basis of a panel of African countries that good governance increases industrialization, this effect being

Dependent variable: Real industrial value added (Log)								
Ln(GDP)	−0.285	5.215***	4.854***	5.367***	4.557***	4.560***	4.630***	4.701***
	(0.329)	(1.291)	(1.322)	(1.312)	(1.338)	(1.299)	(1.350)	(1.326)
Ln(GDP) squared	0.00297	−0.113***	−0.107***	−0.118***	−0.100***	−0.0997***	−0.100***	−0.103***
	(0.00711)	(0.0277)	(0.0283)	(0.0281)	(0.0287)	(0.0279)	(0.0290)	(0.0285)
Political regime	0.0187***	−0.0834***	−0.0796***	−0.0719***	−0.0864***	−0.0909***	−0.159***	−0.091***
	(0.00541)	(0.0115)	(0.0118)	(0.0118)	(0.0125)	(0.0126)	(0.0227)	(0.0134)
Fragility index	0.0119**	0.0160	0.00325	−0.0332	0.00539	0.0324	0.0360	0.0172
	(0.00599)	(0.0233)	(0.0224)	(0.0239)	(0.0226)	(0.0257)	(0.0241)	(0.0255)
Control of corr.		0.426***						
		(0.152)						
Gov. effectiveness			0.274*					
			(0.141)					
Political stability				−0.155				
				(0.111)				
Regulation quality					0.351**			
					(0.162)			
Rule of law						0.564***		
						(0.174)		
Voice and acc.							0.833***	
							(0.199)	
Governance index								0.438**
								(0.192)

Dependent variable: Real industrial value added (Log)								
Ln(population)	−0.297	0.314***	0.320***	0.279**	0.303***	0.311***	0.255**	0.319***
	(0.251)	(0.116)	(0.117)	(0.123)	(0.117)	(0.115)	(0.111)	(0.115)
GFCF (% GDP)	0.00670***	0.0301***	0.0326***	0.0362***	0.0322***	0.0292***	0.0268***	0.0306***
	(0.00184)	(0.0100)	(0.00988)	(0.00983)	(0.0101)	(0.00994)	(0.0101)	(0.0101)
FDI (% GDP)	−0.000791	−0.00347	−0.00384	−0.00552	−0.00408	−0.00158	−0.00346	−0.00345
	(0.00111)	(0.0170)	(0.0174)	(0.0178)	(0.0177)	(0.0168)	(0.0166)	(0.0172)
Primary education	−0.000574	0.00861***	0.00913***	0.00912***	0.00930***	0.00969***	0.0117***	0.00949***
	(0.000964)	(0.00270)	(0.00265)	(0.00272)	(0.00262)	(0.00267)	(0.00263)	(0.00265)
Trade openness	−0.000770	0.00485	0.00469	0.00287	0.00486	0.00553*	0.00630*	0.00516
	(0.000627)	(0.00347)	(0.00354)	(0.00374)	(0.00357)	(0.00336)	(0.00322)	(0.00352)
Constant	33.92***	−44.64***	−39.98***	−45.11***	−36.49**	−37.08**	−37.45**	−38.67**
	(4.238)	(14.71)	(15.08)	(14.91)	(15.27)	(14.80)	(15.45)	(15.12)
Observations	595	595	595	595	595	595	595	595
R-squared	0.991	0.184	0.179	0.176	0.181	0.188	0.201	0.181
Hansen P-value	0.1089	0.6518	0.7550	0.2556	0.7735	0.7735	0.9606	0.8028
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Source: Authors.

Robust standard deviations in parentheses.

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 4.
Institutions and industrialization (augmented model).

limited by capital flight. A second factor put forward in recent literature that weakens the role of governance is terrorism [17], with this effect being more accentuated in developing countries.

Furthermore, income remains a fundamental explanatory factor for industrialization. Indeed, income initially has a positive impact on industrialization. This fundamental result is consistent with those established by Rowthorn and Ramaswamy [53, 54], Kaya [55], Kang and Lee [56], and Dong et al. [57]. However, this effect is not monotonic. Since Clark [30], a consensus has emerged on the non-linearity of the relationship between GDP and industrialization: this is the theory of the inverted U of industrialization.

4.2 Consideration of additional control variables

Our aim here is to check whether institutional indicators retain their explanatory power in relation to industrialization when we take into account socio-economic factors, which may appear to be catalysts or rather detractors. This analysis reveals that taking additional socio-economic factors into account to explain the link between institutions and industrialization in Africa maintains the role of institutional indicators. The regressions show that the additional control variables have varying effects on industrialization (**Table 4**). Indeed, population, domestic investment, the level of human capital and, to a lesser extent, economic openness all appear to be drivers of strong industrialization in Africa [34].

5. Robustness

Confirmation of the institutions-industrialization nexus requires robustness tests. The first approximates institutions by ICRG indicators. The second considers different measures of industrialization. The third uses some competing estimates. The fourth adopts a sub-regional strategy.

5.1 ICRG indicators

The ICRG is one of the best sources for analyzing and rating country risk on the basis of political, socio-economic and institutional indicators. We retain the 12 indicators included in the calculation of political risk, namely:

- Government stability: it assesses both of the government's ability to carry out its declared program(s), and its ability to stay in office;
- Internal conflicts: this is an assessment of political violence in the country and its actual or potential impact on governance;
- External conflicts: this measure is an assessment both of the risk to the incumbent government from foreign action, ranging from non-violent to violent external pressures;
- Ethnic tension: this component is an assessment of the degree of tension within a country attributable to racial, nationality or language divisions;

- Investment profile: this is an assessment of factors affecting the risk to investment that are not covered by other political, economic and financial risk components;
- Corruption: corruption within the political system is a threat to foreign investment for several reasons: it distorts the economic and financial environment; it reduces the efficiency of government and business by enabling people to assume positions of power through patronage rather than ability; and, last but not least, introduces an inherent instability into the political process;
- Socio-economic conditions: this is an assessment of the socio-economic pressures at work in society that could constrain government action or fuel social dissatisfaction;
- Military in politics: its involvement in politics, even at a peripheral level, is a diminution of democratic accountability. However, it also has other significant implications;
- Bureaucracy quality: the institutional strength and the bureaucracy is another shock absorber that tends to minimize revisions of policy when governments change. Therefore, high points are given to countries where the bureaucracy has the strength and expertise to govern without drastic changes in policy or interruptions in government services;
- Democratic accountability: this is a measure of how responsive government is to its people, on the basis that the less responsive it is, the more likely it is that the government will fall, peacefully in a democratic society, but possibly violently in a non-democratic one;
- Religious tensions: they may stem from the domination of society and/or governance by a single religious group that seeks to replace civil law by religious law and to exclude other religions from the political and/or social process; the desire of a single religious group to dominate governance; the suppression of religious freedom; and the desire of a religious group to express its own identity, separate from the country as a whole.
- Law and order: to assess the “Law” element, the strength and impartiality of the legal system are considered, while the “Order” element is an assessment of popular observance of the law.

The results obtained in **Table 5** show that industrialization suffers in the presence of an unstable government, internal and external conflicts, high levels of corruption and religious tensions, this effect being amplified by the deterioration of political regimes. On the other hand, the presence of the military in politics and the level of bureaucracy would be favorable to industrialization in Africa.

5.2 Various industrialization proxies

In addition to the main measure of industrialization used in the main estimates, i.e. real industrial value added, we mobilize other proxies to assess the effect of

Dependent variable: Real industrial value added (Log)												
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Ln(GDP)	7.301*** (2.269)	6.829*** (2.185)	5.818** (2.349)	6.429*** (2.184)	6.182*** (2.207)	5.202** (2.181)	5.066** (2.119)	4.938** (2.352)	6.470*** (2.269)	6.662*** (2.070)	6.784*** (2.212)	4.803*** (1.285)
Ln(GDP) squared	−0.156*** (0.0476)	−0.146*** (0.0457)	−0.125** (0.0492)	−0.137*** (0.0457)	−0.133*** (0.0463)	−0.115** (0.0458)	−0.113** (0.0447)	−0.111** (0.0492)	−0.138*** (0.0474)	−0.144*** (0.0432)	−0.145*** (0.0463)	−0.101*** (0.0276)
Political regime	−0.0508*** (0.0165)	−0.0243 (0.0157)	−0.0420*** (0.0157)	−0.0402*** (0.0155)	−0.0324* (0.0165)	−0.0359** (0.0156)	−0.0700*** (0.0153)	−0.0432*** (0.0158)	−0.0522*** (0.0189)	−0.0334** (0.0154)	−0.00909 (0.0182)	−0.0814*** (0.0116)
Fragility index	0.00849 (0.0278)	−0.0196 (0.0287)	0.0337 (0.0344)	0.0107 (0.0292)	0.00292 (0.0287)	0.0985*** (0.0252)	0.0956*** (0.0263)	0.0382 (0.0258)	0.0371 (0.0314)	−0.0235 (0.0283)	−0.00816 (0.0284)	−0.0373* (0.0209)
Ln(population)	0.0438 (0.192)	−0.123 (0.204)	−0.000712 (0.197)	−0.0498 (0.206)	0.0401 (0.197)	0.212 (0.189)	0.310* (0.173)	0.202 (0.197)	−0.0479 (0.213)	−0.0104 (0.201)	0.0398 (0.201)	0.124 (0.149)
GFCF (% GDP)	0.0525*** (0.0145)	0.0563*** (0.0145)	0.0540*** (0.0149)	0.0532*** (0.0149)	0.0561*** (0.0149)	0.0510*** (0.0140)	0.0470*** (0.0147)	0.0472*** (0.0148)	0.0529*** (0.0148)	0.0369** (0.0159)	0.0553*** (0.0154)	0.0316*** (0.0102)
FDI (% GDP)	−0.0117 (0.0261)	−0.0137 (0.0251)	−0.0176 (0.0279)	−0.0169 (0.0273)	−0.0194 (0.0293)	−0.0134 (0.0272)	−0.0267 (0.0283)	−0.0161 (0.0285)	−0.0201 (0.0277)	−0.0118 (0.0227)	−0.0120 (0.0258)	−0.00852 (0.0188)
Primary education	0.0208*** (0.00439)	0.0182*** (0.00420)	0.0206*** (0.00473)	0.0203*** (0.00445)	0.0221*** (0.00454)	0.0194*** (0.00389)	0.0251*** (0.00390)	0.0187*** (0.00398)	0.0207*** (0.00440)	0.0250*** (0.00451)	0.0197*** (0.00401)	0.00839*** (0.00273)
Trade openness	0.00480 (0.00555)	0.00356 (0.00558)	0.00268 (0.00585)	0.00152 (0.00602)	0.00268 (0.00604)	0.00357 (0.00616)	0.00771 (0.00484)	0.00604 (0.00567)	0.00305 (0.00567)	0.00372 (0.00550)	0.00405 (0.00522)	0.00403 (0.00380)
Gov. stability	−0.241*** (0.0901)											
Internal conflicts		−0.302*** (0.0647)										

Dependent variable: Real industrial value added (Log)												
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Ethnic tension			0.0558									
			(0.110)									
Investment profile				−0.1000								
				(0.0800)								
Corruption					−0.280**							
					(0.124)							
Socio-eco cond.						0.524***						
						(0.0831)						
Military in politics							0.396***					
							(0.0617)					
Bureaucracy quality								0.599***				
								(0.129)				
Democratic accountab.									0.101			
									(0.107)			
Religious tensions										−0.350***		
										(0.0802)		
External conflicts											−0.331***	
											(0.0848)	
Law and order												−0.0382***
												(0.0136)

Dependent variable: Real industrial value added (Log)												
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Constant	−64.71**	−55.30**	−49.41*	−54.87**	−52.63**	−47.17*	−45.89*	−40.52	−56.72**	−55.83**	−57.53**	−37.44**
	(26.75)	(25.73)	(27.75)	(25.94)	(26.21)	(26.01)	(25.16)	(28.13)	(26.87)	(24.64)	(26.21)	(14.73)
Observations	417	417	417	417	417	417	417	417	417	417	417	595
R-squared	0.200	0.217	0.188	0.190	0.195	0.247	0.231	0.218	0.189	0.220	0.215	0.187
Hansen	0.2479	0.4316	0.1024	0.1746	0.2139	0.3665	0.9257	0.4733	0.1092	0.8186	0.8093	0.0809
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Source: Authors.
Robust standard deviations in parentheses
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 5.
Industrialization and ICRG indicators.

	Manufacturing, value added (% of GDP)	Manufacturing, value added (growth)	Manufacturing value added, current (log)	Manufacturing value added, real (log)	Exports of manufactured goods	Employment in industry (% of total employment)	Employment in industry, female (% of female employment)	Employment in industry, male (% of male employment)
Ln(GDP)	2.319	9.345	6.575***	7.594***	−0.772	10.51**	24.75***	2.841
	(4.293)	(10.36)	(1.208)	(1.109)	(19.71)	(4.439)	(4.649)	(4.538)
Ln(GDP) squared	−0.0714	−0.177	−0.144***	−0.165***	−0.189	−0.266***	−0.568***	−0.106
	(0.0891)	(0.217)	(0.0255)	(0.0235)	(0.404)	(0.0954)	(0.0980)	(0.0974)
Ln (population)	0.151	−1.388*	−0.0123	0.0489	10.07***	2.361***	1.294**	3.115***
	(0.356)	(0.722)	(0.137)	(0.138)	(1.967)	(0.494)	(0.509)	(0.552)
GFCF (% GDP)	−0.0391	−0.0867	0.0254***	0.0124	0.0505	0.286***	0.302***	0.299***
	(0.0280)	(0.0536)	(0.00986)	(0.0101)	(0.170)	(0.0556)	(0.0568)	(0.0572)
FDI (% GDP)	−0.00656	−0.0105	−0.000944	0.00776	−0.204	−0.00223	0.00435	−0.0445
	(0.0336)	(0.0572)	(0.0182)	(0.0161)	(0.312)	(0.0700)	(0.0491)	(0.0916)
Primary education	0.0491***	−0.0184	0.0137***	0.0121***	−0.259***	−0.00770	−0.0497***	0.0140
	(0.00924)	(0.0173)	(0.00308)	(0.00286)	(0.0579)	(0.0138)	(0.0135)	(0.0156)
Trade openness	−0.0222	0.0102	−0.00706	−0.00403	0.105	−0.0263	−0.0411**	−0.0216
	(0.0141)	(0.0124)	(0.00547)	(0.00548)	(0.0650)	(0.0171)	(0.0183)	(0.0169)
Political regime	−0.150***	−0.0697	−0.0530***	−0.0951***	−2.384***	−0.0575	−0.0397	−0.120
	(0.0463)	(0.0836)	(0.0144)	(0.0148)	(0.253)	(0.0708)	(0.0749)	(0.0731)
Fragility index	0.0943	0.191	−0.00278	−0.0259	−0.0182	0.0512	0.0116	−0.00452
	(0.0763)	(0.131)	(0.0250)	(0.0260)	(0.430)	(0.118)	(0.123)	(0.128)

	Manufacturing, value added (% of GDP)	Manufacturing, value added (growth)	Manufacturing value added, current (log)	Manufacturing value added, real (log)	Exports of manufactured goods	Employment in industry (% of total employment)	Employment in industry, female (% of female employment)	Employment in industry, male (% of male employment)
Governance index	2.986*** (0.644)	0.310 (0.909)	0.256 (0.209)	0.362* (0.195)	12.74*** (3.388)	1.543* (0.923)	1.861** (0.874)	1.138 (1.047)
Constant	−9.328 (50.64)	−93.46 (122.1)	−55.98*** (13.74)	−67.52*** (12.64)	−1.071 (228.0)	−128.4** (50.79)	−276.3*** (53.32)	−48.43 (51.90)
Observations	591	600	591	554	529	661	661	661
R-squared	0.192	0.016	0.220	0.196	0.248	0.126	0.156	0.128
Hansen p- value	0.3486	0.3503	0.3709	0.3348	0.0358	0.1528	0.4262	0.1869
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Source: Authors.
Robust standard deviations in parentheses
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 6.
Different measures of industrialization.

Dependent variable: Real industrial value added (Log)							
	(2)	(4)	(5)	(6)	(7)	(8)	(9)
Lagged dep. Var.	0.689*** (0.0272)	0.688*** (0.0272)	0.512*** (0.0485)	0.688*** (0.0271)	0.505*** (0.0487)	0.511*** (0.0486)	0.502*** (0.0491)
Ln(GDP)	1.072*** (0.257)	0.977*** (0.259)	2.296*** (0.445)	1.108*** (0.261)	2.231*** (0.444)	2.342*** (0.458)	2.232*** (0.444)
Ln(GDP) squared	−0.0145*** (0.00518)	−0.0125** (0.00521)	−0.0383*** (0.00925)	−0.0151*** (0.00524)	−0.0371*** (0.00923)	−0.0393*** (0.00951)	−0.0372*** (0.00924)
Ln(population)	−0.0737*** (0.0142)	−0.0632*** (0.0149)	−0.107 (0.135)	−0.0787*** (0.0145)	−0.0585 (0.132)	−0.0907 (0.134)	−0.0366 (0.142)
GFCF (% GDP)	−0.00278*** (0.000767)	−0.00298*** (0.000773)	−0.00196** (0.000817)	−0.00276*** (0.000765)	−0.00186** (0.000816)	−0.00181** (0.000815)	−0.00190** (0.000818)
FDI (% GDP)	−1.32e−05 (0.000824)	0.000187 (0.000830)	−0.00124 (0.000866)	−6.56e−06 (0.000821)	−0.00127 (0.000874)	−0.00131 (0.000869)	−0.00126 (0.000869)
Primary education	−0.000556 (0.000448)	−0.000704 (0.000447)	0.00135* (0.000700)	−0.000510 (0.000437)	0.00128* (0.000700)	0.00130* (0.000701)	0.00116 (0.000726)
Trade openness	0.00163*** (0.000311)	0.00169*** (0.000311)	0.00128*** (0.000347)	0.00160*** (0.000311)	0.00128*** (0.000348)	0.00126*** (0.000349)	0.00129*** (0.000348)
Political regime	−0.0546*** (0.0243)	−0.0872*** (0.0257)	−0.0657*** (0.0110)	−0.0549*** (0.0109)	−0.0872*** (0.0119)	−0.0987*** (0.0332)	−0.0743*** (0.0128)
Fragility index	0.0188 (0.0278)	0.00315 (0.0287)	−0.0297 (0.0261)	0.00487 (0.0258)	0.0229 (0.0299)	0.0267 (0.0271)	0.0101 (0.0264)
Voice and account.	0.00478 (0.0120)						
Political stability		0.0162** (0.00812)					

Dependent variable: Real industrial value added (Log)							
	(2)	(4)	(5)	(6)	(7)	(8)	(9)
Gov. effectiveness			–0.0173				
			(0.0138)				
Regulatory Quality				–0.00958			
				(0.0114)			
Rule of law					0.00296		
					(0.0134)		
Control of corruption						–0.0144	
						(0.0141)	
Governance index							0.00971
							(0.0178)
Constant	–8.981***	–7.996***	–20.23***	–9.377***	–19.95***	–20.98***	–20.20***
	(2.875)	(2.892)	(5.452)	(2.916)	(5.454)	(5.579)	(5.485)
Observations	464	464	464	464	464	464	464
Number of countries	43	43	43	43	43	43	43
Number of instruments	28	31	35	31	33	32	34
AR(1) p-value	0.0017	0.0012	0.0012	0.0018	0.0015	0.0014	0.0017
AR(2) p-value	0.6290	0.6894	0.5091	0.6323	0.5824	0.6512	0.6369
Hansen p-value	0.2254	0.3548	0.6571	0.3657	0.4759	0.5134	0.7489

Source: Authors.
Robust standard deviations in parentheses
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 7.
GMM estimates.

Dependent variable: Real industrial value added (Log)					
	Central Africa	Western Africa	Southern Africa	Eastern Africa	Northern Africa
Ln(GDP)	−3.846 (2.937)	13.60*** (4.782)	−10.54*** (2.058)	10.18*** (0.988)	2.854*** (0.569)
Ln(GDP) squared	0.105* (0.0632)	−0.296*** (0.102)	0.211*** (0.0449)	−0.238*** (0.0202)	−0.0486*** (0.0114)
Ln(population)	−1.254* (0.708)	−0.142 (0.305)	1.512*** (0.460)	1.359*** (0.105)	−0.826*** (0.0462)
GFCF (% GDP)	0.0362* (0.0220)	−0.0206 (0.0159)	0.113*** (0.0163)	0.0355*** (0.00769)	−0.0151*** (0.00537)
FDI (% GDP)	−0.00142 (0.0349)	0.00754 (0.0166)	0.0611* (0.0312)	−0.0163 (0.0104)	−0.000284 (0.000394)
Primary education	−0.00871* (0.00471)	0.00459 (0.00579)	0.0221*** (0.00324)	−0.0115*** (0.00340)	0.00481*** (0.00134)
Trade openness	−0.0217** (0.0109)	0.0134* (0.00786)	−0.0260*** (0.00535)	0.00988*** (0.00322)	0.00124*** (0.000376)
Political regime	−0.116*** (0.0366)	−0.135*** (0.0512)	0.0922** (0.0404)	−0.0376*** (0.0107)	0.00304 (0.00601)
Fragility index	−0.0190 (0.0903)	−0.0303 (0.0693)	0.145*** (0.0335)	−0.179*** (0.0333)	−0.00372 (0.0121)
Gov. index	0.427 (0.477)	1.088*** (0.360)	−1.091*** (0.394)	−1.068*** (0.158)	−0.308** (0.136)
Constant	77.03** (31.00)	−131.7** (53.05)	122.5*** (25.45)	−106.4*** (11.38)	−3.009 (6.696)
Observations	139	181	72	158	51
R-squared	0.385	0.544	0.953	0.873	0.987
Hansen P-value	0.9016	0.5310	0.0960	0.9687	0.7923
Time fixed effects	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes

Source: Authors.
 Robust standard deviations in parentheses
 *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 8.
 Sub-regional heterogeneity.

institutions on them. These include manufacturing variables and industrial employment. Using an average indicator of governance, the results confirm the overall robustness of the positive relationship previously identified (Table 6).

5.3 GMM estimates

Indeed, in a dynamic panel model, country-specific unobservable effects are correlated with the lagged dependent variable, providing inconsistent estimators. Using lagged values of the first difference of the endogenous variable as instruments, Holtz-Eakin et al. [58] and Arellano and Bond [59] developed the GMM difference estimator. However, Arellano and Bover [59] and Blundell and Bond [60] demonstrated that when the dependent variable is persistent over time, lagged values are very poor instruments. By using additional moment conditions, these authors succeeded in developing the system GMM, which is a more robust alternative estimator (Table 7).

5.4 Sub-regional heterogeneity

The uniformity of the results obtained at continental level is debatable, given the heterogeneity of the different sub-regions. To this end, we estimate for each sub-region the effect of average governance on industrialization. The results reveal that a tendency towards good institutional practices in West Africa is favorable to industrialization (Table 8). On the other hand, the tendency towards poor practices in the southern, eastern and northern regions of the continent is a depressing factor for industrialization.

6. Conclusion

This article analyzed the specific role of political-institutional factors on industrial development in Africa over the period 1996–2022. Based on the relative gap theory and Kaldor's three laws on the link between productivity and industrialization, we suggest that the quality of political-institutional indicators may be one of the missing pieces in the overall puzzle. At the end of our empirical analyses, we arrive at three main results: (i) weak democratization is an impediment to industrialization in Africa; (ii) political fragility is an obstacle to industrialization in Africa in the absence of good-quality institutions; and (iii) good-quality governance in Africa is a stimulus to industrialization. The robustness tests carried out confirm most of the results, but call for a number of recommendations. These include the reform of political systems conducive to democracy, the development of resilience mechanisms capable of mitigating and reversing the trend towards fragility in certain states, and the implementation of new economic and political reforms appropriate to the structural transformation of the African continent. Over and above these specific measures, the challenge of industrializing Africa will only be possible if the complementary measures set out in the industrialization strategy at different levels are gradually implemented. These include encouraging successful industrial policies, attracting and channeling finance to infrastructure and industrial projects, developing liquid and efficient capital markets, promoting and stimulating business development, promoting strategic partnerships, and creating powerful industrial clusters across the continent.

