

Theory of Constraints and Industry 4.0: mutual contributions and research perspectives

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Abstract

Paper aims: This paper explores the integration of Industry 4.0 digital technologies and the Theory of Constraints (TOC) in manufacturing systems, focusing on their reciprocal enhancement to drive operational improvements.

Originality: It pioneers an examination of how TOC's principles can effectively guide the adoption of I4.0 innovations while also showing how emerging technologies can extend the practical applications of TOC in operations management.

Research method: A systematic literature review was conducted following the PRISMA protocol, ensuring a comprehensive synthesis of existing studies at the intersection of TOC and I4.0.

Main findings: The review identifies three key elements: (i) the critical role of systems analysis in understanding manufacturing constraints, (ii) the effective implementation of I4.0 strategies guided by TOC principles, and (iii) the support provided by advanced technologies—such as artificial intelligence, digital twins, and RFID—in enhancing TOC applications.

Implications for theory and practice: The study offers a robust theoretical framework that bridges traditional operations management with modern digital strategies. Practically, it provides actionable insights for managers seeking to optimize technology adoption and operational efficiency in manufacturing, ultimately paving the way for future research on integrated digital and constraint-based management systems.

Keywords

Industry 4.0. Theory of Constraints. Production planning and control. Digital technologies. Systematic review.

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The authors have no conflict of interest to declare.

Ethical Statement