Several mechanisms can explain the links between institutions and industrialization. Indeed, industrialization induces economic growth, which can reinforce political stability and foster the emergence of democratic regimes, which in turn boosts industrialization. Moreover, industrialization requires a skilled workforce, which stimulates the development of education. This development is likely to condition political life, with citizens demanding more democratic rights. The acquisition of such rights creates a favorable

framework for economic activity in general and industrialization in particular. Also, the size of the middle class often acts as a political stabilizer and a vector for democratization. Thus, in Rodrik's [61] sense, democracy is conceived as a meta-institution that models other institutions and promotes the economic transformation of countries.

This chapter does not exhaust the problem of intrinsic analysis of industrialization through its determinants. While it is appropriate to have focused the objective on political-institutional determinants, it should be noted that other promising avenues exist. Firstly, we might be interested in an in-depth explanation of the causality between institutions and industrialization, as several operative channels could be mobilized to transmit the mechanism under study. Secondly, future perspectives could concern the specific role of history and colonization, given that African countries have had different experiences. Thirdly, particular emphasis could be placed on the legal origin adopted. Indeed, research shows that African countries that adopted the English legal origin rapidly transformed themselves economically compared to other countries. Exploring these avenues would help bridge the gap in the analysis of the industrialization process in Africa.

A. Appendices

B. Appendix 1: Sample countries

Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cape Verde, Cameroon, Comoros, Congo, Côte d'Ivoire, Djibouti, Egypt, Equatorial Guinea, Eritrea, Eswatini, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, South Africa, Madagascar, Malawi, Mali, Mauritius, Mauritania, Morocco, Mozambique, Namibia, Niger, Nigeria, DR Congo, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, Sudan, South Sudan, Tanzania, Togo, Tunisia, Uganda, Zambia, and Zimbabwe.

Conflict of interest

The authors declare no conflict of interest.

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Chapter 4

The Development of Cotton Industry in Vladimir Province (Russia) in Nineteenth Century

Masachika Shiotani

Abstract

Vladimir Province imported chintz from Central Asia after the sixteenth century and first produced chintz in the eighteenth century, based on the printing skills from Central Asia. After England exported cotton products to Russia at the end of the eighteenth century, Vladimir Province introduced technology from Europe and developed the modern cotton industry in the nineteenth century. When we see the process of development in the middle term (100 years), we recognize that because Vladimir Province learned from Europe's experiences, she accomplished the industrialization. But we can also conclude that the industrialization of Vladimir Province was the process of import substitution of chintz from Central Asia, from the viewpoint of a long term (300 years). This is similar to the experience of Europe.

Keywords: Vladimir Province, printed cotton, dyeing, crimson, Central Asia

1. Introduction

The cotton industry developed in the provinces of Moscow and Vladimir in the first half of the nineteenth century.¹ Given that the development of Vladimir's cotton industry is a unique case, reexamining it from the perspective of dyeing technology is a worthwhile endeavor.

Conventional historical studies on the Russian cotton industry have paid little attention to the consumption side, but focusing on this aspect is necessary to examine the industry's history. This paper focuses on the dyeing process, which is closely related to consumer demand. Cotton textiles comprise several types of products, but at that time, dyed cotton fabric (chintz and scarves) attracted many consumers ([1], pp. 111, 123). Designs and dyeing techniques determined the demand for printed cotton, and demand for related products increased as dyed colors shifted from monochromatic to two-toned and multicolor printing.

¹ This region included not only present-day Vladimir Province but also the provinces of Ivanovo and Moscow.

Among a few regions, the cotton industry in Vladimir Province excelled at dyeing. Vladimir supplied printed cotton to Asian markets as well as to the Russian market.² Geographical factors can be cited among the reasons why Vladimir Province excelled at dyeing. The area around Vladimir has a high concentration of churches, and the region's relationship with the Russian Orthodox Church was connected to the production of icon paintings. The dyeing techniques used in icon painting were nurtured in this region and applied to dyeing hemp fabric and later printed cotton ([2], p. 26). Printed cotton from Vladimir was essentially a mass product used by peasants. Existing studies on the history of the cotton industry have undervalued these products, but modern specialists have reassessed the value of Ivanovo chintz [3].

Whereas spinning and weaving are easy to measure quantitatively, dyeing is more difficult to evaluate because it necessitates a qualitative approach. Historians who have examined the Russian cotton industry in the nineteenth century have seldom paid attention to the dyeing process because understanding dyeing requires knowledge of chemistry.³ For a long time, devising a method for dyeing fabrics in multiple colors was an important issue, and modern technological innovations have resolved the difficulty of finding a technique to dye fabrics crimson ([5] p. 66). Dyeing has rarely been a central subject in economic history, and historians have dedicated little attention to dyes and catalysts. After the nineteenth century, dyeing techniques developed in parallel with the progress of chemistry. However, conventional studies have not focused on the link between dyeing and chemistry. For example, the introduction of sulfuric acid shortened the bleaching process and improved dyeing methods ([4], p. 20), demonstrating the great impact of chemistry on the dyeing process.

This paper aims to review the cotton industry in Vladimir Province with a focus on dyeing. I use the Vladimir Provincial Government's weekly newspaper (*Vladimirskie Gubernskie Vedomosti* [*Vladimir Provincial Newspaper*]) from 1838 to 1917 [6] as a basic source. To focus on the period before the emancipation of serfs, I reference articles in the period 1838–1860 and reconsider the history of the cotton industry in Vladimir Province based on the articles published in the newspaper's *Appendix*.

2. Prehistory of Vladimir Province

2.1 Geography of Vladimir Province

Vladimir Province is located approximately 250 km east of Moscow, adjacent to a region with a high concentration of Russian Orthodox churches. **Figure 1** shows the map of Vladimir Province. The soil in Vladimir was unsuitable for grain cultivation, necessitating the development of other industries [7]. Among the alternatives were icon making and hemp cultivation [8]. The Russian Orthodox Church displayed icons depicting Jesus Christ, the Virgin Mary, and saints with biblical motifs. Since icon paintings were objects of worship, displaying icons was customary not only in Russian Orthodox churches but also in homes. Icon painting workshops were concentrated in Suzdal and Shuya in Vladimir, which led to the intense cultivation of icon painting skills in the region ([8], p. 138).

² I examined the exportation of Russian cotton fabric to Asia in detail ([1], pp. 35–60).

³ However, art history specialists are exceptional. They are interested in chemistry and dyeing technology. For example, I refer to Arsenyeva [4].



Figure 1.
The map of Vladimir Province.

Vladimir's geographical advantage is its proximity to the Volga River, which runs from St. Petersburg via Moscow into the Caspian Sea. Before the construction of the railroads, the Volga was an artery in a distribution network. It connected St. Petersburg with the Baltic Sea and Western Europe and linked Astrakhan with Central Asia and Persia. This brought convenience to the province's merchants, allowing them to easily export commodities abroad and import goods from foreign countries.

After Russia annexed Astrakhan in the sixteenth century, it established a trade network with Asia. Russian merchants exported Russian commodities to Asia via the Volga and imported goods from Asia, and trade between Russia and Asia prospered. Because Russia could not produce cotton and silk fabrics at that time, Russians valued Persian silk and printed cotton from Central Asia ([9], p. 5). Subsequently, in the sixteenth century, Russia imported cotton fabrics from Asia and dyed them in Astrakhan near the Caspian Sea. At that time, Russian craftsmen devised dyeing patterns inspired by Asian precious metals and textiles ([5], p. 4). The dyeing business flourished in Astrakhan and expanded along the Volga to Vladimir Province in the seventeenth century ([5], p. 39). When the hemp textile industry began in Vladimir Province in the eighteenth century, local dyers supported the dyeing of hemp fabric.

Given the suitability of the soil in Vladimir Province to hemp cultivation, the region cultivated hemp in the eighteenth century. Hemp was woven into fabric, and oil-based dyeing techniques from icon painting were applied to hemp fabric dyeing. These dyeing techniques later developed into the textile printing industry

([8], p. 138). The region's merchants engaged in Asian trade and used the Volga to transport goods from Vladimir to Astrakhan, supplying hemp fabrics to the domestic market and to Asian markets. Notably, the Ivanovo merchants Gandolin as well as Grachev and Galerin, in the first and second half of the eighteenth century, respectively, transported hemp fabric from Vladimir Province to Astrakhan and Asian markets. They returned home with a load dye ([8], p. 137). Grachev and Galerin were not only involved in commerce but also engaged in hemp printing.

Cultivating cotton in Russia was impossible because of the geographical conditions, but entrepreneurs in Vladimir Province began to dye cotton fabrics in the latter half of the eighteenth century. This necessitated procuring foreign cotton fabric and yarn. Since ancient times, cotton cultivation has flourished in the Asian region near Russia. From the sixteenth century, Russia imported cotton fabric from Central Asia and Persia ([9], p. 5). In the mid-eighteenth century, entrepreneurs in Vladimir Province imported plain cotton fabrics from Central Asia and printed on them by imitating the designs of Bukharan chintz ([10], p. 34). At that time, textile printing was monochromatic and entailed the use of wooden boards. Conventional dyeing methods could not color cotton fabrics ([2], p. 25).

2.2 Diffusion of German staining methods

Germany's role in the evolution of Russian dyeing techniques cannot be underestimated. The Russian government attempted to introduce German dyeing techniques in the early eighteenth century to foster the dyeing industry. Specifically, the Russian government invited German dyeing workshops and craftsmen to Shlisselburg near St. Petersburg ([8], pp. 140–141). Among the companies in the city, the Reimann workshop's dyeing techniques were outstanding, but a few Russian specialists kept the workshop's excellent dyeing techniques secret among themselves. Dyers from Vladimir Province visited the Reiman workshop to learn to color fibers in the mid-eighteenth century [11]. Upon returning home, they introduced new dyeing techniques, and a limited number of craftsmen monopolized the new techniques in Vladimir Province. In 1772, the Russian government adopted a mercantilist policy that opened the dyeing techniques to the public and encouraged the development of the dyeing industry. This promoted the spread of dyeing techniques throughout Russia ([2], p. 25).

Once German dyeing techniques had been disseminated throughout Russia, dyers had easier access to new techniques. Many dyers from Vladimir Province visited Shlisselburg to learn new techniques, stimulating the development of Vladimir's hemp industry. However, as German dyeing techniques became more popular, regional competition in the dyeing industry increased. If similar patterns and colors were used, textile printing would lose its competitiveness in the market. Therefore, dyers were forced to express their region's uniqueness in their products. Whereas dyers in St. Petersburg aimed for European-oriented dyeing, those in Vladimir Province focused on Asian-inspired dyeing because of their trade relations with Asia ([2], p. 25).

Vladimir Province included Lord Sheremetev's vast territory. Unlike in other regions, serf entrepreneurs played an important role in the hemp and cotton textile industries.⁴ Since serfs had no property rights before their emancipation in

⁴ Rosovsky [12] explains serf entrepreneurs in detail.

1860, their production equipment belonged to the lords, and serf entrepreneurs had to obtain the lord's permission to conduct business. Grachov, Yamanovsky, and Garelin are representative serf entrepreneurs from that time. In the early nineteenth century, the main industry in Vladimir Province shifted from hemp to cotton textiles, and these entrepreneurs changed the type of business which they were conducting. In fact, Grachev and Garelin were the first to transform their business from hemp to cotton. Some successful serf entrepreneurs used their money to purchase their freedom.

After 1787, entrepreneurs engaged in the dyeing industry in Vladimir Province imported cotton yarn from Bukhara and wove and printed cotton fabric ([8], p. 161). This production entailed "fustian weaving," which mixed cotton and hemp yarn. Fustian weaving also became popular in Europe.

When Russia began to import cotton fabric from England in the 1790s, the Russian cotton industry underwent fundamental change ([8], p. 163). In the early stage of the cotton industry's development in England, cotton yarn and fabric were produced in large quantities and exported to foreign countries. British cotton fabric reached St. Petersburg, from which entrepreneurs in Vladimir Province obtained plain British cotton fabric (calico) and printed them. In the early nineteenth century, dyeing workshops in Vladimir Province foresaw the demand trend and shifted their dyeing focus from hemp to cotton fabric, causing the amount of dyed hemp textiles to decline by 1809 ([4], p. 9).

After 1803, Russia began to import cotton yarn from England in addition to cotton fabric [13]. British cotton yarn imported to Russia (St. Petersburg) traveled via the Volga to Vladimir Province, where entrepreneurs wove the yarn and bleached and printed the resultant cotton fabric. At the beginning of the nineteenth century, a spinning mill was built in St. Petersburg to spin cotton into yarn. However, the amount of cotton yarn produced was insufficient to meet the domestic demand. Hence, entrepreneurs in Vladimir Province used British cotton yarn, instead of depending on the domestic supply.

Whereas British cotton yarn was cheaper and suitable for weaving, Bukharan cotton yarn from Central Asia was coarse and difficult to weave. However, some cotton fabric required Bukharan cotton yarn for the warp; therefore, entrepreneurs in Vladimir Province used both British and Bukharan cotton yarn either together or separately [14]. The cotton fabric woven from imported cotton yarn was sold cheaply. As the domestic demand for cotton fabric grew, entrepreneurs expanded production accordingly. We will examine the paths by which their businesses developed.

3. Staining and chemistry

3.1 Cotton yarn and the dyeing industry

The production process in the cotton industry entailed spinning, weaving, and dyeing. When Russia began to import British cotton yarn at the beginning of the nineteenth century, Russian weaving companies began to weave the imported yarn. They outsourced the weaving of fabric to neighboring farms [15]. Since peasants spare time during the off season, women obtained cotton yarn from weaving companies and manufactured it into fabric at home. This system of weaving outsourcing was called the wholesale cottage industry. The cotton fabric peasants wove was collected and sent to dyeing workshops for printing. In the first half of the nineteenth century, the

cotton industry in Vladimir Province changed dramatically in terms of production, evolving sequentially from dyeing to weaving to spinning. The dyeing process was the main factor underlying the transformation ([16], p. 42). This section examines the transformation of the cotton industry in Vladimir Province from the perspective of dyeing.

Although customer demand evidently drove the development of the Russian cotton industry, the external environment surrounding the industry cannot be overlooked. Therefore, I will describe important external environmental factors related to the cotton industry in the first half of the nineteenth century.

Two important factors are the Russian industrial protection policy and the effects of Napoleon's actions. At the end of the eighteenth century, Russian companies believed that restricting the importation of foreign products would further develop the Russian cotton industry. In 1804, the government was asked to restrict the importation of cotton products (chintz and calico) to protect the domestic industry. The government responded ([17], p. 51) by restricting the importation of British cotton fabric, but it allowed the importation of British cotton yarn. These restrictions not only protected the Russian cotton industry but also encouraged the importation of cotton yarn.

In 1808–1812, Napoleon confronted England and imposed a continental blockade that ceased trade between England and Europe, diminishing Russia's ability to import British cotton yarn.⁵ In other words, the continental blockade limited England's ability to export cotton products to Russia, which indirectly protected the Russian cotton industry from British products, exerting an industrial protection policy effect. When Napoleon invaded Moscow in 1812, factories were burned, and displaced Moscow dyers evacuated to Vladimir Province [13]. In effect, the dyeing industry partially moved from Moscow to Vladimir Province, meaning that Napoleon contributed to the development of the dyeing industry in Vladimir Province.

After the early nineteenth century, entrepreneurs in Vladimir Province imported cotton yarn and wove and dyed it. When demand for cotton fabric increased in Russia in the 1810s, Vladimir entrepreneurs endeavored to import cotton yarn. Kiselyov, a merchant from Shuya, Vladimir, was among the merchants who established a distribution network for imported cotton yarn [18]. He was born in Moscow in 1765 as the son of a serf, but he purchased his freedom in 1779. In 1783, Kiselyov registered himself as the third guild merchant in Moscow. In 1793, he moved to Shuya, Vladimir, where he established the Kiselyov Brothers' Trading Company. Some weaving companies in Vladimir Province imported and spun cotton from Central Asia, but those aiming to produce high-quality cotton fabric demanded cotton yarn from England. After Napoleon's withdrawal from Russia in 1812, Kiselyov began to import British cotton yarn in response to local companies' requests.

In addition to importing foreign goods, Kiselyov traded commodities with Ukraine and Little Russia. After he became a merchant of the first guild in 1822, he specialized in importing British cotton yarn and dyes up to 1827. When Kiselyov died in 1831, his son succeeded to the helm of his father's business. In the 1830s, the Kiselyov Brothers' Trading Company began to import steam engines from John Cockerill's factory in the Belgian city of Liege, in addition to cotton yarn and dyes [19]. Although Belgian machines were inferior to those from England, the British government's prohibition

⁵ Russia attempted to import British cotton yarn through Prussia.

of the export of machines until 1842 forced entrepreneurs in Vladimir Province to use alternatives.

3.2 Steam engines and dyeing

Technology is usually transferred through people, and dyeing techniques are no exception. When dyeing techniques were transferred from Europe to Russia, European dyers visited Russia and taught Russian dyers what they had learned. When the economic crisis befell Europe in 1825, many dyers lost their jobs, and some who wanted to use their skills abroad emigrated to Russia ([4], p. 20). At that time, European dyers' chemistry-based techniques were evaluated in Russia. Representative examples are *bleaching techniques* and *Adrianople dyeing*. Russian dyers realized that bleaching cotton fabric helped with coloring it, so they bleached the cloth before printing. However, cloth was traditionally bleached in meadows during the summer, which meant that bleaching was not always possible in Russia. As an alternative to outdoor bleaching, indoor bleaching using sulfuric acid had taken root in Europe. European dyers taught specialists in Vladimir Province how to bleach with sulfuric acid in 1828, and dyers began applying the new bleaching method regardless of the season ([4], p. 20).

In 1813, James Thompson's English firm established a method to dye cotton yarn and fabric in the Adrianople style (Turkish red) using Dutch crops, madder, and other materials ([20], p. 182). This technique marked a milestone in European dyeing history. In the 1820s, three dyers from Europe, namely Geppel, Baruk, and Brugsdolv, immigrated to Vladimir Province and engaged in dyeing at the Galerin factory in Ivanovo. They taught Russian dyers the technique to produce the Adrianople style. The Galerin factory mastered the Adrianople dyeing technique in 1829 and successfully produced crimson chintz ([8], p. 195). The domestic market greatly appreciated the supply of Adrianople chintz, and demand for the Galerin factory's products increased. At that time, the Russian cotton textile industry classified chintz into six grades according to dyeing level and fabric [21]. Adrianople crimson chintz was the highest grade (Grade 1).⁶ Given the profitability of high-grade chintz, dyeing companies devoted themselves to producing Adrianople chintz.

Once the English mechanic Watt had established a method to use steam engines to power factories in the early nineteenth century, steam engines became widespread in the British cotton industry in the 1830s ([22], p. 19). Steam engines later spread to continental Europe, revolutionizing the way factories were powered. However, steam engines were not uniformly introduced in Europe; rather, they initially spread to regions where waterpower was unavailable. Although Russia had rivers, many regions' flat terrain prevented factories from relying on waterpower. In the Russian cotton industry, steam engines were first used to power dyeing workshops. In the 1820s, G. Belt, an entrepreneur in St. Petersburg, imported a Watt-type steam engine from Belgium and novelly installed it in his foundry [23]. The first steam engines were introduced in dyeing workshops in Vladimir Province in the 1830s.

The Galerin factory introduced the first steam engine (18 horsepower) to a dyeing workshop in Vladimir Province in 1832 ([5], p. 62). Steam engines were later installed

⁶ Grade 2 applies to machinery woven chintz dyed with madder and spots. Grade 3 applies to machinery woven chintz dyed using a roller copper Perrotin printer. Grade 4 applies to cashmere chintz dyed with indigo. Grade 5 applies to scarves dyed with two kinds of indigo. Grade 6 applies to Saxon style scarves.

in over 10 workshops in the region. Printing conventionally entailed engraving on a wooden plate, but when steam engine-powered printing machines were introduced to dyeing workshops, the advent of rotary copper plates changed the printing process ([4], p. 18). This technological advancement realized multicolored printing on cotton fabric and improved the clarity of chintz. As the demand for steam engines increased, a steam engine production movement emerged in Russia. The Shepelevi factory in Nizhny Novgorod Province produced Russia's first domestically built steam engine [23]. Thereafter, steam engine production progressed in Russia, but many Russian companies still imported steam engines from Belgium because the local steam engines were not up to their standards.

3.3 Mordants and dyes

In addition to cotton cloth, dyeing workshops also needed mordants and dyes from chemical factories. Vladimir Province housed several chemical factories that made mordants and dyes and supplied them to dyeing workshops. One example is the Dmitrovsk chemical factory near Ivanovo, which ground and supplied dyestuffs such as sandalwood and madder to dyeing workshops in the 1830s [24]. Traditional chemical factories manually ground the dyes, but the Dmitrovsk chemical factory imported a high-pressure steam kiln from Belgium for grinding dyes. Steam was used not only to heat and condense chemical solutions but also to heat rooms, which contributed to fuel savings. Chemists in Vladimir Province attended a technical school in Moscow to learn how to use steam engines in chemical factory work; they then applied their knowledge locally [24].

As dyeing technology advanced, dyeing workshops began to use chemicals. Sulfuric acid was essential for bleaching. Sulfur (iron sulfide ore) was needed to produce concentrated sulfuric acid, but no veins of sulfur were found in Russia until the early nineteenth century, necessitating the importation of sulfur from abroad. As dyeing technology improved, the importance of sulfur increased. When geologists confirmed that sulfur veins existed in Russia in 1812, the nation became self-sufficient in sulfur, which made the production of concentrated sulfuric acid easier and cheaper [25].

In the first half of the nineteenth century, before the advent of artificial dyes, natural dyes were mainly used. Dyers soaked cotton yarn and cloth in a dye solution in which the dyes had been dissolved, but fixing the dye to the fibers required a mordant, which is a substance that absorbs the dye into the fiber ([26], p. 36). Major mordants included lye, aluminum, and lead. Aluminum mordants included alumite (potassium aluminum sulfate) and acetate aluminum, etc. Alum predominated in Russia at that time. Among lead mordants, lead acetate (lead sugar) was also used. Dyeing entailed dipping fibers in a soap (surfactant) solution to prepare them to absorb the dye components. For example, dyeing fibers red required soaking the prepared fibers in an alum-based mordant solution. The fibers were dipped in a dye solution made by boiling the madder. Thus, mordant was an indispensable material.

In Northern Germany and Switzerland, alum was cheap because of the ease of mining alum rock from underground. Russia initially imported alum from Europe, but upon discovering in the 1840s that the high-quality pottery clay of Glukhvosk in Chernigov Province could be used to produce alum, Russia became self-sufficient in alum [25]. The alum production process entailed dissolving fine pottery clay in acid to allow the alum to accumulate. It was then crystalized by adding sulfur to the alum, diluting it with hot water, and drying it. This resulted in alum salt. When alum and aluminum sulfate were mixed and decomposed with lead acid, a solution

of aluminum acetate and sulfate was formed. Aluminum acetate could be used as a mordant when dyeing cotton fabrics with spots.

Lead acetate (lead sugar) was an important mordant synthesized from lead and vinegar [27]. Lead was rare in Russia and was therefore imported from abroad. However, vinegar could be produced from birch, linden, and *Populus tremula*. Chemical factories usually extract vinegar from birch.

Madder was necessary for dyeing Adrianople style chintz, but Russia's climatic conditions were inconducive to its growth. Therefore, madder was imported from Europe and Asia [27]. Specifically, Russia imported crushed madder called crops from Europe. Since Russia's neighboring Asian regions of Derbent (Dagestan City, Russia) and Khiva (Central Asia) also cultivated madder, Russia procured madder from both regions [27]. Madder contains alizarin, which dyes fabric crimson. Given that madder from Derbent contained more alizarin than crops, it dyed the cotton fabric vivid crimson. Madder from Khiva contained xanthine, which, when fermented, yielded alizarin.

4. Innovations in production processes driven by the dyeing industry

4.1 Integration of spinning and weaving

We have established that the introduction of new technology led to the mechanization of the production process, which enabled the manufacturing of large volumes of products and the overall development of the cotton industry. Although the explanation provided thus far represents one aspect of industrialization, it focused on the supply side. Progress due to innovations in printing followed the introduction of steam engines to the printing process in Vladimir's cotton industry. Such innovation promoted the introduction of mechanical looms into the weaving process and the use of steam engines in spinning, which transformed conventional production [28]. Recognizing that demand for cotton fabrics drove the industry's development is important. The dyeing process evolved from woodblock printing to the use of the Perrotin printing machine (roller printing using a rotating copper plate) in Vladimir Province in the 1830s.⁷ Printing achieved mass production and saw much acceleration due to this transition, lowering the price of cotton fabric. Although the design of printed cotton became standardized, multicolor printing was realized ([29], pp. 104–105), and the vivid colors of printed cotton combined with lower-priced products stimulated mass demand in Russia.

Traditionally, weaving enterprises wove at their mills in Vladimir Province and distributed cotton yarn to neighboring peasants for weaving. Additionally, many farmers subcontracted weaving. Although farmhouses undertook weaving in the off seasons, farmers prioritized agriculture in the summer, and cotton production fluctuated as a result [14]. Since people's activities had been based on the annual cycle before industrialization, production that fluctuated according to the season was natural. However, with the spread of the roller printing machine in the 1840s, people could move rotating copper plates to print multicolored designs ([4], p. 18). Although operating medium-sized rotary copper plates was difficult, printing machines were steam engine powered, which eased some of the manual labor. The use of roller

⁷ Ref. [28]. The French engineer Perrot invented the Perrotin printer, a type of roller printer capable of printing three colors simultaneously.

printing machines in Vladimir Province dramatically increased the printing capacity ([8], p. 203), necessitating a regular supply of cotton fabrics to ensure that textile printers would never be idle. This prompted weaving companies to attempt to control the seasonal fluctuations in cotton fabric production so that they could always supply the dyeing workshops.

Weaving companies internalized the weaving sector in the 1840s, especially in Shuya, Vladimir. Shuya's cotton cloth production overwhelmed other regions, positioning Shuya as the Russian center of cloth production in the middle of the nineteenth century. Companies in Shuya bought over 60% of Russia's total British cotton yarn imports in the 1840s and manufactured the yarn into cotton cloth [21]. These companies reduced their weaving outsourcing and began in-house weaving. This led to the introduction of machine looms to weaving factories to improve the weaving process ([2], pp. 27–28). Companies' practice of in-house weaving at mills contributed to reducing seasonal fluctuations.

In the early 1840s, several spinning mills were established near Moscow. A merchant named L. Knoop sold British spinning machines to the mills. Knoop was born in Bremen, Germany, in 1821. In 1839, when he was 18 years old, he stayed in Moscow, where he worked as an agent for De Jersey, an English trading company ([30], p. 119). In Moscow, Knoop met Morozov, an entrepreneur in the cotton industry who placed an order for British spinning machines. Knoop imported the machines from De Jersey and sold them to Morozov. This prompted Knoop to establish a trading company in Russia to import machinery. He fostered close relations with Russian entrepreneurs and almost monopolized the trade of British spinning machinery.⁸ Spinning mills were established in Vladimir Province in the late 1840s, and Knoop played an important role when companies in this region imported British spinning machinery ([31], p. 48).

Given that several independent spinning mills were established in St. Petersburg and Moscow before the 1840s, Russia achieved self-sufficiency in cotton yarn ([32], pp. 128–129). However, mills were rarely established in Vladimir Province because the region's main industries were textile printing and weaving. Therefore, weaving companies in Vladimir Province bought cotton yarn from St. Petersburg, Moscow, and foreign countries [33]. Enterprises that combined spinning and weaving arose in England in the 1830s ([22], p. 34). Entrepreneurs in Vladimir Province modeled their example and built factories that integrated spinning, weaving, and printing in the late 1840s [34]. Such factories were established in Shuya and areas adjacent to Moscow Province. The companies that built these factories started out in the dyeing industry.

Here, I explain the position of textiles in Russian industries from the number of workers. **Figure 2** shows the number of workers in Russian industries (1804–1860). In the first half of the nineteenth century, textiles, sugar, and iron were prominent industries in Russia. As the Russian iron industry was historically developed, it exported iron to Europe. According to **Figure 2**, the textile workers occupied the biggest proportion in Russian industries. Textiles consisted of cotton, linen, silk, and wool. From the 1830s, the cotton and wool industries rapidly grew. Therefore, a higher increase of workers in textiles means cotton and wool industries. The cotton industry was an important element in Russian industries from the number of workers. Then, let us look at specific examples of the cotton industry in Vladimir Province.

⁸ Young Russian entrepreneurs in the cotton industry spoke English fluently after the middle of nineteenth century and therefore easily communicated with European companies.

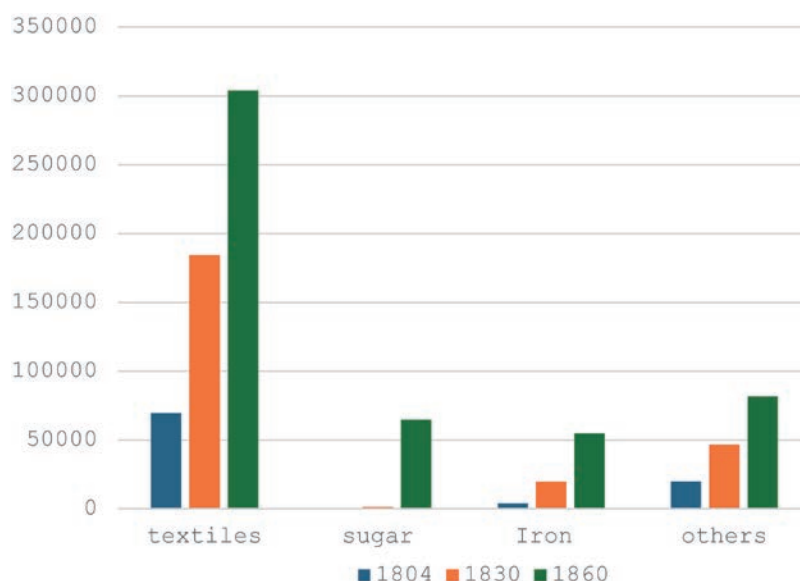


Figure 2.
The number of workers in Russian industries (1804–1860). The horizontal axis means the number of workers in Russian industries. Source: ([35], p. 423).

4.2 Examples of integrated factories in Vladimir Province

Stepan Posylin, a leading entrepreneur in Shuya who engaged in commerce in neighboring Asia, established a dyeing workshop in Shuya and began printing cotton fabrics in 1821 ([36], p. 408). Posylin started trading with Asia after 1828 and sold his cotton products in Caucasus and Persia. He built the first steam-powered spinning mill in Vladimir Province [19], but after 2 years of operation, it was destroyed in a fire. In 1838, Posylin's company installed an 8-horsepower steam engine for mechanized printing. Posylin and other entrepreneurs founded the Moscow Asian Trading Company to promote trade with Persia in 1845 [37]. At the same time, he imported a Perrotin printing machine from the Gummel factory in Berlin, Germany, that could simultaneously print three colors [38].

Nikon Galerlin, a leading Ivanovo entrepreneur, inherited his father's printing business in 1825. He acquired land for his printing factory from Lord Sheremetyev in 1837 and established the factory in 1843 ([39], p. 114). He imported a 40-horsepower steam engine and a Perrotin printing machine from England and partially mechanized the dyeing process, which shortened working hours at the factory. He also installed looms to weave cotton yarn [28]. Many spinning mills were established in Vladimir Province in the 1840s, and Garelin's company participated in the trend. The spinning mill he established in 1848 to produce cotton yarn had 29,000 spindles ([39], p. 114). Garelin imported machinery for the spinning mills from England through Knoop's trading company. Garelin's company used its integrated printing and spinning factory to engage in comprehensive cotton manufacturing.

Ivan Popov was the first guild merchant in Shuya, Vladimir, to undertake the weaving business. Notably, he built the first Shuya factory that combined spinning and weaving in 1847 [40]. At that time, printing productivity increased, as did the demand for cotton yarn and fabric, which transformed the spinning and weaving processes. Popov combined a weaving mill with a spinning mill [41] and installed

108 weaving machines in the integrated factory, situating the weaving process in one place [42] and allowing spinning and weaving to be performed in the same factory.

The Kaletnikov, who were also merchants in Shuya, were involved in the dyeing business since 1787 [43]. Peter Kaletnikov established a new dyeing factory with Perrotin printing machines in 1840. This promoted the mechanization of the printing process, and as the new printing machines increased the demand for cotton fabrics, he undertook weaving in his factory in the 1840s. He initially used British steam engines to power the Perrotin dyeing machines; eventually, he realized that Belgian steam engines also performed excellently.

Consequently, he imported 35–40-horsepower steam engines from the Gilain factory in Tienen, Belgium, in 1851 and 1852. In 1855, he installed five-color Belgian roller printing machines in his factory [43]. Kaletnikov built a new spinning mill and introduced weaving machinery in 1858–1860 ([39], p. 186). This mechanization allowed Kaletnikov's enterprise to become comprehensive by encompassing three processes: spinning, weaving, and dyeing. He employed 2200 weavers and 350 yarn winders in the weaving department and 555 dyers in the dyeing department.

Ivan Baranov inherited his father's dyeing workshop and produced chintz in the city of Alexandrov [44], which lies on the border between the provinces of Moscow and Vladimir. His father opened the dyeing workshop in 1834 and dyed cotton yarn and fabrics in crimson and plaid patterns, producing chintz and other products. As his father's successor, Baranov's outstanding achievement was becoming the first in Russia to use Caucasian madder as a dye [45]. At that time, using crops to dye cotton cloth crimson was common, but its drawback was its high cost since it had to be imported. Baranov reduced costs by renting land in Derbent to grow madder for use as dye. Given the innovations in the printing process, Baranov established the Troitsko-Alexandrov spinning and weaving factory in 1846. Situated beside the printing factory, it performed three in-house processes: spinning, weaving, and dyeing ([39], p. 44). The factory employed about 1000 weavers. The company's main markets were the Asian market, including Central Asia, the Caucasus, and Persia, as well as the Russian market.

The Morozov family were the leading Russian entrepreneurs in the nineteenth century. Sava Morozov started in the silk weaving business and eventually founded his family business. He emigrated from Zuevo in Moscow Province to Nikoliskoe in Vladimir Province (present-day Plehkovo-Zuevo in Moscow Province) in 1797 and established his factory there, where he manufactured silk products ([39], p. 264). He built the Zuevo dyeing and bleaching factory in Bogorodsk in 1830, where he printed cotton and hemp fabrics. Sava's second son, Elisei Morozov, established the Nikolisk dyeing company in 1840 and employed 60 dyers [46]. He established a spinning and weaving factory beside the dyeing factory in 1847, which integrated spinning, weaving, and dyeing [19]. He controlled all the processes, from spinning to printing, and steadily supplied cotton fabric for dyeing. The Nikolisk dyeing company imported a four-cylinder steam engine from England in 1853 and introduced British 50-belt spinning machines in the following year [23]. In the 1850s, the Nikolisk dyeing company became the leading producer of cotton yarn in Vladimir Province.

5. Conclusion: Russia and Central Asia

Russia is usually described as a region where European and Asian cultures intersect. The city of Kazan, near Vladimir Province, has a high concentration of Muslim Tatars. Vladimir Province is on the cultural border between Russia and Asia.

The river once connected the region to Arkhangelsk, the window of European trade, allowing European and Asian knowledge to converge. This factor may have promoted Vladimir's cotton industry.

According to world history since the seventeenth century, there was a period when Europe actively imported Asian goods through the East Indian Company. Among these, cotton textiles (chintz) were important. Europe faced a deficit in Asian trade and banned calico imports ([47], p. 70). From a long-term perspective, European industrialization intended to substitute imported Asian goods ([48], pp. 200–202). This view relativizes modern Europe's superiority, but there is no logical contradiction during events. This reversal between Europe and Asia can also be applied to the relationship between Russia and Central Asia.

If we focus on European-promoted substitutions of imported Asian cotton fabrics, their success can be attributed to dyeing methods based on chemistry and powered by steam engines. Since dyeing techniques were historically developed in Asia, their transfer was challenging ([49], pp. 157–159). When Europe introduced the scientific method of reductionism ([50], p. 23) to dyeing and began to understand dyeing as a chemical reaction, the Asian dyeing methods were elucidated, and Europe overcame its reliance on Asian dyeing techniques. The nineteenth century can be called the age of the steam engine. Traditionally, work required manpower, animal power, or natural energy (water and wind power), but the steam engine used fossil fuels to perform that workload a dozen times over. Steam engines facilitated high-speed mass production. Work was no longer done according to the rhythm of nature but rather by machines. Hence, introducing the steam engine to production changed the conception of time.

In the first half of the nineteenth century, the cotton industry in Vladimir Province developed with printing technology from Europe. In the medium term (100 years), Vladimir Province followed Europe's industrialization. In the long term (300 years), however, a different view can be presented. Since the sixteenth century, Russia has imported cotton fabric from Central Asia, and Vladimir Province first learned dyeing and weaving from Central Asia. Imagining that Vladimir Province adored Central Asia for this is plausible. Russia imported products from Central Asia for a long time, perpetuating the cotton fabric trade ([51], pp. 236–239). Subsequently, the region introduced science and technology from Europe and developed its own cotton industry. In the medium term, the industrialization of Vladimir Province appears to have been a process of substituting imported European goods. **Figure 3** shows imports of cotton yarn and Russian production of cotton yarn (1801–1860). The decrease in cotton yarn imports means the increase of Russian cotton yarn. 1840s shows the import substitution period of cotton yarn.

However, the region's industrialization was essentially the substitution of commodities imported from Central Asia in the long term. **Figure 4** shows the import and export of cotton fabrics between Russia and Asia (1831–1860). Though Russia produced cotton fabrics and exported the products to Asian markets, it continued to import Asian cotton fabrics in the 1840s. This means that Russian consumers used Asian cotton fabrics. Russia realized the import substitution of Asian cotton fabrics in 1850s. When the region began mass producing cotton fabrics, it immediately exported them to Central Asia, which later became an important market for Russian printed cotton.

Soviet historians extended Russia's annexation of Central Asia in the late nineteenth century and described the history of Russia's (militarily) forced sale of cotton fabrics on the Central Asian market.⁹ We must look at actual objects to understand

⁹ For example, ([54], pp. 383–386).

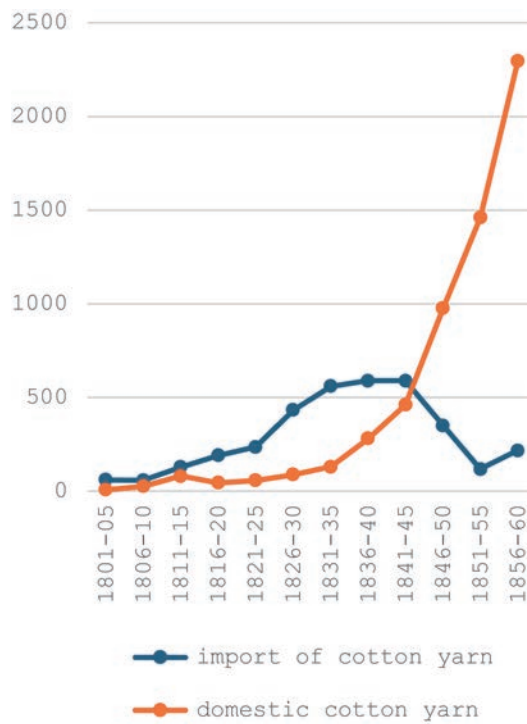


Figure 3.
Imports of cotton yarn and Russian production of cotton yarn (1801–1860). The horizontal axis means the average of 5 years. The unit of cotton yarn is a thousand pood (old Russian measurement). Sources: ([32], p. 182; [51], p. 119).

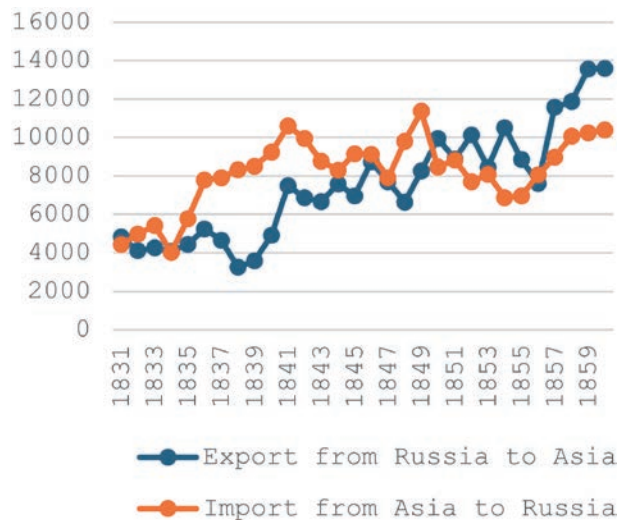


Figure 4.
The import and export of cotton fabrics between Russia and Asia (1831–1860). The horizontal axis means the year. The unit of import and export is a thousand assignat ruble. Source: [52, 53].

how Central Asian consumers used Russian cotton fabrics (chintz). Central Asian women used the chintz from Vladimir Province to line theirhalat (jackets) ([3], p. 44). Since Central Asia was influenced by Islam at that time, women covered their skin with veils when they were outside their homes. The lining was an esthetic feature to be presented to members of the same sex and was by no means a Russian compulsion. Printed cotton from Vladimir Province clearly attracted women in Central Asia. From a long-term perspective of 300 years, Russia and Central Asia belonged to a cultural sphere that shared some elements. Russia's industrialization substituted imported Central Asian goods. This resembles European industrialization, which also substituted imported Asian goods.

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Minimizing Residual Stress in Aesthetic Automotive Components: A Study of Injection Pressure in ICM and IM Processes

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and Christopher W.K. Chow*

Abstract

This study investigates the injection pressure differences between Injection Moulding (IM) and Injection Compression Moulding (ICM) processes for crafting aesthetic automotive interior components, such as Radome Badges and Hidden-Til-Lit (HTL) components. Using Autodesk Moldflow® software, simulation-based analysis of ICM injection pressure is conducted for various specimens with wall thicknesses from 1 to 4 mm and flow lengths from 50 to 300 mm, using PC Lexan™ Resin LS1 material. Results show that pressure disparity between IM and ICM increases with thicker walls and shorter flow lengths, ranging from 30 to 51%. Correlation analysis indicates a strong positive relationship ($r^2 = 0.999$) between IM and ICM, supported by regression analysis. Physical trials validate simulation outcomes. Implementation of ICM could enhance manufacturing efficiency for aesthetic automotive components, offering cost reduction and business opportunities.

Keywords: ICM, simulation, injection pressure, moldflow®, radome badges, automotive, injection moulding

1. Introduction

Aesthetic automotive components are manufactured through injection moulding, over-moulding, annealing, coating, and further over-moulding. Components such as Radome Badges (radar sensors combined with camera systems assembled to the badge as part of the Advanced Driver Assistance Systems to increase road safety) and Hidden-Til-Lit (HTL) components (interior/ambient lighting with adjustable colour and intensity) generally require multiple component injection moulding to produce the final product. The moulding will become complicated when considering the detailed profiles

of various emblems, as in the case of radar badges which often include a 3D-shaped logo, must satisfy the aesthetic appearance requirement, which could often conflict with the radio frequency (RF) performance. For HTL components, the manufacturing process remains almost similar, but instead of transmitting radio waves, ambient lights need to be transmitted from the source hidden inside through the transparent, metallic-coated window. These products require a high level of manufacturing expertise and knowledge in product development. In most such products, the manufacturing involves thin plastic components that need to be injection moulded at very high pressure, which often generates high residual stress and may deform the part insert/previous shot (as in the case of over-moulding). Having residual stress will not have the expected durability in the field as this stress starts relieving when energised. These residual stresses will cause cracking and delamination of Anti-Static Treatment (AST) coating through the Physical Vapour Deposition (PVD) process. To minimise this residual stress and eliminate the deformation of the mask (part insert) while over-moulding, Injection Compression Moulding (ICM) or Injection Expansion Compression Moulding (IECM) technique, is a technique that incorporates both the benefits of Injection Moulding (IM) and Compression Moulding (CM), is adopted. This gives an acceptable result and eliminates the deformation of the mask. A comparison sketch of IM, ICM & IECM processes is given in **Figure 1**.

Manufacturing organisations worldwide use this ICM technique to produce high-quality plastic products that cannot be efficiently made using conventional IM. This process has many benefits; the most significant ones are uniform stress and pressure distribution inside the mould cavity and minimising the residual stresses, which are the main reason for ICM being used instead of IM in producing aesthetic components [1]. However, it is not practical to adopt the ICM technique in all applications due to process limitations and design constraints [2–4]. Little research has been conducted on the ICM technique in developing aesthetic automotive components. Though many organisations are experimenting with this technique to manufacture plastic products, not much information is available due to the confidentiality of their projects. Information regarding the pressure difference between IM and ICM for the transparent Polycarbonate (PC) material is curial, so it will be challenging to predict the maximum injection pressure at the starting stage of the development project. The current assumption is that the injection pressure of ICM is 25–30% less than the conventional IM for LEXAN™ Resin LS1 material, but this is not yet studied and proved. This makes selecting appropriate injection moulding machines challenging,

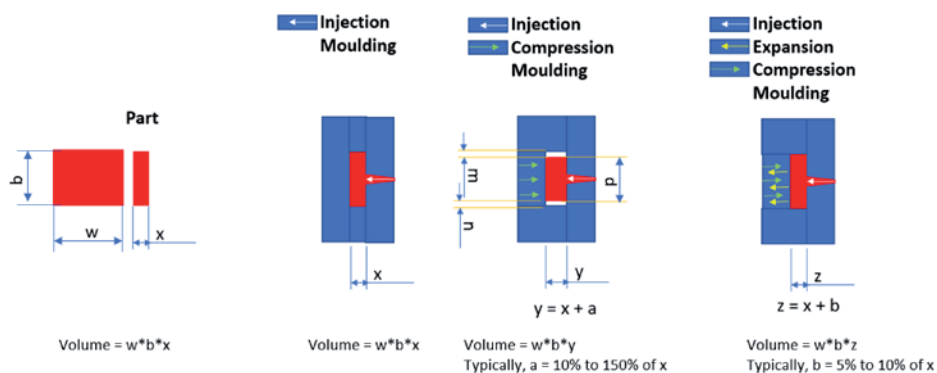


Figure 1.
IM, ICM & IECM process comparison.

and the quotes' assumptions generally deviate around 15–25% from the actual. So, it is essential to understand the actual injection pressure of parts in the ICM process with respect to the available data for the IM process.

This research aims to verify the assumption that the injection pressure required for the ICM process is 20% less than the conventional IM process. The research aims to find the actual variation of injection pressure in the ICM process for a given wall thickness of part moulded with PC LEXAN™ Resin LS1 material with respect to IM processes, and to derive a relationship, if any, on the variation of injection pressure for these processes. The research is based on computer simulations but has limitations in verifying the results in the physical environment due to the high costs of manufacturing prototype ICM moulds. Research is explicitly for uniform wall thickness parts and thus does not aim to provide a single solution to calculate the injection pressure variation in the ICM process for various feed system designs and parts with variable thicknesses.

Understanding the injection pressure behaviour in the ICM process using PC LEXAN™ Resin LS1 material with respect to the conventional IM process will narrow the knowledge gap in applying the ICM process in aesthetic automotive components, and the results will further help in developing the plastic products, especially in the automotive sector which can be successfully moulded using ICM process. This study's findings will further support the research of clamping force, shrinkage, and other critical moulding factors, thus drawing a quantitative and reliable conclusion.

2. Methodology

The methodology of this study consists of two parts, (1) literature review and (2) computer simulation. The literature review aims to better understand the ICM process compared with conventional IM. The findings help determine the simulation method and parameter range for the simulation study. Then followed by a simulation-based experimental study to draw the relationship between two quantitative processes, but qualitative research on the physically moulded part is also recommended to find the effects of both processes. The proposed methodology is an expert knowledge approach where the study is commenced by an assumption (raw data), and then a quantitative analysis is performed on the specimens to refine the results after an application in a case study.

2.1 Literature review

Three parameters: injection pressure, clamping force and shrinkage allowance, and the benefits of adopting ICM over IM, were selected for the initial search using Google Scholar and UniSA Open Athens. Initially search indicated limited availability of recent research publication for IM & ICM processes comparison and most of the literature is 5 years or older. The search was then refined by accessed directly through the UniSA library and Organisation details and product-specific information from their respective websites which successful found additional literatures.

The literature search results were categorised into (i) the benefits and limitations of ICM over IM, (ii) comparison of process parameters - injection pressure, clamping force and shrinkage allowance, (iii) the current research on the methodologies adopted in the ICM process and (v) identified the knowledge gaps in developing the ICM process.

2.2 Simulation approach

A multiple computer simulation on specimens to derive the relationship between ICM and conventional IM and then compare the result with a prototype tool was setup. An expert knowledge approach was commenced by an assumption (raw data), and then a quantitative analysis performed on the specimens to refine the results after an application in a case study. Only a specific grade of Polycarbonate (PC) thermo-plastic material is considered to simplify the research. A research flowchart for the proposed methodology is given in **Figure 2**.

The simulation-based experimental analysis was used to derive the relationship between different conditions.

- Flow simulation was performed on the specimens with various combinations of with, length and thickness using Autodesk Moldflow® Ultimate 2022 software.
- ICM and IM processes were performed to analyse the injection pressure variation for each specimen.
- Injection pressure results were collected for statistical analysis.

The injection pressure of ICM and IM clamping force collected through multiple analyses on prepared specimens using Autodesk Moldflow® Ultimate software. Specimens of different wall thicknesses and sizes were modelled using CatiaV5 software. The data thus collected through simulation experiments were analysed and compared using SPSS software, and a relationship between ICM and IM on injection pressure and clamping force were derived. A prototype injection mould was used to verify this later in a selected case study.

2.2.1 Specimen preparation and analysis setup

2.2.1.1 Specimen preparation

Aesthetic automotive components generally have wall thicknesses ranging from 1.5 to 3.5 mm, so the research excludes wall thicknesses below 1 mm and above 4 mm. Similarly, the study was exclusively for the flow lengths up to 300 mm as most of the products are within this length or multiple gates are placed in series within this flow length. The flow length and wall thickness range were selected by reviewing various literature that underpins the generation of high injection pressure for high aspect ratio parts [5, 6].

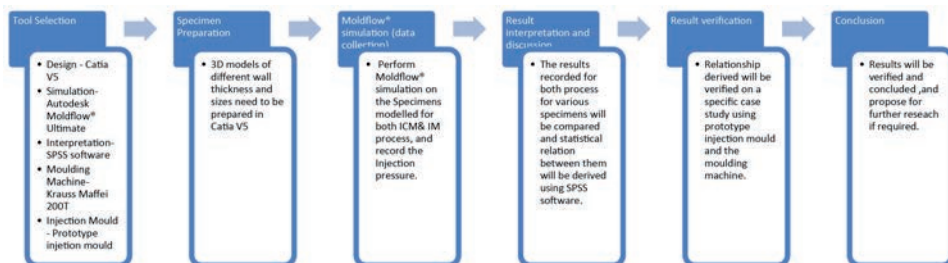


Figure 2.
Research flow chart.

3D models of these specimens were designed using Catia V5 R30 software [7]. The width of the part was set to 20 mm for consistency in comparing the injection pressure results. The feed system was designed with minimal runner length, and the gate thickness was set to the same wall thickness of the part. The gate width was set to 5 mm, and the length was set to 3 mm on all specimens. The runner diameter was set to 6 mm on all specimens for a length of 20 mm. Designing a gate thickness not less than the part wall thickness can avoid any possible pinch point that can affect the pressure. As the injection node was placed at the end of the runner, the flow length was increased by 25 mm, but the pressure drop along the cold feed system was disregarded in this study as the pressure was measured at the end of the gate, thus measuring only the cavity pressure.

Table 1 lists models to be analysed using the IM & ICM processes. In total, 42 combinations of wall thickness and flow length were analysed.

Autodesk-Moldflow® [8] software recommends limiting the injection pressure to 100 MPa as a design guideline, though depending on case to case in industry practice, this could be accepted up to 150 MPa. Research by Yao and Kim [6] identified that injection pressure for the PC part with 1 mm thickness and 50 mm flow length was approximately 125 MPa, and the pressure increases exponentially. So utmost care should be taken while considering the pressure results of thin specimens with longer flow lengths, which may give unrealistic results.

2.2.1.2 Moldflow® analysis setup

All 42 models to be analysed were imported to the Moldflow® software. Then the mesh was generated on the model containing the part and the feed system. A global edge length of 0.5 mm was selected for all models, and the minimum number of tetra layers was selected to 10 to increase the prediction accuracy. Once the meshing was done, the tetras comprising the cold runner and cold gate were assigned as cold runners and moved to a different layer for easy interpretation of analysis results. As the research was only to find the injection (cavity) pressure distribution, only Fill + Pack analysis was selected for the analysis sequence. No cooling channels were designed for the project, thus assuming uniform and constant cooling throughout the moulding phase. Material was then selected to LEXAN™ Resin LS1 for analysis. This material was thoroughly tested for the filling and packing analysis, thus bearing a ‘gold rating’ for both. This means the viscosity, Specific Heat Capacity, pvT and Thermal

		Flow length					
		50 mm	100 mm	150 mm	200 mm	250 mm	300 mm
Wall Thickness	1.0 mm	1.0 × 50	1.0 × 100	1.0 × 150	1.0 × 200	1.0 × 250	1.0 × 300
	1.5 mm	1.5 × 50	1.5 × 100	1.5 × 150	1.5 × 200	1.5 × 250	1.5 × 300
	2.0 mm	2.0 × 50	2.0 × 100	2.0 × 150	2.0 × 200	2.0 × 250	2.0 × 300
	2.5 mm	2.5 × 50	2.5 × 100	2.5 × 150	2.5 × 200	2.5 × 250	2.5 × 300
	3.0 mm	3.0 × 50	3.0 × 100	3.0 × 150	3.0 × 200	3.0 × 250	3.0 × 300
	3.5 mm	3.5 × 50	3.5 × 100	3.5 × 150	3.5 × 200	3.5 × 250	3.5 × 300
	4.0 mm	4.0 × 50	4.0 × 100	4.0 × 150	4.0 × 200	4.0 × 250	4.0 × 300

Table 1.
List of specimens.

Conductivity of this material were tested and verified by Autodesk Moldflow®, so the accuracy of results would be the highest.

The IM & ICM process settings were different, so the analysis needs to be set up differently. The melt temperature, mould temperature and injection flow rate were set to the same value for both processes. The mould temperature was set to 95°C, and the melt temperature was set to 300°C. A pilot analysis was carried out with the above temperature settings, with the filling control set to automatic. This provided the optimum flow rate of 5.5 cm³/s required for the part to fill 100% under optimum conditions. The same flow rate was populated for all specimens for analysis. Further, the V/P switchover was set to automatic for uniformity between analyses.

For ICM analysis, the press compression direction was set to the Z direction, and the press compression was set to start at the end of packing. This ensures that the press compression has no influence on the pressure profile during the packing phase. Press speed and press compression cap were set to a higher-than-usual amount to negate any influence due to limitations. Multiple analyses were carried out to set up the right compression gap and found that a press open distance of 0.26 mm was the optimum for compressing the press back to zero when packing. Specimens were then ready to run the simulations on IM and ICM processes and to review the results in detail.

2.2.1.3 Material selection

PC LEXAN™ Resin LS1 has been selected as suitable for these products and compatible with various PVD coatings. Moldflow® software has the complete material data information available, which was tested and confirmed at Autodesk Moldflow® Plastic Labs. PC LEXAN™ Resin LS1 available in the Moldflow® database has a gold rating (a high confidence in the material quality, thus expecting the most reliable result) for all the analysis types.

2.2.1.4 Selection of mesh for analysis

The model was imported as the native CATIA Part (CATPart) file and generated Dual Domain mesh (one of the three available mesh types: Midplane, Dual Domain and tetrahedral-3D Mesh). An edge length of 0.5 mm was selected to generate at least two outer layers along the thickness for the smallest wall thickness to be analysed, which was 1 mm. Then the mesh statistics were diagnosed and confirmed that the match and reciprocal percentages were more than 99% which was suitable for analysis. Then it was re-meshed to 3D mesh with a minimum of 10 layers of tetra layers as recommended by Moldflow® for plastic parts.

2.2.1.5 Selection of appropriate analysis sequence & boundary conditions

Moldflow® software has various analysis sequences appropriate for evaluating different results. While the packing phase is more controlled with the set packing pressure, the injection pressure is mainly driven by the factors such as injection time and flow rate to fill the part. Thickness and flow length have a more significant impact on injection pressure. The Fill + Pack sequence was selected to study the variation of injection pressure for IM & ICM processes. The Z direction was selected for the research as the compression direction. Only the part's surface was considered for compression surface, while the feed system did not go through the compression sequence.

2.2.1.6 Selection of process settings

Optimum process settings to mould the part within the maximum shear stress and a shear rate of the material were found by multiple analyses on one of the specimens. Below are the process settings selected for the research.

Injection Moulding

Mould Temperature: 95°C

Melt Temperature: 300°C

Flow Rate: 5.5 cm³/s

V/P Switchover: 98%

Viscosity model: Standard viscosity model (from material data)

PVT model: Standard PVT model (from material data)

Solidification model: Standard Transient Temperature model (from material data)

Additional settings for Injection Compression Moulding

Press open distance: 0.5 mm.

Press Compression: starts at the end of packing.

Press force switchover: 99%.

Press compression time, Press speed cap and press compression force cap were set to the machine's maximum limit.

2.2.1.7 Moldflow® simulation IM & ICM (data collection)

Moldflow® analysis on the IM process was first checked the predicted injection pressure. The machine injection pressure has 240 MPa limit, so considering the Moldflow® recommendation and the industry best practices, any specimen with a pressure less than 120 MPa should be considered for this research (Figure 3).

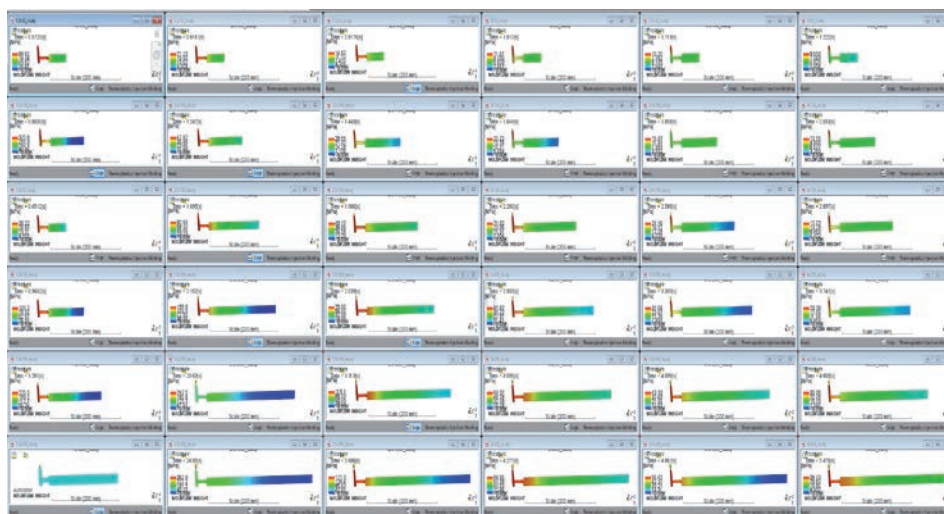


Figure 3.
Moldflow® analysis of specimens using the IM process.

Higher injection pressure (hp) above 120 MPa was predicted for a few specimens (**Figure 4**) with high aspect ratios (thin and long), and short shot (ss) was predicted for extreme aspect ratios. The predicted injection pressure for all specimens was recorded (**Figure 5**).

The specimens with the injection pressure less than 120 MPa for the IM process were further considered only for the ICM analysis to draw a meaningful comparison. This means the specimens with high pressure or short shot predicted were neglected for further analysis. The exact process settings adopted for IM analysis used for ICM analysis, and the corresponding results are recorded (**Figure 6**).

2.2.2 Statistical analysis and result validation

Injection pressure results obtained from Moldflow® analysis were statistically analysed using SPSS software to derive any relationship and variation between

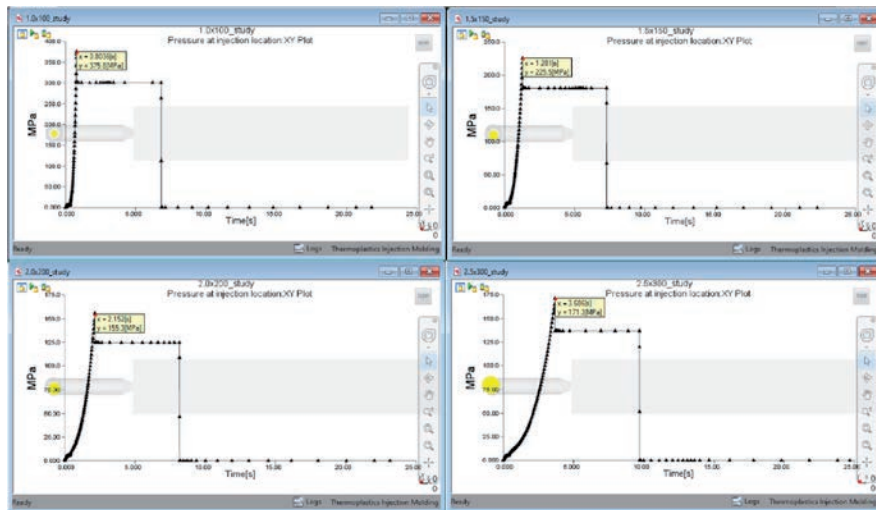


Figure 4.
Specimens that exceeded the injection pressure of 120 MPa.

Predicted Injection (cavity) Pressure (MPa) for flow length vs thickness for IM							
		Flow Length					
		50	100	150	200	250	300
Thickness	1	83	hp	ss	ss	ss	ss
	1.5	28	82	hp	ss	ss	ss
	2	17	38	78	hp	ss	ss
	2.5	13	19	38	65	117	hp
	3	8	13	22	36	55	90
	3.5	6	10	14	21	34	45
	4	3	6	12	15	22	34

Figure 5.
Predicted injection (cavity) pressure for IM.

Predicted Injection (cavity) Pressure (MPa) for flow length vs thickness for ICM							
		Flow Length					
		50	100	150	200	250	300
Thickness	1	54.0					
	1.5	18.1	52.0				
	2	10.9	24.0	51.0			
	2.5	8.1	12.2	24.0	44.0	80.0	
	3	4.7	7.9	13.9	23.0	36.0	62.0
	3.5	3.5	5.6	8.6	12.2	21.0	31.0
	4	1.6	3.2	7.2	8.3	12.5	22.0

Figure 6.
 Predicted injection (cavity) pressure for ICM.

ICM & IM. Findings from the simulation and statistical analysis were validated by moulding the parts using a prototype tool and were compare the actual injection pressure obtained. A prototype tool incorporated with IM and ICM techniques were used for the trials. These trials were done at the Motherson Australia production plant in Lonsdale, South Australia. The injection Moulding machine, Prototype tool, Polycarbonate (PC) material and standard moulding accessories were utilised to do the trials.

3. Results and discussion

3.1 Benefit and limitation of ICM over IM

IM technology, widely used to manufacture plastic products, has limitations, resulting in borrowing other technologies from various branches of science to develop high-quality products [9]. Being a versatile process with many variables involved, it is essential to study the effect of process parameters on ICM. Most of the literature aimed at deriving the benefits of ICM over IM; As Shoemaker [10] explained, the ICM process is an extension of conventional IM, which can produce dimensionally stable, relatively low residual stress parts at a lower clamping force. Further, Yilmaz et al. [11] found that the ICM technique minimised the required injection pressure compared with IM. At the same time, ICM is considered a complex process; the selection of ICM over IM is based on accuracy, the geometry of the part and cost [1, 4].

Aesthetic automotive components are critical for their transmission performances, which moulding can enhance at minimal residual stress. This can be achieved by moulding the part with very low injection and packing pressure in the ICM process, as Michaeli et al. [12] concluded in their comparison study of IM and ICM on the optical performance of moulded parts. Chen et al. [3], Young [13] and Zhu et al. [14] also highlighted in their research the higher optical performance, especially lesser birefringence when using the ICM process.

Though ICM & IECM are used in industries and studied by a few research groups, obtaining the process in detail is challenging due to the confidentiality or limitation of studies [3]. The same is underpinned by Malkin and Isayev [15] that there are few theoretical and practical studies in the literature on ICM & IECM. Further, Loaldi et al. [1] highlighted the significance of the compression gap in their study; a lower compression gap is preferred for optimal conditions. Thus, this study indirectly

points out the benefit of IECM, as it is very similar to an ICM process with a minimal compression gap. This is also highlighted earlier in a patent filed by Clarke [16] on how the IECM process differs from ICM and the benefits of adopting the process in terms of lower residual stress.

Nevertheless, a comparison study on both processes is essential to determine the risk of producing poor-quality parts; Michaeli and Wielpuetz [17] highlighted that the processing window is very narrow for ICM compared to IM. Similarly, a study at IKV highlighted the importance of calculating the clamping force at the design phase [18]. Even though none of these studies provided any quantitative comparison of ICM or conventional IM, thus resulting in the inaccurate selection of moulding machine and appropriate shrinkage.

3.2 Methodologies adopted in current research

Most of the works of literature followed an experimental method to test the cause-and-effect relationships, and the outcomes are primarily quantitative. However, as indicated by Dang [19], most approaches are purely academic and thus difficult to apply in practice due to the lack of detailed study about the scope of application. As the injection moulding process involves many variables, most researchers limited their study to very few variables with relatively few experiments to get satisfactory results [20]. At the same time, few pieces of literature focused on the responses and conclusions of various studies by different researchers, giving a complete snapshot of the [21]. Simulation-based research is quite common in the field of injection moulding, which will reduce the environmental impact by reducing the wastage of physical moulding and achieving the results through a faster and cost-effective way [3, 22]. This is underpinned by Spina [23] who adopted a Moldflow® simulation-based comparison study of hot runner systems in injection moulds to mould aesthetic automotive components. On the other hand, few researchers adopted a case study-based approach, which directly correlates with application, and the results are primarily qualitative [13].

3.3 Comparison of process parameters

Flow Length (FL) to Wall Thickness (WT) ratio is important for all injection moulded parts, the primary factor contributing to injection pressure. Yao and Kim [6] investigated the effect of the rapid increase in frozen layer thickness due to cooling happening in the thin-walled parts, which increases flow resistance. Various simulation results are discussed, which indicate the rapid increase in injection pressure for thin-walled parts, but this study has limitations as they considered only two levels of mould temperature; 25°C which is the room temperature and 265°C which is the melt temperature of the selected Polycarbonate material [6]. These two temperatures are impractical for conventional moulding as the recommended mould temperature is between 70 and 100°C. However, it is evident from their research that injection pressure for the part with 1 mm thickness and 50 mm flow length is approximately 125 MPa [6]. Industry-wide practice is to limit the injection pressure to half of the maximum limit of the moulding machine; Moldflow® software recommends limiting this pressure to 100 MPa as a design guide line [8].

The criticality of the flow-length-to-wall-thickness ratio is widely discussed in many other research and by manufacturers; Hinterdorfer [5] explained about the

	Injection moulding	Injection compression moulding
Application	All plastic parts except those with less wall thickness (less than 0.5 mm).	Thin-walled parts, parts with longer flow length (high aspect ratio).
Process Sequence	Injecting the plastic into an empty closed fixed cavity (impression), then allowing it to cool until ejection.	Injecting the plastic into a slightly opened cavity, the compression plate is moved to compress the molten plastic, reach the final size/shape, and then allow it to cool until ejection.
Process complexity	Very versatile and easy to process.	Rarely applied and for specific products only.
Machine requirements	Any injection moulding machine can perform the task.	An injection moulding machine with special provisions for the movement of compression plates is required.
Product quality aspects	High in mould residual stress, stress concentration, high warpage.	Low residual stress and uniformly distributed comparatively less warpage.
Product design limitations	Difficult to fill thin wall sections.	Suitable only for parts with less projecting features such as clips, bosses etc.

Table 2.
Comparison of IM & ICM.

effectiveness of ‘ENGEL coinmelt process’ which is essentially an ICM process to consistently achieve high part quality for a ratio of 1:400. Lower injection pressure, lower clamping forces and high repeatability with highly viscous material are the advantages of this process [5]. Spina [23] highlighted the effectiveness of a multi-gate feed system in filling the aesthetic automotive components to reduce the injection pressure and improve the part quality. The sprue, runner and gate design have a greater impact on the injection pressure and the quality of the parts. Their cross-section and length vary based on the applications and the design restriction, which could increase the injection pressure at the nozzle. So, to understand the actual injection pressure on the moulded parts, it is essential to consider the cavity pressure instead of the injection pressure or the pressure developed in other areas [24]. Tsai and Lan [25] explained the variation of injection pressure along a sensor point in the cavity throughout the moulding phase.

Sortino et al. [26] compared IM & ICM processes for producing optical parts. They reviewed multiple research projects that compare these processes and found out through their experimental studies that ICM is the most precise and repeatable process among the compared. Both IM and ICM have pros and cons from an application perspective; the data collected through the literature review is summarised in **Table 2**.

The growing trend of automotive product design with thin-walled components for weight reduction is being researched thoroughly. Thinner components have a greater environmental impact by reducing fuel consumption and better performance by being lighter [27, 28].

3.4 Simulations: Initial consideration

High residual stress within the initial moulded parts relieve can passing through subsequent processes and causing dimensional errors in later stages with excessive warpage and may fail in the field. Parts with wall thicknesses

less than 1.5 mm will exhibit excessive residual stress. On the other hand, if the wall thickness is more than 3.5 mm, this will affect the effective transmission of signals. Also, increasing the wall thickness will make the part stiffer and heavier, thus restricting the assembly process's flexibility. Thus, most aesthetic automotive components have wall thicknesses ranging from 1.5 to 3.5 mm. So, the research excludes the wall thicknesses below 1 mm and above 4 mm, considering 0.5 mm above and below the design range.

Similarly, this study is exclusively for the flow lengths up to 300 mm as most of the products are within this length or multiple gates are placed in series for parts more than 300 mm in length. From the industry best practices, other research, and recommendations by Moldflow® software, it is anticipated that the pressure results on high aspect ratio specimens (thin and long) may give unrealistic injection pressure results. Hence, these values need to be neglected to derive meaningful conclusions.

In practice, the gates can vary in shape and size, like edge gate, cashew gate, sub gate, fan gate etc. Similarly, the runner length can range from a few millimetres and can be as long as the flow length for the part. These factors can affect the injection pressure on the part. So, this research excludes any deviation in injection pressure due to the feed system design constraints and considers only the pressure inside the part cavity, which is the cavity pressure. However, the outcome of the results needs to be carefully interpreted as it is based on the cavity pressure and excludes the higher injection pressure generated by the relatively smaller gates in some products. This is critical, especially when moulding the parts with fan gates or sub gates, as their effective opening diameter is less than the actual part wall thickness for easy de-gating. This project explicitly studies the injection pressure differences in ICM & IM process with PC Lexan LS1 material as this is the most compatible special material identified to develop aesthetic automotive components.

Injection moulding is a versatile process that involves numerous process variables. Significant process variables affecting this research are melt temperature, mould temperature, injection time, flow rate, injection speed, packing time, and packing pressure. ICM is complicated as it involves the compression phase where the compression gap, compression speed, etc., further complicates the process. For this research, a single practical value is considered for all these variables and all the specimens are analysed using the same process settings. Thus, this research has limitations in predicting the injection pressure for other possible hundreds of combinations of process variables.

There is expected to be some difference between simulation results and the actual moulding results, but this research does not bridge any gap between the accuracy of the simulation results with respect to the physical moulded parts. This research is exclusively to identify, through simulation, the relationship in injection pressure between IM & ICM for various flow lengths to the wall thickness and validate the same difference in physical moulding. This project focuses only on the study of injection pressure on ICM and IM processes of aesthetic automotive components and does not investigate the complete manufacturing process of these components, including annealing, coating, further over-moulding and compliance tests.

Injection Pressure for both IM & ICM processes are recorded and compared using different applications. Firstly, the percentage of injection pressure between both processes is calculated using Microsoft Excel and checked for consistency. Correlation and Regression analysis on injection pressures recorded is done using IBM SPSS Statistics software. From this, a regression equation is expected to be derived to calculate the ICM process's injection pressure from a known IM process. Injection

moulding trials for both IM & ICM processes on a prototype tool are carried out, and the resulting pressure obtained is analysed and compared with simulation results.

3.5 Result comparison

Injection pressure predicted from Moldflow® analysis on both processes is compared. It is found that the pressure remains almost the same for the samples when the thickness is increased by 0.5 mm, and the flow length is increased by 50 mm for specimens of lesser flow length and thickness (**Figure 7**).

The current assumption is that the injection pressure of ICM is 20% less than the IM process. The injection pressure predicted for each specimen for both processes is compared in **Table 3**.

Table 4 shows the injection pressure of the ICM process as a percentage factor with respect to the comparison of pressure difference in specimens between the IM and ICM process, revealing that the 20% injection pressure reduction of the ICM process is invalid. This varies along the flow lengths and across the wall thickness of the moulded parts. Within the acceptable range of injection pressure (120 MPa) compared among the specimens, 3 x 300 mm has the least reduction of 30.33% and 4 x 50 mm has the most reduction, 51.09%. Another trend highlighted from the comparison study is that the variation in difference increases with an increase in wall thickness and a decrease in flow length, and this indicates that the reduction of injection pressure is not consistent for all the specimens. Thus, the current assumption is not valid, which is to consider a single value (20%) as the injection pressure reduction factor (**Figure 8**).

3.6 Correlation and regression analysis

The project's main aim is to find the linear relationship between the injection pressure of IM & ICM. Correlation analysis measures the linear relationship between two variables. It has a value between -1 and $+1$, where the result closer to these extremes

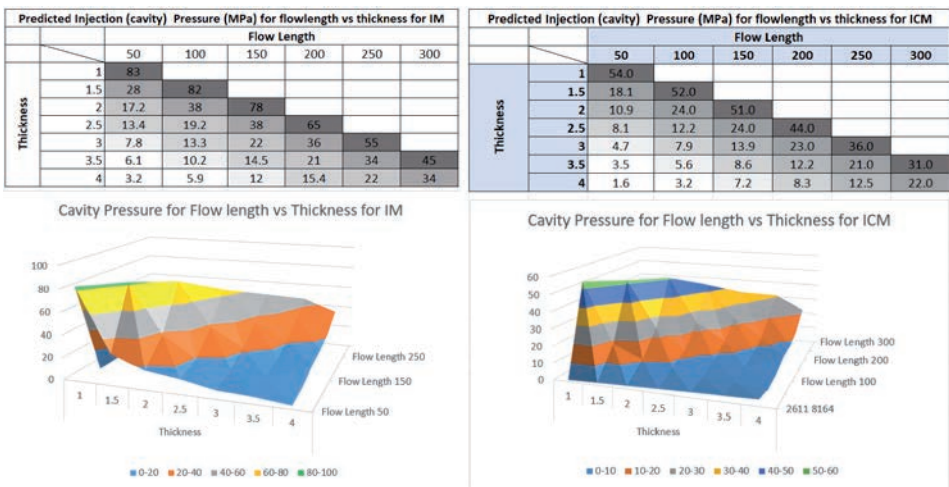


Figure 7.
Injection pressure comparison of the specimen within each process.

Predicted injection pressure (MPa) for flow length vs. thickness						
	50	100	150	200	250	300
1	65.06%					
1.5	64.64%	63.41%				
2	63.54%	63.04%	65.38%			
2.5	60.24%	63.62%	63.04%	67.69%	68.38%	
3	60.18%	59.17%	62.96%	63.89%	65.45%	69.66%
3.5	57.48%	55.06%	59.25%	58.06%	61.76%	68.89%
4	48.91%	53.79%	59.88%	54.21%	56.67%	64.71%

Table 3.
Percentage of injection pressure in ICM with respect to IM.

Predicted injection pressure (MPa) for flow length vs. thickness						
	50	100	150	200	250	300
1	34.94%					
1.5	35.36%	36.59%				
2	36.46%	36.96%	34.62%			
2.5	39.76%	36.38%	36.96%	32.31%	31.62%	
3	39.82%	40.83%	37.04%	36.11%	34.55%	30.34%
3.5	42.52%	44.94%	40.75%	41.94%	38.24%	31.11%
4	51.09%	46.21%	40.12%	45.79%	43.33%	35.29%

Table 4.
ICM vs. IM - The percentage difference.

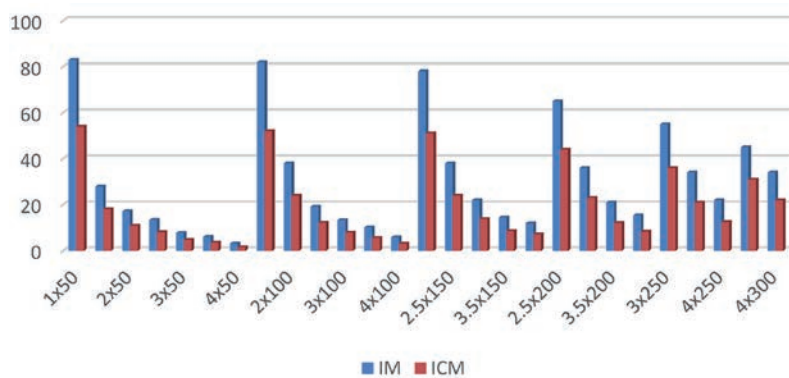


Figure 8.
Pressure comparison-IM vs. ICM.

indicates a strong correlation. A weak or no correlation exists if the value is closer to 0. IBM SPSS Statistics software is used to analyse the correlation between the injection pressures of IM & ICM. A strong positive correlation value of 0.999 is identified between IM & ICM.

Regression analysis is performed on the injection pressure data collected from both processes. Injection pressure recorded for the IM process for the samples is considered Predictors (Constant), and ICM is considered a dependent variable. The P-value identified is less than 0.001, which means the data is statistically significant.

A scattered graph (**Figure 9**) shows the relationship between the injection pressures on IM & ICM.

The regression equation derived for the positive correlation is
 $Y = a + bx = -0.88 + 0.66x$

$$ICM = -0.88 + 0.66(IM) \quad (1)$$

when simplified considering the acceptable deviation of ± 5 MPa,

$$ICM = 0.7(IM) - 0.9 \quad (2)$$

This equation is cross verified by calculating the injection pressure of ICM using the known pressure of IM for the simulated samples and compared with the simulated pressure of ICM for the respective samples as given in **Table 5**. The maximum difference observed between simulated results and pressure calculated using the regression equation is less than 1.12%, and this is generally acceptable for predicting injection pressure for ICM, which is expected to be within $\pm 5\%$.

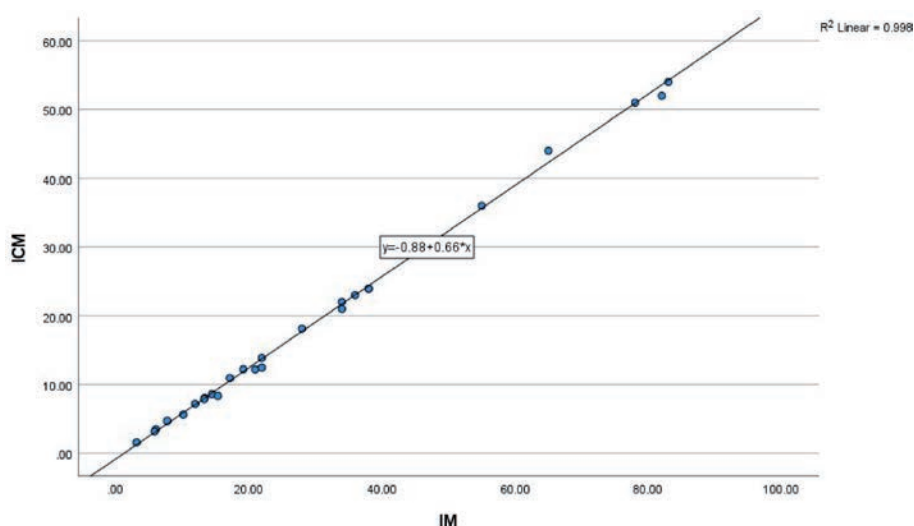


Figure 9.
Scatter plot with a linear relationship between injection pressures of IM & ICM.

FL_WT (mm)	IM (MPa)	Injection pressure		
		ICM (MPa)		
		MF analysis	Regression equation	Difference (%)
1 × 50	83.0	54.0	53.9	1.00
1.5 × 50	28.0	18.1	17.6	0.97
2 × 50	17.2	10.9	10.48	1.02
2.5 × 50	13.4	8.1	7.96	0.96
3 × 50	7.8	4.7	4.26	1.01
3.5 × 50	6.1	3.5	3.14	0.99
4 × 50	3.2	1.6	1.23	0.99
1.5 × 100	82.0	52.0	53.24	0.97
2 × 100	38.0	24.0	24.2	1.01
2.5 × 100	19.2	12.2	11.79	0.96
3 × 100	13.3	7.9	7.9	0.91
3.5 × 100	10.2	5.6	5.85	1.00
4 × 100	5.9	3.2	3.01	0.98
2 × 150	78.0	51.0	50.6	0.99
2.5 × 150	38.0	24.0	24.2	0.98
3 × 150	22.0	13.9	13.64	0.90
3.5 × 150	14.5	8.6	8.69	1.04
4 × 150	12.0	7.2	7.04	1.01
2.5 × 200	65.0	44.0	42.02	1.06
3 × 200	36.0	23.0	22.88	1.03
3.5 × 200	21.0	12.2	12.98	0.93
4 × 200	15.4	8.3	9.28	0.79
3 × 250	55.0	36.0	35.42	0.95
3.5 × 250	34.0	21.0	21.56	0.98
4 × 250	22.0	12.5	13.64	1.11
3.5 × 300	45.0	31.0	28.82	1.09
4 × 300	34.0	22.0	21.56	0.98

Table 5.
Injection pressure results' comparison-simulation vs. regression equation.

3.7 Result validation

To ensure an error-free prediction of the injection pressure of ICM from a known injection pressure of IM, it is essential to validate the relationship derived through the regression analysis. Current Moldflow® analyses use simple specimens of uniform wall thickness and simplified gate and runner systems. It is essential to test this in a live project to ensure the underlying objectives of the research are achieved. A prototype tool is used for validating the results.

The part to be moulded is of 2.5 mm wall thickness and a total flow length of 295 mm (**Figure 10**). While performing the simulation studies, the injection pressure generated for the IM process for the 2.5 x 300 mm part was 125 MPa. This specimen has not been considered for statistical analysis as the injection pressure exceeds the recommended acceptable range of 120 MPa. Process settings used for the simulation are adopted for the moulding trials. The prototype tool is manufactured so that IM, ICM & IECM processes can be trialled using the movable core feature, which is mechanically equipped within the mould.

To maintain the confidentiality with the customer project, excluding the customer emblem and key identification features, a model similar to the one used for manufacturing the prototype mould is first analysed for the conventional IM process using Autodesk Moldflow® software, applying the same process settings as the research specimens. Unlike the specimens analysed, this part does not have a uniform wall thickness all over the sections. So, a difference in injection pressure results compared to the specimens is expected. The pressure result obtained after Moldflow® analysis is recorded, and the maximum injection pressure observed is 137 MPa (**Figure 11**).

The prototype tool is prepared for the moulding trials of both IM and ICM processes. PC LEXAN™ Resin LS1 material is preheated per the manufacturer's recommendations, and the process settings are entered in the machine interface the same as the simulation. The conventional Injection Moulding process is first tried. Once the mould is well heated and after initial trial shots to stabilise the process, a few continuous shots are taken, and the resultant injection pressure is noted.

Observed average pressure = 1408 bar = 140.8 MPa.

The simulation result for the same prototype lens is 137 MPa, a difference of 10 MPa is observed between the simulation results and the actual. Though the trial results are expected to be closer to the simulation results, some variation is expected due to different factors, such as the mould and machine conditions.

The regression Eq. 1 is applied to the injection pressure results obtained through simulation and moulding trials.

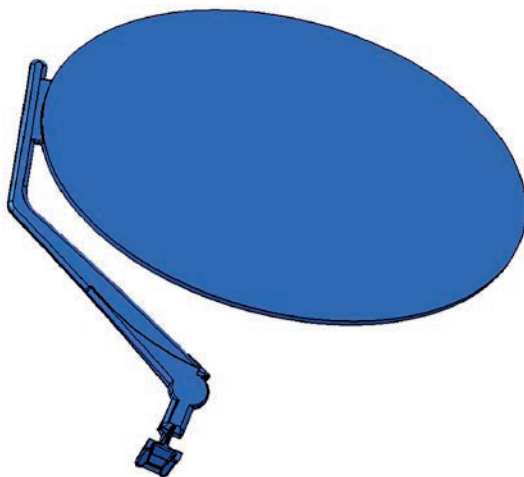


Figure 10.
Prototype lens (similar to the part designed for moulding trials).

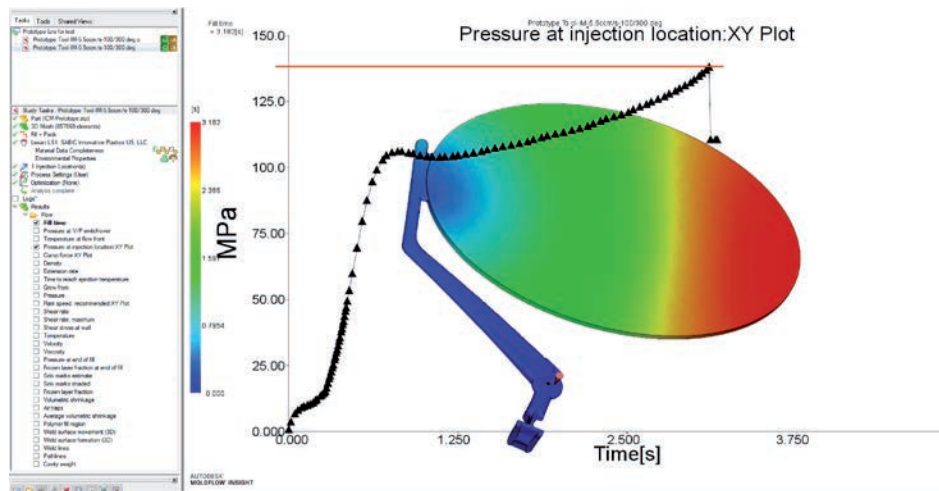


Figure 11.
Injection pressure plot for prototype lens.

$$ICM = 0.7(IM) - 0.9 \quad (3)$$

Using simulation results, $ICM_{(pressure)} = 0.7 \times 137 - 0.9 = 95 \text{ MPa}$

Using moulding trial results, $ICM_{(pressure)} = 0.7 \times 141 - 0.9 = 98 \text{ MPa}$

The machine setting is now changed to ICM, and the compression gap is set to 0.5 mm. Mould & melt temperatures, flow rate etc., are the same value as the IM process. After a couple of trial shots with ICM to stabilise the moulding process, a few continuous shots are taken, and the pressure result is noted.

Observed average pressure = 969 bar = 96.9 MPa

The injection pressure observed from the actual moulding is 97 MPa which is very close to the calculated injection pressure for the ICM process using the derived regression equation.

4. Conclusions

Several gaps identified after the literature review that justifies the ICM process are not well explored in the studies, and most of the studies directly focus on applying the ICM process to specific products. There is no detailed comparison study regarding the differences in Injection pressure, clamping force and shrinkage allowances between IM & ICM processes. The literature review also identified only a handful of mentions of the ICM process, and none of them compares it with IM process using PC LEXAN™ Resin LS1 material. Research on injection pressure has many limitations and are not addressing the conventional working mould temperature range of the IM or ICM process. Currently, no research identifies the injection pressure & compression pressure value and its distribution for ICM (which results in residual stress and warpage) and the clamping force required to select the appropriate moulding machine (tonnage). It is essential to understand the injection pressure distribution for the ICM process in comparison with conventional IM for PC material so that manufacturers can accurately predict them at the quotation stage of the project to select an

appropriate moulding process/machine. Further, understanding the correct injection pressure will help decide the minimum mouldable part wall thickness and flow length, thus enabling business to capture new projects on Automotive Radome Badges and HTL components.

This research uses Moldflow® simulations of specimens with various wall thickness and flow length combinations to capture their injection pressure results on both IM & ICM processes for PC LEXAN™ Resin LS1 material. The injection pressure values of both processes are compared to check the consistency in the pressure difference between both processes. It is identified that the variation in difference increases with an increase in wall thickness and a decrease in flow length. This indicates that the injection pressure reduction is inconsistent for all the specimens. Thus, the current assumption is to consider a single value (20%) as the injection pressure reduction factor at is found to be invalid. To derive the injection pressure of the ICM process with respect to the known injection pressure of the IM process, results obtained from Moldflow® analysis are statistically analysed using IBM SPSS statistics software. Correlation and Regression analysis performed using IBM SPSS Statistics software revealed a strong positive correlation value of 0.999 between IM & ICM. The regression equation is derived and cross-checked with the simulation results. The regression equation is finally validated by comparing the results obtained through injection moulding trials of a prototype tool.

This research aims to study the injection pressure of the ICM process to manufacture aesthetic automotive components. The research aimed to validate the current assumption of a 20% reduction in injection pressure of the ICM process compared to the IM process and found that this is not true in all cases. Research derived a regression equation that can calculate the injection pressure of the ICM process from the known injection pressure of the IM process for the same part, thus helping engineers in manufacturing sector, to predict the pressure accurately and select the suitable machine and process to manufacture the components. The findings of this study will take one giant step towards capturing the aesthetic automotive component market, especially for the Radome badges and the Hidden-unTil-Lit interior components. Understanding the injection pressure behaviour in the ICM process using PC LEXAN™ Resin LS1 material with respect to the conventional IM process will narrow the knowledge gap in applying the ICM process in aesthetic automotive components, and the results will further help in developing the plastic products, especially in the automotive sector which can be successfully moulded using ICM process. This study's findings will further support the research of clamping force, shrinkage, and other critical moulding factors, thus drawing a quantitative and reliable conclusion.

Although the results are significant regarding the injection pressure of the ICM process, the limitations of this study should also be acknowledged. The results are limited to a range of factors such as material, design constraints, sample range, processing conditions, the accuracy of simulations, boundary conditions etc. Further research considering these limitations will bridge the knowledge gap in the ICM process. Current research only considered the part with uniform wall thickness, though the moulding trial results confirmed that the results could be extended to those with non-uniform wall thickness. Further studies need to be done considering the variations in feed system designs which is another critical element that can influence the injection pressure results. This result's findings can also facilitate research on IECM to produce the same product with improved product quality. Experimental assessment of simulation results could be extended to a broader range of products to consider these variables mentioned above and improve the accuracy of the current findings.

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Smart Supply Chain Systems Subject to Design Change

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Abstract

The smart supply chain system is a complex distributed cyber-physical system (CPS) that includes a multitude of unmodeled dynamics and uncertainties. The system's structure and parameters are highly vulnerable to changes due to significant demand fluctuations and unexpected network events. Consequently, product design modifications are crucial for maintaining the stability of the synchronous evolution system, fulfilling customer requirements, and ensuring economic efficiency. This chapter investigates the emergency change control issue of distributed CPS-based PSCSES under deny of service (DoS) attacks. Firstly, an emergency change compensation mechanism is proposed, featuring a Recurrent Neural Networks (RNN)-based predictor to counteract inventory data loss due to cyberattacks. Secondly, by employing game theory, the H_∞ consensus control problem is recast as a multiplayer zero-sum graph game, and a Q-learning-based H_∞ consensus control protocol is designed to derive sufficient conditions so that the system consensus can be guaranteed. The bullwhip effects, which are resulted by customer demand and design changes, are also analyzed. Thirdly, the strategy iteration algorithm is utilized to resolve the online solution for controller design under unknown models. Lastly, the effectiveness of the proposed method is demonstrated by simulation study.

Keywords: cyberattack, data driven, supply chain systems, change control design, multi-agent

1. Introduction

A smart supply chain system consists of various enterprises such as suppliers, manufacturers, distributors, and retailers that serve the production, design, and distribution of products. By controlling the information, materials, and capital flows, these systems transform raw materials into finished products and deliver them to consumers, which play the role of a distributed networked control system (NCS) [1]. With the rapid development of artificial intelligence technology, the manufacturing industry is gradually transforming to collaborative intelligent manufacturing from automated manufacturing. As a support for the national intelligent manufacturing major project, smart supply chain systems have broad application prospects in fields such as power supply, intelligent manufacturing, bio-pharmaceuticals, and food processing [2–5].

Traditional smart supply chain systems are primarily demand-driven, using dedicated channels for data transmission. During their operation, they often experience slow logistics, untimely information transfer, and an inability to achieve customized production, which leads to inventory backlogs due to inaccurate production design, resulting in very low resource utilization rates [6]. Thanks to the rapid development of big data and artificial intelligence technologies, smart supply chain systems are beginning to transform into digital, intelligent, and organizable systems, becoming cyber-physical systems that integrate data-driven approaches, comprehensive computing, and network communication [7]. Considering that complex products are made up of various components, each of which is often produced by different sub-chains, the smart supply chain system can be viewed as a complex multi-agent system composed of multiple sub-chains [8]. Based on cyber-physical systems and multi-agent technology, smart supply chain systems can achieve demand-oriented customized production, real-time production monitoring, and intelligent warehousing, thereby greatly reducing the phenomenon of excessive commodity inventory, simplifying the production process, and improving business efficiency.

Cyber-physical system-based smart supply chain systems offer significant convenience for the production and sales of complex products with their reliable, efficient, and real-time collaborative advantages. However, the introduction of a large number of network devices makes these systems more susceptible to malicious cyberattacks. In recent years, frequent cyberattack incidents have caused severe economic losses to enterprises. For example, on June 8, 2020, the server of the Japanese car manufacturer Honda was attacked by the industrial ransomware *Ekans*, leading to partial production system interruptions [9]. Such cybersecurity events indicate that smart supply chain systems have become major targets for cyberattacks, and frequent cyberattacks can cause severe economic losses to the enterprises in the system and may even endanger social stability and national development. Therefore, improving the emergency response capability and stability of smart supply chain systems under sudden cyberattack incidents is of great practical significance.

Cyberattacks on CPS-based smart supply chain systems are mainly divided into two categories: integrity attacks and availability attacks. Integrity attacks aim to reduce system reliability and security by tampering with the information in the transmitted data packets; availability attacks, on the other hand, block the normal transmission of data and control commands between various parts of the CPS, causing some services of the system to be suspended or even paralyzed [10–12]. DoS attacks belong to the category of availability attacks, where attackers occupy communication or device resources to prohibit data transmission, causing the loss of normal data packets in the communication channel [13], thereby weakening or destroying network services with great destructive power. Therefore, if the data packet loss issue under DoS attacks is not effectively handled, it may lead to network collapse and, in more severe cases, may even damage the physical system [14–18]. At present, a large number of effective studies have been carried out by researchers to address system security issues caused by DoS attacks, mainly from the following aspects:

1. Study the optimal DoS attack timing from the attacker's perspective, such as Zhang and others, [19] who studied the optimal attack scheduling of energy-constrained DoS jammers in CPS. They considered the following situation: sensors send data packets to remote estimators through wireless channels, and DoS jammers launch jamming attacks to increase the possibility of data packet loss in the wireless channel. Within a limited time, the DoS jammer with limited

energy budget can only launch n attacks, and the strategy of continuous attacks can achieve the best attack effect. In the literature [20], Zhang and others further studied the periodic attack strategy of the DoS jammer, that is, attacking the wireless channel for n units during the active period, and then moving to the inactive period to replenish its energy for the next attack period, and extended the optimal attack plan to NCS with multiple subsystems.

2. Study effective control strategies from the defender's perspective, such as Foroush et al. [21] who studied the secure control of CPS in response to periodic DoS interference attacks encountered in the control channel and proposed an energy-constrained DoS interference model, using periodic attack strategies to destroy the quality of the communication channel. To counter the impact of DoS interference attacks, sufficient conditions for ensuring the asymptotic stability of CPS were given under the known part of the attack strategy. In the literature [22], by choosing different frequency and duration values, an energy-budget-constrained DoS periodic attack strategy was proposed, and the stability of CPS under DoS attacks was studied.
3. Study the confrontation between defenders and denial-of-service attackers based on game theory methods, such as the literature [23], which defined a random variable a_i^k according to the Bernoulli distribution to represent the impact of attacks on the control channel, and proposed a resilient control method using game theory to resist DoS interference attacks in CPS. Zhao and others [24] studied the case where both DoS jammers and triggers have limited energy and obtained the optimal strategies for both parties using a fully informed zero-sum game.

It is not difficult to find from the above research results that, although extensive research has been conducted on CPS-based secure control issues, there is still a lack of research on DoS attack defense strategies for distributed CPS and smart supply chain systems with unknown models. Conducting emergency change defense strategies for smart supply chain systems based on DoS attacks is one of the main tasks of this study.

To overcome the dependence of controller design on the model, model-free data-driven control research has attracted extensive attention from the academic community in recent years and has achieved rich results [25–36]. Data-driven control has been widely used in fields such as intelligent transportation, aerospace, and intelligent manufacturing, such as [31, 37, 38]. In the literature [29], a distributed model-free adaptive iterative learning control method was used to solve the consensus tracking problem of a class of unknown nonlinear multi-agent systems. The literature [35] proposed a fault-tolerant model-free adaptive control scheme to solve the tracking problem of a class of single-input single-output nonlinear NCS under DoS attacks. In recent years, with the development of artificial neural network technology, a new type of data-driven technology has been widely applied to system identification, algorithm design, and other fields, providing new solutions for model-free control, such as [28, 30] which applied neural network technology to system identification, effectively avoiding the dependence on the mechanism model. However, the errors caused by system identification based on neural networks have brought new uncertainties to controller design, thereby reducing system performance. To overcome the errors brought by neural networks used for system identification, reinforcement Q-learning, as an effective method to solve model-free problems, has been widely used

[25, 32, 39, 40]. For example, the literature [39] used Q-learning to solve the model-free H_∞ control problem, but model-free control based on multi-agent and cyberattacks needs further research. Reference [40] designed a policy iteration-based Q-learning algorithm to achieve consensus control of multi-agent systems, but did not give enough consideration to cyberattacks and disturbance problems. It is worth noting that as an important distributed CPS, smart supply chain systems have a large number of unmodeled dynamics and uncertainties, and drastic demand fluctuations and sudden network events, such as supply chain disruptions caused by trade wars and supply chain blockages caused by COVID-19, make the system structure and parameters highly susceptible to changes. Product design changes are an important means to maintain the stability of smart supply chain systems, meet user needs, and ensure economic efficiency. How to use data-driven technology to design emergency change compensation mechanisms to solve the change control of product and supply chain systems under DoS attacks is another important research task of this chapter.

This chapter studies the emergency change control problem of distributed CPS-based smart supply chain systems under DoS attacks. For the situation where the sensor-controller communication channel of the collaborative evolution system is attacked by DoS, a data-driven technology is used to design an emergency defense change mechanism based on historical data and reference information. By using zero-sum differential graph game theory and reinforcement Q-learning technology, an H_∞ consensus controller is designed to ensure that the smart supply chain system achieves leader-follower H_∞ consensus under DoS attack-induced design changes and can suppress the bullwhip effect brought by uncertain demand and design changes (that is, the phenomenon of uncertain customer demand information being amplified step by step from the bottom to the top of the supply chain [41]), while ensuring that the system has a certain level of product adaptability and user satisfaction. The main contributions of this chapter are as follows: first, an emergency change compensation mechanism is designed using historical data and reference information; that is, when DoS attacks cause inventory state data loss, an RNN-based inventory forecaster is designed using the historical data in the buffer to compensate for the loss of inventory data; second, by combining zero-sum dynamic graph games, optimal control, and reinforcement learning theory, the optimal consensus production rate is obtained, that is, according to the inventory tracking error performance index function, the Bellman equation is derived, and the continuous-time HJI equation is obtained using the Bellman optimality principle, thereby obtaining the optimal production rate and the worst-case uncertain demand. It is worth noting that the HJI equation is usually difficult to obtain an analytical solution, so we introduce the policy iteration-based Q-learning method to solve the H_∞ consensus controller; finally, the effectiveness of the proposed method is verified through simulation examples.

2. Prerequisite knowledge and problem description

2.1 Prerequisite knowledge

$\mathcal{G} = (V, E, \mathcal{A})$ is a directed graph, where $V = \{\nu_1, \nu_2, \dots, \nu_N\}$ and $E = \{a_{ij} = (\nu_i, \nu_j)\} \in V \times V$ represent a finite, non-empty set of N nodes and a set of edges, respectively. $\mathcal{A} = [a_{ij}]$ is a weighted adjacency matrix with adjacency elements $a_{ij} \geq 0$. For the i th and j th nodes in graph $\mathcal{G}$, if $a_{ij} = (\nu_j, \nu_i) \in E$, then $a_{ij} > 0$ (indicating

that node i can receive information from node j), otherwise $a_{ij} = 0$. If node i can receive information sent by node j , then node j is called a neighbor of node i and the set of neighbor nodes of node j can be represented as $N_i = \{\nu_j : (\nu_j, \nu_i) \in E\}$. If there is a node in the graph that can reach any other node through a directed path, then the graph is said to contain a spanning tree. Let $\mathcal{D} = \text{diag}\{d_i\}$ represent the in-degree matrix of the graph, where $d_i = \sum_{j \in N_i} a_{ij}$ represents the in-degree of node i . The

Laplacian matrix of the graph can be defined as $L = \mathcal{D} - \mathcal{A}$.

2.2 Problem description

Consider a supply chain configured for the production of a certain product, composed of N sub-chains that produce collaboratively. Assume the dynamics of the i th sub-chain are given by:

$$\begin{cases} \dot{x}_i(t) = Ax_i(t) + Bu_i(t) + D\bar{w}_i(t), \\ y_i(t) = Cx_i(t) \end{cases} \quad (1)$$

where $x_i(t)$, $u_i(t)$, $\bar{w}_i(t)$, and $y_i(t)$ represent the production inventory state, production rate, user demand, and current finished product output of the i th sub-chain, respectively. From the perspective of control theory, $x_i(t)$, $u_i(t)$, $\bar{w}_i(t)$, and $y_i(t)$ are the state variables, control inputs, external disturbances, and system outputs of the i th sub-chain at time t . A , B , and C are system matrices and are unknown. Without loss of generality, based on practical experience, the uncertain user demand $\bar{w}_i(t)$ can be decomposed into constant demand d and energy-limited demand $\omega_i(t)$, that is, $\omega_i(t) \in L_2[0, \infty)$.

Remark 1. A product is usually composed of several components, each of which requires corresponding raw material supply. Therefore, a change in a component usually accompanies a corresponding change in the supply chain. On the other hand, if the supply chain changes, it may also lead to changes in the product components, that is, the product design needs to be changed. For this reason, we call such interrelated systems smart supply chain systems.

Consider that there is a chain leader in the smart supply chain system, and the sub-chains need to adjust their own inventory state according to the changes in the inventory state of the chain leader and neighboring supply chains. It is assumed that the dynamics of the chain leader are given by the following equation:

$$\dot{x}_0(t) = Ax_0(t) + Dd \quad (2)$$

where $x_0(t)$ is the inventory demand target, that is, the tracking target for the inventory state of the sub-chains. Considering some limiting factors in the actual production process, the following assumptions are made:

Assumption 1. The production rate $u_i(t)$ will have an upper limit $u_{\max}$, that is, $0 \leq u_i(t) \leq u_{\max}$.

Assumption 2. In the actual storage environment, the inventory capacity is limited. Therefore, it is assumed that the inventory level satisfies $0 \leq x_i(t) \leq x_{\max}$. Here, $x_{\max}$ represents the maximum storage capacity of the i th sub-supply chain.

In the supply chain system, when the inventory state $x_i(t)$ of the i th sub-chain is transmitted to the distributed control center, if the sensor-to-controller (S-C) channel

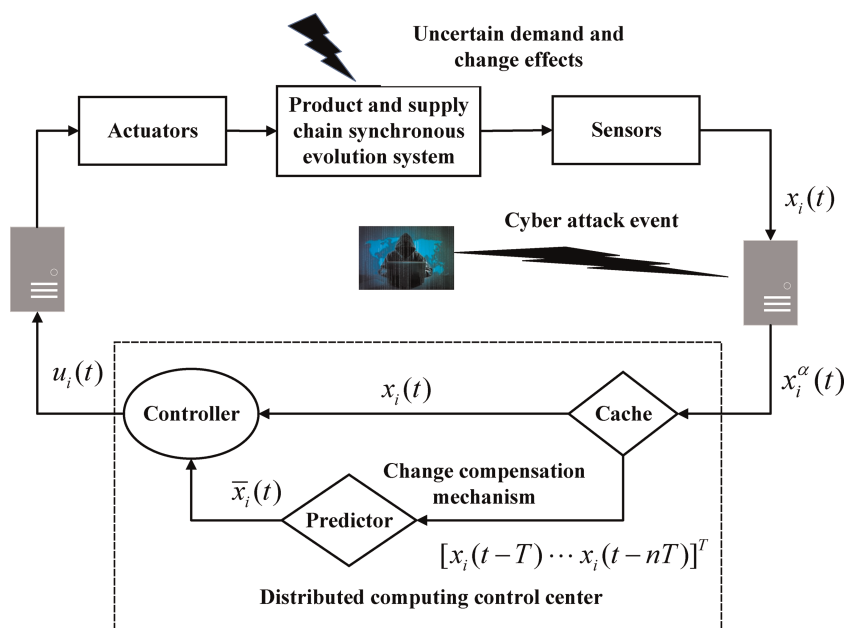


Figure 1.
Diagram of change mechanism under cyberattack.

is attacked by DoS, data packet loss may occur, as shown in **Figure 1**, T is a very small sampling time, $\bar{x}_i(t)$ is the inventory state of the i th sub-chain after change compensation, and the inventory state $x_i^\alpha(t)$ of the i th sub-chain that the distributed control center can obtain can be expressed as

$$x_i^\alpha(t) = \alpha(t)x_i(t) + (1 - \alpha(t))\bar{x}_i(t) \quad (3)$$

where $\alpha(t) \in \{0, 1\}$, $\alpha(t) = 0$ represents the occurrence of a network attack event, that is, the S-C channel is attacked by DoS, $\alpha(t) = 1$ represents that no network attack event has occurred, that is, the S-C channel can transmit data normally. Without loss of generality, the following assumptions are made about the DoS attack.

Assumption 3. The number of continuous attacks by the network attacker is limited, that is, the maximum number of continuous packet losses caused by the network attack is bounded and denoted as $\bar{n}_i^\alpha$.

Assumption 4. The network attacker only launches attacks against sub-chains.

This chapter starts from the perspective of actively preventing DoS attacks and designs a reasonable change mechanism to compensate for the loss of data packets caused by the attack. Since the system is affected by uncertain demand and the change mechanism may trigger the bullwhip effect, it is necessary to further design an H_∞ controller based on optimal control to suppress the bullwhip effect caused by uncertain demand and the change mechanism, thereby ensuring that the inventory state $x_i(t)$ of the sub-chains can still be consistent with the inventory state $x_0(t)$ of the chain leader under DoS attacks. First, from (1) and (2), the local neighborhood inventory synchronization error of each sub-chain can be defined as follows

$$\delta_i(t) = \sum_{j \in N_i} a_{ij} (x_i^\alpha(t) - x_j^\alpha(t)) + g_i (x_i^\alpha(t) - x_0(t)), \quad (4)$$

where $g_i \geq 0$ is the traction gain of sub-chain i . If there is a directed path between the i th sub-chain and the chain leader, $g_i > 0$, otherwise, $g_i = 0$. The global inventory synchronization error vector of the sub-chains can be expressed as

$$\delta(t) = ((L + G) \otimes I_n)(x^\alpha(t) - \bar{x}_0(t)), \quad (5)$$

where the global inventory synchronization error vector is $\delta(t) = [\delta_1^T(t), \delta_2^T(t), \dots, \delta_N^T(t)]^T$, the global inventory state vector is $x^\alpha(t) = [(x_1^\alpha(t))^T, (x_2^\alpha(t))^T, \dots, (x_N^\alpha(t))^T]^T \in \mathbb{R}^{Nn}$, $L = [l_{ij}] \in \mathbb{R}^{N \times N}$ is the Laplacian matrix of the directed topology graph; $G = [g_{ij}] \in \mathbb{R}^{N \times N}$ is a diagonal matrix with traction gains as diagonal elements ($g_{ii} = g_i$), which shows the connection relationship between the supply chain leader and each sub-chain; I_n is the n -dimensional identity matrix, $\bar{x}_0(t) = \underline{I}x_0(t)$, $\underline{I} = \underline{1} \otimes I_n$, $\underline{1}$ is an N -dimensional vector with elements of 1, that is, $\bar{x}_0(t) = [x_0^T(t), x_0^T(t), \dots, x_0^T(t)]^T \in \mathbb{R}^{Nn}$.

Assume that the topology of the smart supply chain system includes a spanning tree, so the inventory tracking error of the i th sub-chain can be denoted as $\eta_i(t) = x_i^\alpha(t) - x_0(t)$, and the global inventory tracking error can be obtained as $\eta(t) = x^\alpha(t) - \bar{x}_0(t)$. Furthermore, the relationship between the global inventory tracking error vector and the global synchronization inventory error vector can be expressed as

$$\delta(t) = ((L + G) \otimes I_n)\eta(t). \quad (6)$$

Lemma 1. Assume that $(L + G)$ is a non-singular matrix, the range of the global inventory tracking error $\eta(t)$ is

$$\|\eta\| \leq (\lambda_{\min}(L + G))^{-1} \|\delta\|, \quad (7)$$

where $\lambda_{\min}(L + G)$ is the smallest singular value of the matrix $(L + G)$.

Lemma 1 indicates that when $(L + G)$ is a non-singular matrix, by reducing the global synchronization inventory error vector, the global inventory tracking error vector can be made arbitrarily small, that is, $\|\delta(t)\| \rightarrow 0 \leftrightarrow \|\eta(t)\| \rightarrow 0_s$, which also indicates that the inventory state of each sub-chain is consistent with that of the chain leader.

Remark 2. If the graph $\mathcal{G}$ contains a spanning tree and for a root node, its traction gain $g_i \neq 0$, then $(L + G)$ is a non-singular matrix.

According to (4), the dynamics of the local neighborhood synchronization inventory error of the i th sub-chain can be defined as

$$\dot{\delta}_i(t) = \sum_{j \in N_i} a_{ij} (\dot{x}_i^\alpha(t) - \dot{x}_j^\alpha(t)) + g_i (\dot{x}_i^\alpha(t) - \dot{x}_0(t)), \quad (8)$$

Therefore, combining with (1), we can further obtain

$$\dot{\delta}_i(t) = A\delta_i(t) - \sum_{j \in N_i} a_{ij} Bu_j(t) + (d_i + g_i)Bu_i(t) - \sum_{j \in N_i} a_{ij} D\omega_j(t) + (d_i + g_i)D\omega_i(t). \quad (9)$$

According to (9), it can be seen that the synchronization inventory error of each sub-chain can be represented as a dynamic system driven by the control actions of

itself and all adjacent sub-chains, with uncertain user demand. Therefore, the consensus problem of the supply chain system is transformed into designing a reasonable production rate to minimize the local neighborhood synchronization inventory error $\delta_i(t)$ under uncertain user demand and change mechanism, and then according to Lemma 1, it can be ensured that the inventory of the chain leader and all sub-chains tends to be synchronized, and the production rate can make each agent shown in (1) satisfy the following definition:

Definition 1. The smart supply chain system (1) is said to be able to suppress the bullwhip effect at the $\gamma > 0$ (γ is the constant to be optimized) level if it meets the following H^∞ consensus condition:

1. When the uncertain demand $\omega_i(t) = 0$, the system can be designed to meet $\lim_{t \rightarrow \infty} \|x_0(t) - x_i(t)\| = 0$ with a reasonable production rate;
2. When the uncertain market demand satisfies $\omega_i(t) \neq 0$, if each sub-chain satisfies the following bullwhip effect suppression condition

$$\begin{aligned} \int_0^T \|z_i(t)\|^2 dt &= \int_0^T \left(\delta_i^T Q_{ii} \delta_i + u_i^T R_{ii} u_i + \sum_{j \in N_i} u_j^T R_{ij} u_j \right) dt \\ &\leq \gamma^2 \int_0^T \left(\omega_i^T T_{ii} \omega_i + \sum_{j \in N_i} \omega_j^T T_{ij} \omega_j \right) dt + \beta(\delta_i(0)), \end{aligned} \quad (10)$$

then the smart supply chain system is said to be able to suppress the bullwhip effect at the γ level. Here $v_i(t) = [\omega_i^T(t), \omega_j^T(t)]^T$; the performance output $z_i(t) = [\delta_i^T(t), u_i^T(t), u_j^T(t)]^T$; $Q_{ii} \geq 0$, $R_{ii} > 0$, $R_{ij} \geq 0$, $T_{ii} > 0$ and $T_{ij} > 0$ are positive definite symmetric weight matrices; β is a bounded function and satisfies $\beta(0) = 0$. Let $\gamma_{\min}$ be the minimum value of γ . For any $\gamma \geq \gamma_{\min}$, (10) holds. For convenience of expression, $u_j(t)$, $\omega_j(t)$, $\delta_j(t)$ and so on are abbreviated as u_j , ω_j , δ_j in the following text without causing misunderstanding.

3. Zero-sum graph game and model-free solution for smart supply chain systems under cyberattack

In this section, first, the current inventory state is predicted based on the historical inventory state data with time characteristics to solve the change design problem caused by data packet loss in the sensor-controller (S-C) network communication channel under DoS attack; second, the consistency problem of the smart supply chain system under change and uncertain demand is solved by using the concept of zero-sum graph game; finally, the game solution is solved by the model-free Q-learning algorithm, and the optimal production rate and the worst-case uncertain demand are determined.

3.1 RNN inventory state predictor under CyberAttack

An RNN-based inventory state predictor is designed, that is, the number of continuous packet losses that occurred before time t is defined as $n_a(t - T)$. If $x(t)$ is

successfully transmitted at time t , then $n_\alpha(t - T) = 0$. Obviously, $0 \leq n_\alpha(t) \leq \bar{n}_\alpha$. Thus, at time t , the latest inventory state that the distributed control center can obtain is

$$x_i^\alpha(t) = x(t - n_\alpha(t - T)), \quad (11)$$

Then the historical inventory state data that the distributed control center can obtain is $X(t) = [x(0), x(T), \dots, x_i^\alpha(t)]$. If a packet loss occurs due to an attack on the S-C communication channel at time t , the current inventory state data $\bar{x}_i(t)$ is predicted based on the historical inventory state data X using the predictor, that is

$$\begin{aligned} h(t) &= f(U \cdot X(t) + W \cdot h(t - T)), \\ \bar{x}_i(t) &= g(V \cdot h(t)), \end{aligned} \quad (12)$$

where h is the hidden layer, U , V , and W represent the ideal weights of the input layer, output layer, and hidden layer, respectively; $f(\cdot)$ and $g(\cdot)$ are the activation functions of the hidden layer and output layer, respectively.

Remark 3. The learning method of the Recurrent Neural Network (RNN) adopts the gradient descent method (as in [42]). Due to space limitations, it will not be discussed further here.

3.2 Zero-sum graph game and coupled HJI equation and Nash equilibrium

First, the following performance index function is designed for the i th sub-chain

$$\begin{aligned} J_i(\delta_i(0), u_i, u_{-i}, \omega_i, \omega_{-i}) &= \frac{1}{2} \int_0^\infty \left(\delta_i^T Q_{ii} \delta_i + u_i^T R_{ii} u_i + \sum_{j \in N_i} u_j^T R_{ij} u_j \right. \\ &\quad \left. - \gamma^2 \omega_i^T T_{ii} \omega_i - \gamma^2 \sum_{j \in N_i} \omega_j^T T_{ij} \omega_j \right) dt. \end{aligned} \quad (13)$$

Based on (13), the value function of the i th sub-chain is defined as

$$V_i(\delta_i(t)) = \frac{1}{2} \int_t^\infty \left(\delta_i^T Q_{ii} \delta_i + u_i^T R_{ii} u_i + \sum_{j \in N_i} u_j^T R_{ij} u_j - \gamma^2 \omega_i^T T_{ii} \omega_i - \gamma^2 \sum_{j \in N_i} \omega_j^T T_{ij} \omega_j \right) dt. \quad (14)$$

In this chapter, the production rate and uncertain demand can be regarded as two sides of the game. Then, the consistency of the supply chain system is equivalent to solving the following zero-sum differential graph game problem of the supply chain system

$$V_i(\delta_i(0)) = \min_{u_i} \max_{\omega_i} J_i(\delta_i(0), u_i, u_j, \omega_i, \omega_j). \quad (15)$$

If there exists a saddle point (u_i^*, ω_i^*) , then the game has a unique solution, that is

$$V_i^* = \min_{u_i} \max_{\omega_i} J_i(\delta_i(0), u_i, u_j^*, \omega_i, \omega_j^*) = \max_{\omega_i} \min_{u_i} J_i(\delta_i(0), u_i, u_j^*, \omega_i, \omega_j^*), \quad (16)$$

which is equivalent to the following Nash equilibrium condition

$$J_i(u_i^*, u_j^*, \omega_i, \omega_j^*) \leq J_i(u_i^*, u_j^*, \omega_i^*, \omega_j^*) \leq J_i(u_i, u_j^*, \omega_i^*, \omega_j^*). \quad (17)$$

According to the Leibniz formula and the Bellman equation, an Hamiltonian function equivalent to (14) can be obtained ($V_i(0) = 0$)

$$\begin{aligned} & H_i\left(\delta_i, \frac{\partial V_i}{\partial \delta_i}, u_i, u_j, \omega_i, \omega_j\right) \\ & \equiv \frac{\partial V_i^T}{\partial \delta_i} \left(A\delta_i - \sum_{j \in N_i} a_{ij} B u_j + (d_i + g_i) B u_i - \sum_{j \in N_i} a_{ij} D \omega_j + (d_i + g_i) D \omega_i \right) \\ & + \frac{1}{2} \delta_i^T Q_{ii} \delta_i + \frac{1}{2} u_i^T R_{ii} u_i + \frac{1}{2} \sum_{j \in N_i} u_j^T R_{ij} u_j - \frac{1}{2} \gamma^2 \omega_i^T T_{ii} \omega_i - \frac{1}{2} \gamma^2 \sum_{j \in N_j} \omega_j^T T_{ij} \omega_j = 0. \end{aligned} \quad (18)$$

The stability condition can be obtained as

$$0 = \frac{\partial H_i}{\partial u_i} \Rightarrow u_i = -(d_i + g_i) R_{ii}^{-1} B^T \frac{\partial V_i}{\partial \delta_i}, \quad (19)$$

$$0 = \frac{\partial H_i}{\partial \omega_i} \Rightarrow \omega_i = \frac{1}{\gamma^2} (d_i + g_i) T_{ii}^{-1} D^T \frac{\partial V_i}{\partial \delta_i}, \quad (20)$$

Substitute the control strategy (19) and disturbance strategy (20) into (18) to obtain the following coupled HJI equation ($V_i(0) = 0$)

$$\begin{aligned} & \frac{\partial V_i^T}{\partial \delta_i} A_i^c + \frac{1}{2} \delta_i^T Q_{ii} \delta_i + \frac{1}{2} (d_i + g_i)^2 \frac{\partial V_i^T}{\partial \delta_i} B R_{ii}^{-1} B^T \frac{\partial V_i}{\partial \delta_i} - \frac{1}{2\gamma^2} (d_i + g_i)^2 \frac{\partial V_i^T}{\partial \delta_i} D T_{ii}^{-1} D^T \frac{\partial V_i}{\partial \delta_i} \\ & + \frac{1}{2} \sum_{j \in N_i} (d_i + g_i)^2 \frac{\partial V_j^T}{\partial \delta_j} B R_{jj}^{-1} R_{ij} R_{jj}^{-1} B^T \frac{\partial V_j}{\partial \delta_j} - \frac{1}{2\gamma^2} \sum_{j \in N_i} (d_i + g_i)^2 \frac{\partial V_j^T}{\partial \delta_j} D T_{jj}^{-1} T_{ij} T_{jj}^{-1} D^T \frac{\partial V_j}{\partial \delta_j} = 0, \end{aligned} \quad (21)$$

where

$$\begin{aligned} A_i^c &= A\delta_i - (d_i + g_i)^2 B R_{ii}^{-1} B^T \frac{\partial V_i}{\partial \delta_i} + \sum_{j \in N_i} a_{ij} (d_i + g_i) B R_{jj}^{-1} B^T \frac{\partial V_j}{\partial \delta_j} + \frac{1}{\gamma^2} (d_i + g_i)^2 D T_{ii}^{-1} D^T \frac{\partial V_i}{\partial \delta_i} \\ & - \frac{1}{\gamma^2} \sum_{j \in N_i} a_{ij} (d_i + g_i) D T_{jj}^{-1} D^T \frac{\partial V_j}{\partial \delta_j}. \end{aligned}$$

For a given solution V_i , define $u_i^* = u_i(V_i)$, $u_j^* = u_j(V_j)$, $\omega_i^* = \omega_i(V_i)$, and $\omega_j^* = \omega_j(V_j)$, then (21) can be rewritten as

$$H_i\left(\delta_i, \frac{\partial V_i}{\partial \delta_i}, u_i^*, u_j^*, \omega_i^*, \omega_j^*\right) = 0, \quad V_i(0) = 0. \quad (22)$$

The value function of the i th sub-chain can be further written in the form of a quadratic, that is

$$V_i(\delta_i) = \frac{1}{2} \delta_i^T P_i \delta_i, \quad (23)$$

where P_i is a positive definite symmetric matrix, and further

$$\begin{aligned} & \delta_i^T P_i \bar{A}_i^c + (\bar{A}_i^c)^T P_i \delta_i + \sum_{j \in N_i} (d_i + g_i)^2 \delta_j^T P_j B R_{jj}^{-1} R_{ij} R_{jj}^{-1} B^T P_j \delta_j - \gamma^2 (d_i + g_i)^2 \delta_i^T P_i T_{ii}^{-1} P_i \delta_i \\ & + \delta_i^T Q_{ii} \delta_i + (d_i + g_i)^2 \delta_i^T P_i B R_{ii}^{-1} B^T P_i \delta_i - \gamma^2 \sum_{j \in N_i} (d_i + g_i)^2 \delta_j^T P_j T_{jj}^{-1} T_{ij} T_{jj}^{-1} P_j \delta_j = 0, \end{aligned} \quad (24)$$

where

$$\begin{aligned} \bar{A}_i^c &= A \delta_i - (d_i + g_i)^2 B R_{ii}^{-1} B^T P_i \delta_i + \sum_{j \in N_i} a_{ij} (d_i + g_i) B R_{jj}^{-1} B^T P_j \delta_j \\ &+ \frac{1}{\gamma^2} (d_i + g_i)^2 D T_{ii}^{-1} D^T P_i \delta_i - \frac{1}{\gamma^2} \sum_{j \in N_i} a_{ij} (d_i + g_i) D T_{jj}^{-1} D^T P_j \delta_j. \end{aligned}$$

According to (24), (19), and (20), they can be further expressed as

$$u_i = -(d_i + g_i) R_{ii}^{-1} B^T P_i \delta_i, \quad (25)$$

$$\omega_i = \frac{1}{\gamma^2} (d_i + g_i) T_{ii}^{-1} D^T P_i \delta_i. \quad (26)$$

Remark 4. (24) is highly coupled and usually difficult to solve directly, and the solution of (25) and (26) must know the system matrix, so a model-free solution algorithm based on Q-learning will be provided in the following text.

Lemma 2. If the production strategy of adjacent sub-chains and the strategy of uncertain demand are optimal, then for each u_i, ω_i , the following (27) is satisfied

$$H_i \left(\delta_i, \frac{\partial V_i}{\partial \delta_i}, u_i, u_i^*, \omega_i, \omega_i^* \right) = \frac{1}{2} (u_i - u_i^*)^T R_{ii} (u_i - u_i^*) - \frac{1}{2} \gamma^2 (\omega_i - \omega_i^*)^T T_{ii} (\omega_i - \omega_i^*). \quad (27)$$

3.3 Inventory synchronization and Nash solution of smart supply chain system under graph game

3.3.1 Inventory synchronization of smart supply chain system

This section will prove that the production rate obtained by solving the coupled associated HJI equation can make the smart supply chain system suppress the bullwhip effect at the γ level and achieve synchronization with the leader.

Theorem 1. For the smart supply chain system (1), assuming conditions (1)–(4) are met, if there exists a positive definite function $V_i (i \in N)$ satisfying the HJI (21), that is, there exists a smooth positive definite solution $V_i^* > 0 (i \in N)$, making the production strategy and uncertain demand strategy of adjacent sub-chains optimal, then the production rate $u_i^* = u_i(V_i^*)$ can ensure that sub-chain i can achieve synchronization with the leader's inventory and suppress the bullwhip effect at the γ level.

Proof: Assume that $V_i^*(\delta_i(k))$ satisfies the coupled HJI equation shown in (24), and the adjacent sub-chains of sub-chain i satisfy $u_{-i} = u_{-i}^*, \omega_j = \omega_j^*$. According to Lemma 2, we have

$$\begin{aligned} & H_i\left(\delta_i, \frac{\partial V_i^*}{\partial \delta_i}, u_i, u_j, \omega_i, \omega_j\right) \\ &= \frac{dV_i^*}{dt} + \frac{1}{2}\delta_i^T Q_{ii}\delta_i + \frac{1}{2}u_i^T R_{ii}u_i + \frac{1}{2}\sum_{j \in N_i} u_j^T R_{ij}u_j - \frac{1}{2}\gamma^2 \omega_i^T T_{ii}\omega_i - \frac{1}{2}\gamma^2 \sum_{j \in N_i} \omega_j^T T_{ij}\omega_j \quad (28) \\ &= \frac{1}{2}(u_i - u_i^*)^T R_{ii}(u_i - u_i^*) - \frac{1}{2}\gamma^2 (\omega_i - \omega_i^*)^T T_{ii}(\omega_i - \omega_i^*). \end{aligned}$$

When $u_i = u_i^*$, we have

$$\frac{dV_i^*}{dt} + \frac{1}{2}\delta_i^T Q_{ii}\delta_i + \frac{1}{2}u_i^T R_{ii}u_i + \frac{1}{2}\sum_{j \in N_i} u_j^T R_{ij}u_j - \frac{1}{2}\gamma^2 \omega_i^T T_{ii}\omega_i - \frac{1}{2}\gamma^2 \sum_{j \in N_i} \omega_j^T T_{ij}\omega_j \leq 0. \quad (29)$$

When the uncertain demand satisfies $\omega_i = \omega_j = 0$, we have

$$\frac{dV_i^*}{dt} \leq -\frac{1}{2}\left(\delta_i^T Q_{ii}\delta_i + u_i^T R_{ii}u_i + \sum_{j \in N_i} u_j^T R_{ij}u_j\right) \leq -\frac{1}{2}\delta_i^T Q_{ii}\delta_i \leq 0. \quad (30)$$

Therefore, according to the Lyapunov stability theorem, the inventory error system of sub-chain i tends to be asymptotically stable under the optimal production rate u_i^* . When $\omega_i \neq 0$, integrating (29) yields

$$\begin{aligned} & V_i^*(\delta_i(t)) - V_i^*(\delta_i(0)) \\ &+ \frac{1}{2}\int_0^t \left(\delta_i^T Q_{ii}\delta_i + u_i^T R_{ii}u_i + \sum_{j \in N_i} u_j^T R_{ij}u_j - \gamma^2 \omega_i^T T_{ii}\omega_i - \gamma^2 \sum_{j \in N_i} \omega_j^T T_{ij}\omega_j\right) dt \leq 0, \quad (31) \end{aligned}$$

and since $V_i^*(\delta_i(t)) > 0$, it further obtains

$$\int_0^t \left(\delta_i^T Q_{ii}\delta_i + u_i^T R_{ii}u_i + \sum_{j \in N_i} u_j^T R_{ij}u_j\right) dt \leq \gamma^2 \int_0^t \left(\omega_i^T T_{ii}\omega_i + \sum_{j \in N_i} \omega_j^T T_{ij}\omega_j\right) dt + V_i^*(\delta_i(0)), \quad (32)$$

Thus, under the optimal production rate u_i^* , according to Definition 1, the i th sub-chain can suppress the bullwhip effect at the γ level and achieve synchronization with the leader's inventory state.

3.3.2 Nash equilibrium solution under graph game

This section proves that under certain conditions, the optimal production rate and the worst-case uncertain demand meet the Nash equilibrium conditions (17), and then the zero-sum graph game solution is obtained.

Theorem 2. For the smart supply chain system (1), assuming conditions (1)–(4) are met, if there exists a positive definite function $V_i (i \in N)$ satisfying the HJI Eq. (21),

that is, there exists a smooth positive definite solution $V_i^* > 0$ ($i \in N$), making the production strategy and uncertain demand strategy of adjacent sub-chains optimal, then there exists a graph game Nash equilibrium solution, that is, the saddle point $(u_i^*, u_j^*, \omega_i^*, \omega_j^*)$ exists, and the game value is given by the solution of the HJI equation $V_i^*(\delta_i(0))$.

Proof. For any smooth function $V_i(\delta_i)$, (13) can be further rewritten as

$$\begin{aligned} J_i(\delta_i(0), u_i, u_j, \omega_i, \omega_j) &= \frac{1}{2} \int_0^\infty \left(\delta_i^T Q_{ii} \delta_i + u_i^T R_{ii} u_i + \sum_{j \in N_i} u_j^T R_{ij} u_j - \gamma^2 \omega_i^T T_{ii} \omega_i - \gamma^2 \sum_{j \in N_i} \omega_j^T T_{ij} \omega_j \right) dt \\ &+ \frac{1}{2} \delta_i^T(0) P_i \delta_i(0) - \frac{1}{2} \delta_i^T(\infty) P_i \delta_i(\infty) + \int_0^\infty \frac{\partial V_i^T}{\partial \delta_i} (A \delta_i + (d_i + g_i) B u_i \\ &- \sum_{j \in N_i} a_{ij} B u_j + (d_i + g_i) D \omega_i - \sum_{j \in N_i} a_{ij} D \omega_j) dt. \end{aligned} \quad (33)$$

Assuming that the production rates u_i^*, u_j^* and uncertain demands ω_i^*, ω_j^* are given by (25) and (26), and by completing the square for (33), we obtain

$$\begin{aligned} J_i(\delta_i(0), u_i, u_j, \omega_i, \omega_j) &= \frac{1}{2} \delta_i^T(0) P_i^* \delta_i(0) - \frac{1}{2} \delta_i^T(\infty) P_i^* \delta_i(\infty) + \int_0^\infty \left(\frac{1}{2} \sum_{j \in N_i} (u_j - u_j^*)^T R_{ij} (u_j - u_j^*) \right. \\ &+ \frac{1}{2} (u_i - u_i^*)^T R_{ii} (u_i - u_i^*) - \frac{\partial V_i^T}{\partial \delta_i} \sum_{j \in N_i} a_{ij} B (u_j - u_j^*) + \sum_{j \in N_i} u_j^{*T} R_{ij} (u_j - u_j^*) \\ &- \frac{1}{2} \gamma^2 \sum_{j \in N_i} (\omega_j - \omega_j^*)^T T_{ij} (\omega_j - \omega_j^*) - \frac{1}{2} \gamma^2 (\omega_i - \omega_i^*)^T T_{ii} (\omega_i - \omega_i^*) \\ &- \left. \frac{\partial V_i^T}{\partial \delta_i} \sum_{j \in N_i} a_{ij} D (\omega_j - \omega_j^*) - \gamma^2 \sum_{j \in N_i} \omega_j^{*T} T_{ij} (\omega_j - \omega_j^*) \right) dt, \end{aligned} \quad (34)$$

According to Theorem1, the inventory error system is asymptotically stable, so $V_i^*(\delta_i(\infty)) = 0$. Assuming $u_j = u_j^*, \omega_j = \omega_j^*$, it can be further obtained

$$\begin{aligned} J_i(\delta_i(0), u_i, u_j^*, \omega_i, \omega_j^*) &= \frac{1}{2} \delta_i^T(0) P_i^* \delta_i(0) + \int_0^\infty \left(\frac{1}{2} (u_i - u_i^*)^T R_{ii} (u_i - u_i^*) - \frac{1}{2} \gamma^2 (\omega_i - \omega_i^*)^T T_{ii} (\omega_i - \omega_i^*) \right) dt, \end{aligned} \quad (35)$$

From (35), (17) can be established. Further, let $u_i = u_i^*, \omega_i = \omega_i^*$, we have

$$J_i^*(\delta_i(0), u_i^*, u_j^*, \omega_i^*, \omega_j^*) = V_i^*(\delta_i(0)) = \frac{1}{2} \delta_i^T(0) P_i^* \delta_i(0), \quad (36)$$

That is, the optimal game solution for production rate and uncertain demand is obtained.

3.4 Model-free strategy solution based on Q-learning algorithm

Since the operation process of the distributed smart supply chain system is very complex, it is usually not feasible to establish an accurate system model. Existing model-based control design algorithms are often not feasible. Although system identification based on neural networks has been committed to solving the problem of unknown models, errors in the identification process reduce the effectiveness of the controller. The Q-learning algorithm based on reinforcement learning can update the controller in real time through data generated by the system without relying on the system model. This chapter will use the Q-learning algorithm to solve the inventory consistency problem of the system under the design change caused by network attacks, that is, to solve (25) and (26) through the policy iteration Q-learning algorithm. First, based on the Hamiltonian function (18) and the value function (23), the following Q-function for the i th sub-chain is defined:

$$Q_i(\delta_i, u_i, u_j, \omega_i, \omega_j) = V_i(\delta_i) + H_i\left(e_i, \frac{\partial V_i}{\partial \delta_i}, u_i, u_j, \omega_i, \omega_j\right), \quad (37)$$

where $H_i\left(e_i, \frac{\partial V_i}{\partial \delta_i}, u_i, u_j, \omega_i, \omega_j\right)$ is given by (24), and the value function $V_i(\delta_i)$ is given by (23), so (37) can be written as

$$\begin{aligned} & Q_i(\delta_i, u_i, u_j, \omega_i, \omega_j) \\ &= \frac{1}{2}\delta_i^T P_i \delta_i + \frac{1}{2}\delta_i^T P_i \left(A\delta_i - \sum_{j \in N_i} a_{ij} B u_j + (d_i + g_i) B u_i - \sum_{j \in N_i} a_{ij} D \omega_j + (d_i + g_i) D \omega_i \right) \\ &+ \frac{1}{2} \left(A\delta_i - \sum_{j \in N_i} a_{ij} B u_j + (d_i + g_i) B u_i - \sum_{j \in N_i} a_{ij} D \omega_j + (d_i + g_i) D \omega_i \right) P_i \delta_i \\ &+ \frac{1}{2}\delta_i^T Q_{ii} \delta_i + \frac{1}{2}u_i^T R_{ii} u_i + \frac{1}{2} \sum_{j \in N_i} u_j^T R_{ij} u_j - \frac{1}{2}\gamma^2 \omega_i^T T_{ii} \omega_i - \frac{1}{2}\gamma^2 \sum_{j \in N_j} \omega_j^T T_{ij} \omega_j, \end{aligned} \quad (38)$$

(38) can be further obtained

$$\begin{aligned} & Q_i(\delta_i, u_i, u_j, \omega_i, \omega_j) \\ &= \frac{1}{2} Z_i^T \begin{bmatrix} P_i + Q_{ii} + P_i A + A^T P_i & (d_i + g_i) P_i B & -\text{row}(a_{ij} P_i B) & (d_i + g_i) P_i D & -\text{row}(a_{ij} P_i D) \\ (d_i + g_i) B^T P_i & R_{ii} & 0 & 0 & 0 \\ -\text{col}(a_{ij} B^T P_i) & 0 & \text{diag}(R_{ij}) & 0 & 0 \\ (d_i + g_i) D^T P_i & 0 & 0 & -\gamma^2 T_{ii} & 0 \\ -\text{col}(a_{ij} D^T P_i) & 0 & 0 & 0 & \text{diag}(-\gamma^2 T_{ij}) \end{bmatrix}_{j \in N_i} Z_i, \end{aligned} \quad (39)$$

where $Z_i = \begin{bmatrix} \delta_i^T & u_i^T & u_j^T & \omega_i^T & \omega_j^T \end{bmatrix}^T$. To avoid dependence on the system dynamics information, H_i represents the matrix in (39), which is

$$Q_i(\delta_i, u_i, u_j, \omega_i, \omega_j) = \frac{1}{2} Z_i^T H_i Z_i = \frac{1}{2} Z_i^T \begin{bmatrix} H_{\delta_i \delta_i} & H_{\delta_i u_i} & H_{\delta_i u_{N_i}} & H_{\delta_i \omega_i} & H_{\delta_i \omega_{N_i}} \\ H_{u_i \delta_i} & H_{u_i u_i} & H_{u_i u_{N_i}} & H_{u_i \omega_i} & H_{u_i \omega_{N_i}} \\ H_{u_{N_i} \delta_i} & H_{u_{N_i} u_i} & H_{u_{N_i} u_{N_i}} & H_{u_{N_i} \omega_i} & H_{u_{N_i} \omega_{N_i}} \\ H_{\omega_i \delta_i} & H_{\omega_i u_i} & H_{\omega_i u_{N_i}} & H_{\omega_i \omega_i} & H_{\omega_i \omega_{N_i}} \\ H_{\omega_{N_i} \delta_i} & H_{\omega_{N_i} u_i} & H_{\omega_{N_i} u_{N_i}} & H_{\omega_{N_i} \omega_i} & H_{\omega_{N_i} \omega_{N_i}} \end{bmatrix} Z_i, \quad (40)$$

where $H_{u_i u_i}$, $H_{u_i \delta_i}$, $H_{u_i \omega_i}$, $H_{\delta_i \delta_i}$, $H_{\delta_i \omega_i}$, $H_{\omega_i \omega_i}$ are the notations for the matrix elements corresponding to the multiplication with the variables u_i , δ_i , ω_i in Z_i .

Corollary 1. Assuming that the sub-chains in graph $\mathcal{G}$ are strongly connected, and the production strategies and uncertain demand strategies of adjacent sub-chains are optimal, if the Q-function of the i th sub-chain is as shown in (40), then

$$Q_i^*(\delta_i, u_i^*, u_j^*, \omega_i^*, \omega_j^*) = \min_{u_i} \max_{\omega_i} Q_i(e_i, u_i, u_j^*, \omega_i, \omega_j^*), \quad (41)$$

By using integral reinforcement learning technology, the value function of the i th sub-chain (14) can be written in the form of an integral Bellman equation

$$V_i^*(\delta_i(t+T)) = V_i^*(\delta_i(t)) - \frac{1}{2} \int_t^{t+T} \left(\delta_i^T Q_{ii} \delta_i + u_i^T R_{ii} u_i + \sum_{j \in N_i} u_j^T R_{ij} u_j - \gamma^2 \omega_i^T T_{ii} \omega_i - \gamma^2 \sum_{j \in N_i} \omega_j^T T_{ij} \omega_j \right) dt. \quad (42)$$

Then, according to Corollary 1,

$Q_i^*(\delta_i(t+T), u_i^*(t+T), u_j^*(t+T), \omega_i^*(t+T), \omega_j^*(t+T))$ can be rewritten under the conditions of the above integral Bellman equation

$$\begin{aligned} & Q_i^*(\delta_i(t+T), u_i^*(t+T), u_j^*(t+T), \omega_i^*(t+T), \omega_j^*(t+T)) \\ &= Q_i^*(\delta_i(t), u_i^*(t), u_j^*(t), \omega_i^*(t), \omega_j^*(t)) \\ & - \frac{1}{2} \int_t^{t+T} \left(\delta_i^T Q_{ii} \delta_i + u_i^T R_{ii} u_i + \sum_{j \in N_i} u_j^T R_{ij} u_j - \gamma^2 \omega_i^T T_{ii} \omega_i - \gamma^2 \sum_{j \in N_i} \omega_j^T T_{ij} \omega_j \right) dt, \end{aligned} \quad (43)$$

According to (40), it can be further obtained

$$\begin{aligned} & Z_i^{*T}(t+T) H_i Z_i^*(t+T) \\ &= Z_i^{*T}(t) H_i Z_i^*(t) - \int_t^{t+T} \left(\delta_i^T Q_{ii} \delta_i + u_i^T R_{ii} u_i + \sum_{j \in N_i} u_j^T R_{ij} u_j - \gamma^2 \omega_i^T T_{ii} \omega_i - \gamma^2 \sum_{j \in N_i} \omega_j^T T_{ij} \omega_j \right) dt, \end{aligned} \quad (44)$$

where $Z_i^*(t) = \begin{bmatrix} \delta_i^T(t) & u_i^{*T}(t) & u_j^{*T}(t) & \omega_i^{*T}(t) & \omega_j^{*T}(t) \end{bmatrix}^T$.

According to the Q-function of the i th sub-chain (39), an optimal production rate u_i^* equivalent to (25) can be obtained through the following formula

$$u_i^* = \arg \min_{u_i} Q_i(\delta_i, u_i, u_j, \omega_i, \omega_j) = -H_{u_i u_i}^{-1} H_{u_i \delta_i} \delta_i, \quad (45)$$

Similarly, it can be obtained

$$\omega_i^* = \arg \max_{\omega_i} Q_i(\delta_i, u_i, u_j, \omega_i, \omega_j) = -H_{\omega_i \omega_i}^{-1} H_{\omega_i \delta_i} \delta_i. \quad (46)$$

According to (44), (45), and (46), strategy evaluation and strategy updates do not require model information of the smart supply chain system. The matrix H_i can be solved using the least squares method with data obtained within the sampling interval T . The policy iteration is applied to the Q-learning algorithm to obtain the following algorithm 1.

Algorithm 1. Policy iteration-based Q-learning algorithm.

let for each sub-chain i , given the initial allowable production rate u_i^0 , uncertain demand ω_i^0 , the initial value of the bullwhip effect suppression level γ^0 , and $H_i^0, \forall i = 1, 2, \dots, N$.
for $r = 0, 1, \dots$,

1. Strategy evaluation: Solve the matrix H_i for the $(r + 1)$ th time according to (44)

$$\begin{aligned} & Z_i^T(t + T)H_i Z_i(t + T) \\ &= Z_i^{*T}(t)H_i Z_i^{(t)} - \int_t^{t+T} \left(\delta_i^T Q_{ii} \delta_i + u_i^T R_{ii} u_i + \sum_{j \in N_i} u_j^T R_{ij} u_j - \gamma^2 \omega_i^T T_{ii} \omega_i - \gamma^2 \sum_{j \in N_i} \omega_j^T T_{ij} \omega_j \right) dt. \end{aligned} \quad (47)$$

2. Policy iteration: Update the production rate u_i^{r+1} and uncertain demand ω_i^{r+1} for the $(r + 1)$ th time using the obtained matrix $H_i, \forall i = 1, 2, \dots, N$

$$u_i^{r+1} = -H_{u_i u_i}^{-1} H_{u_i \delta_i} \delta_i, \quad \omega_i^{r+1} = -H_{\omega_i \omega_i}^{-1} H_{\omega_i \delta_i} \delta_i, \quad \gamma^{r+1} = \gamma^r + \epsilon_0, \quad (48)$$

until $\|H_i^{r+1} - H_i^r\| \leq \epsilon_0$ (ϵ_0, ϵ_0 are specified constants), stop the iteration.
end

The convergence of the Q-learning algorithm for solving the zero-sum graph game problem can be found in the literature [40]. The zero-sum graph game solution obtained by Q-learning can approximate the saddle point with any precision without the need for a system model. In other words, the H_∞ controller can be solved online using the Q-learning-based reinforcement learning method.

Theorem 3. For the smart supply chain system (1), assuming conditions (1)–(4) are met, and the sub-chain nodes and their connections form a strongly connected topology graph $\mathcal{G}$, if there exists a positive definite function $V_i (i \in N)$ satisfying the HJI (24), making the production strategy and uncertain demand strategy of adjacent sub-chains optimal, then the smart supply chain system can achieve consistency of inventory state between each sub-chain and the leader under model unknown and DoS network attacks, and the system can meet certain user demands and suppress the bullwhip effect at a level of $\gamma \geq \gamma_{min}$.

Proof. It can be easily obtained from Theorem 1, Theorem 2, and Corollary 1.

Remark 5. Different from existing results such as [43–46] that use static models to study the change design of product and supply chain systems, this chapter uses dynamic models based on data-driven technology to study the change control problem of product

and supply chain systems, and the results obtained can better reflect the dynamic characteristics of system evolution. On the other hand, the design of data-driven Q-learning algorithms is mostly implemented through adaptive dynamic programming in current research results, such as [47] which uses evaluation neural networks to approximate the Q-function of each agent, and execution neural networks to approximate the controller, but this method inevitably leads to approximation errors, bringing new uncertainties to controller design. This chapter combines the least squares method with reinforcement learning technology to solve the core matrix of the Q-learning algorithm, effectively avoiding the errors brought by neural network approximation.

4. Case simulation

This section takes the Sinopec gasoline collaborative production supply chain as an example to conduct simulation experiments to verify the feasibility and effectiveness of the proposed algorithm.

The production process of gasoline mainly includes steps such as crude oil pretreatment and atmospheric pressure distillation. The specific process is as follows:

1. *Pretreatment of crude oil*: Crude oil sent from oil fields to refineries often contains salts (mainly chlorides) and water (dissolved in oil or in an emulsified state), which can cause equipment corrosion and scale formation on the inner walls of equipment, affecting the composition of finished products. It needs to be removed before processing. The common method is to add demulsifiers and water to gather the water in the oil and separate it from the oil, while the salt dissolves in water. With the cooperation of a high-voltage electric field, larger water droplets are formed and easily removed.

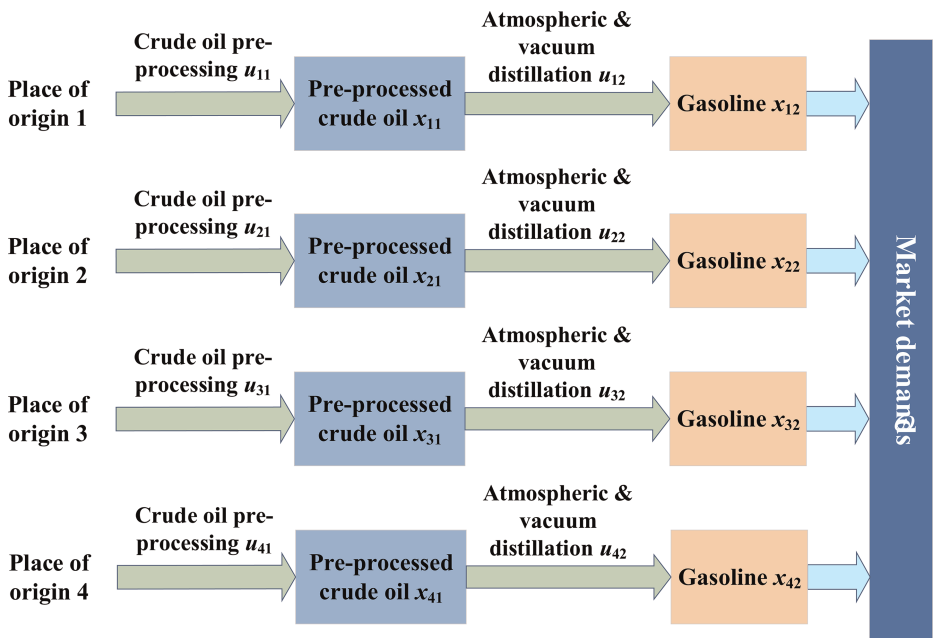


Figure 2.
Schematic diagram of gasoline production process

2. *Atmospheric and vacuum distillation:* It is customary to collectively refer to atmospheric distillation and vacuum distillation as atmospheric and vacuum distillation, which is basically a physical process. The raw material oil is divided into oil products with different boiling point ranges (called fractions) in the distillation tower according to the evaporation ability. Some of these oils are blended and added with additives to be shipped as products, and a considerable part is the raw material for subsequent processing units. Therefore, atmospheric and vacuum distillation is also called the first processing of crude oil. It includes three processes: desalting and dehydration of crude oil; atmospheric distillation, vacuum distillation. The main products of the atmospheric and vacuum unit are used as raw materials for downstream production units, including naphtha, kerosene, diesel, fuel oil, slack wax, and gasoline, etc.

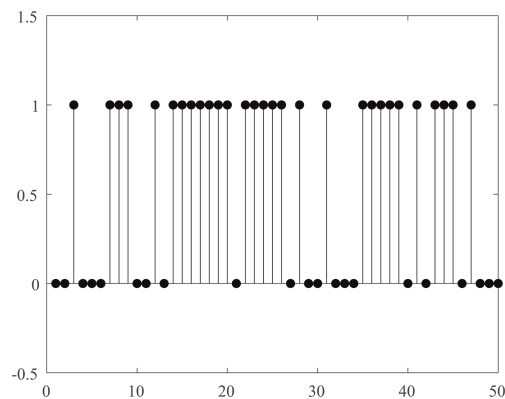


Figure 3.
S-C channel packet loss.

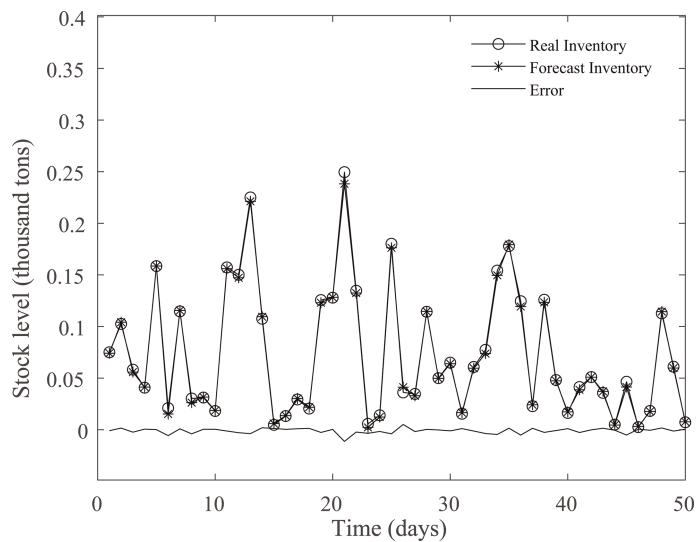


Figure 4.
Plot of forecast inventory for crude oil pretreatment process.

Taking the four refining enterprises of Sinopec's gasoline production supply chain as a collaborative scenario, considering that each enterprise includes two main production processes and has a similar structure, thus forming four sub-chains, as shown in **Figure 2**. Set the initial inventory (unit: thousand tons) of the two main production processes of the four sub-chains to be $x_1 = [0.3, 0.2]^T$, $x_2 = [0.7, 0.5]^T$, $x_3 = [0.6, 0.7]^T$, $x_4 = [0.8, 0.55]^T$. To verify the effectiveness of the adopted prediction algorithm, in the historical inventory data of the first sub-chain for 200 days are used to test and predict the inventory data for the next 50 days, and the forecast results are shown in **Figures 4 and 5**.

Under the packet loss situation caused by the network attack as shown in **Figure 3**, consider the change compensation design for the gasoline production supply chain

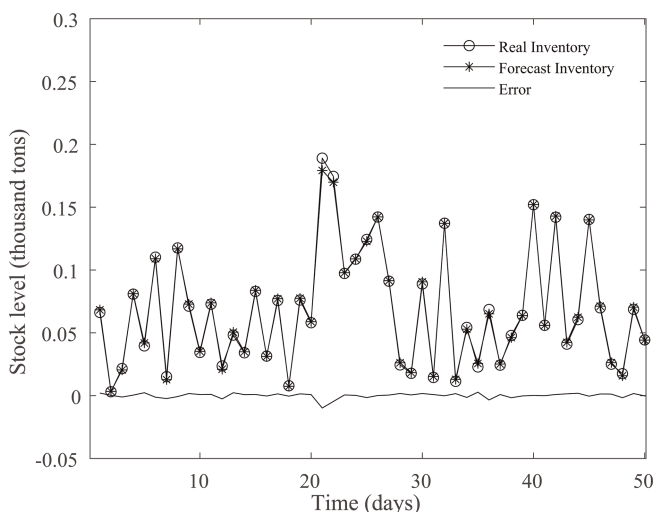


Figure 5.
Plot of forecast inventory for atmospheric vacuum distillation process.

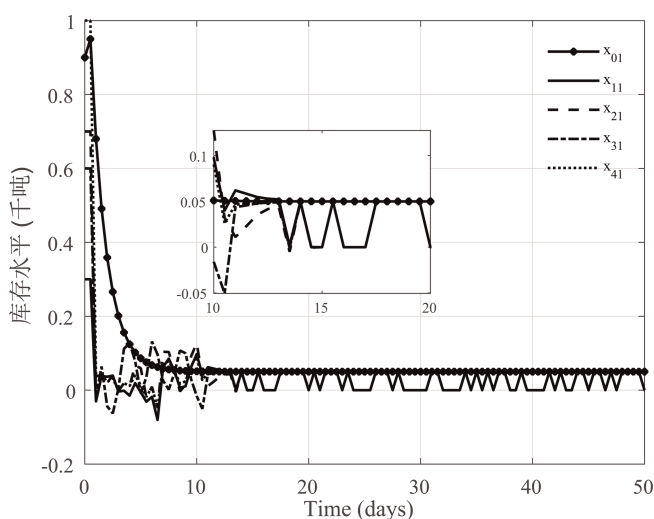


Figure 6.
Inventory status change curve of crude oil pretreatment process before change.

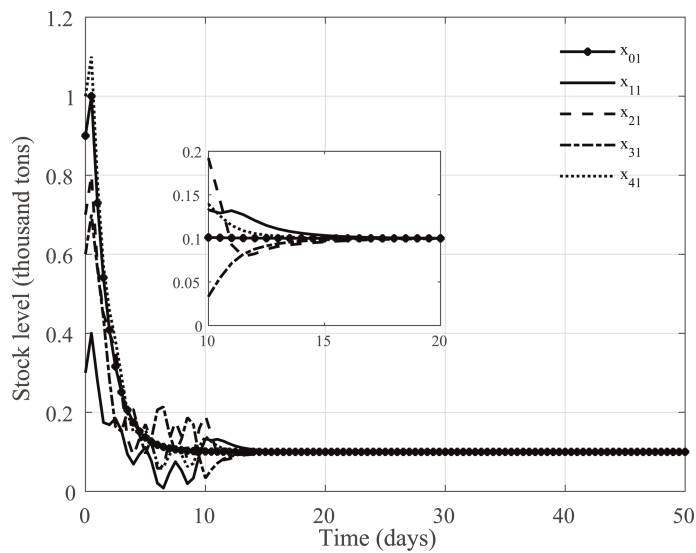


Figure 7.
Inventory status change curve of crude oil pretreatment process after change.

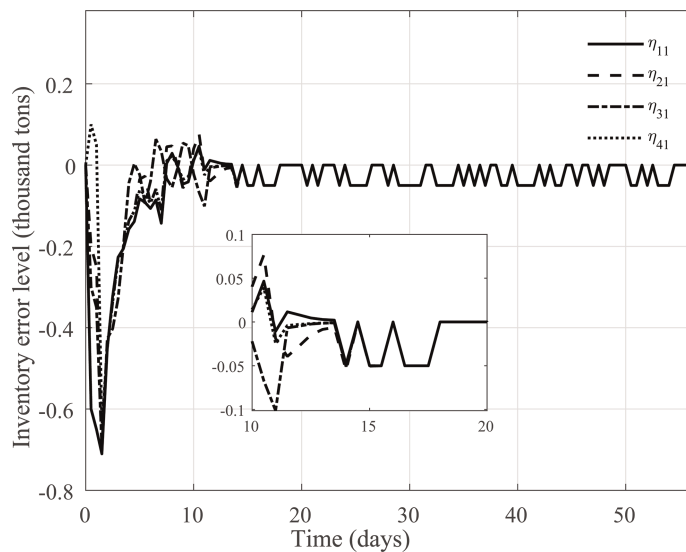


Figure 8.
Inventory tracking error curve for crude oil pretreatment process before change.

system to ensure the consistency of the system's inventory state and effective suppression of the bullwhip effect. Choose appropriate weight matrices and solve for the minimum production rate and maximum uncertain demand through the policy iteration Q-learning algorithm to obtain the inventory state and tracking error state curves of each sub-chain. To verify the effectiveness of the change compensation measures, this chapter compares the inventory situation and tracking error of each sub-supply chain before and after the introduction of the change. **Figures 6-11**, respectively,

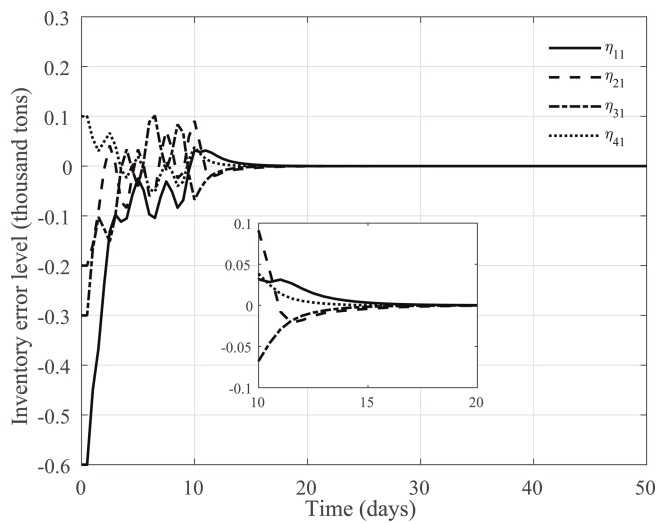


Figure 9.
 Inventory tracking error curve for crude oil pretreatment process after the change.

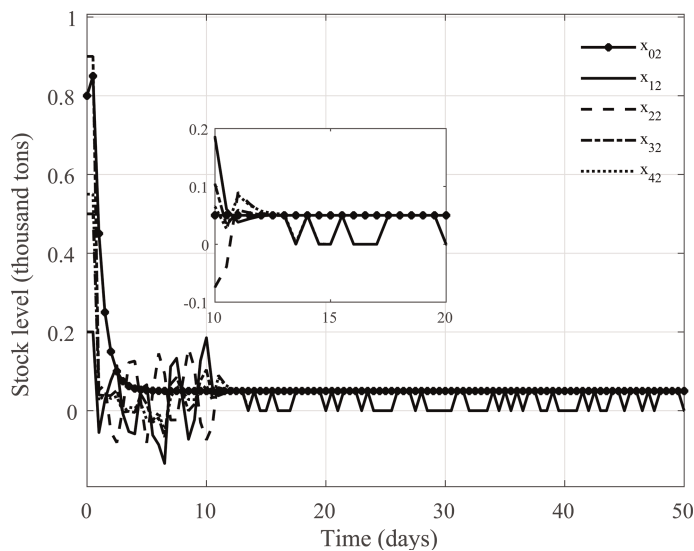


Figure 10.
 Stock status change curve of the usual vacuum distillation process before change.

show the change in inventory levels of each sub-chain under the DoS attack before and after the introduction of the change compensation mechanism. The simulation results from the figures show that after the introduction of the change compensation mechanism, the system can effectively track the user requirements set by the collaborative evolution system on about the 19th day, that is, to achieve consistency. **Figures 8, 9, 12, and 13** show the change in the inventory tracking error levels between each sub-chain and the leader before and after the introduction of the change

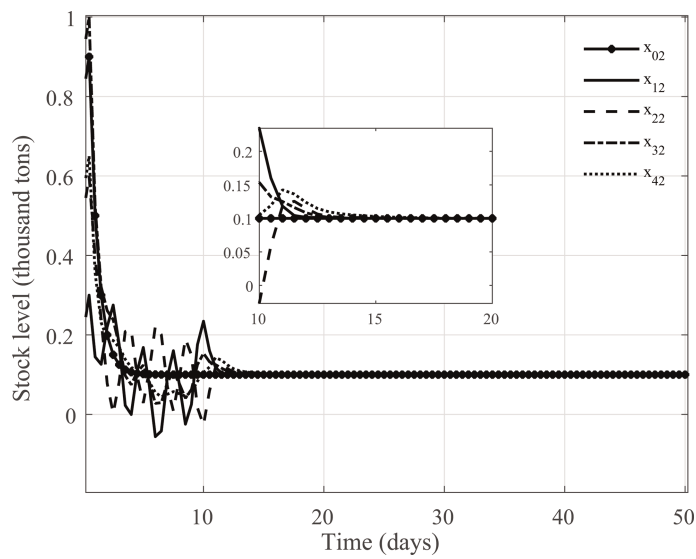


Figure 11.
Stock status change curve of the usual vacuum distillation process after change.

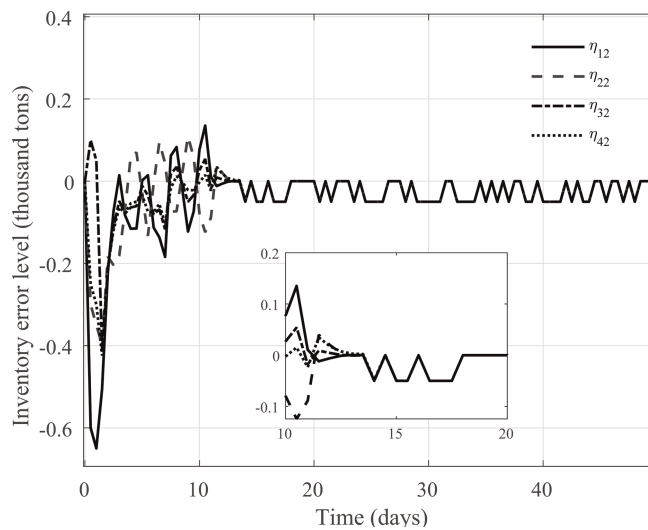


Figure 12.
The stock tracking error curve for the usual vacuum distillation process before change.

compensation mechanism, that is, after the introduction of the change compensation mechanism, the inventory state error between the four sub-chains and the leader's inventory state gradually tends to 0, which also verifies that the inventory state of the sub-chains can be synchronized with the user requirements. To further verify the impact of the change compensation mechanism on product adaptability and user satisfaction, this chapter considers the indicators listed in **Table 1**, that is, delivery time and average inventory tracking error under network attacks. **Table 1** shows that under network attacks, the introduction of the change compensation mechanism can

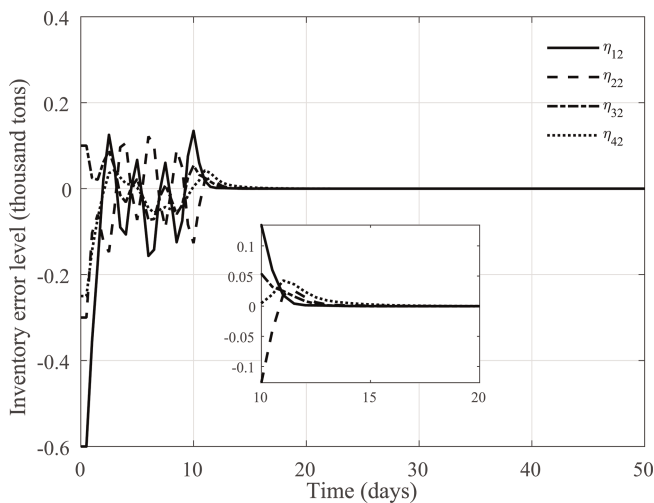


Figure 13.
The stock tracking error curve for the usual vacuum distillation process after change.

Index (under cyberattacks)	Before design	After design
Delivery time t	∞	19
Average tracking error of inventory level $\eta(t)$	0.042164	0.017594

Table 1.
Comparison of indicators before and after the proposed change control method.

effectively improve the system’s delivery time (i.e., the time for the system to achieve inventory consistency and deliver the product to the customer as stipulated in the contract) and reduce the average inventory tracking error. In summary, the H_∞ controller based on the Q-Learning proposed in this chapter can make the smart supply chain system resist DoS attacks while effectively suppressing the bullwhip effect and achieving leader-follower consistency.

5. Conclusion

In response to the distributed CPS-based smart supply chain system, this chapter studies the emergency change control problem of the system with unknown models under DoS attacks. Using data-driven technology, an emergency defense change mechanism is designed according to historical data and reference information to deal with the situation where the system’s sensor-controller communication channel is attacked by DoS. By using zero-sum differential graph game theory and reinforcement Q-learning technology, an H_∞ consensus controller is designed to ensure that the smart supply chain system achieves leader-follower H_∞ consistency under DoS attack-induced design changes, and can suppress the bullwhip effect brought by uncertain

demand and design changes, while ensuring that the system has a certain level of product adaptability and user satisfaction. Simulation examples verify the correctness and effectiveness of the methods proposed in this chapter. Carrying out research on data-driven change effect propagation analysis, multi-agent system simulation, and data visualization system for smart supply chain systems will be an important topic for further study in the change control design of smart supply chain systems.

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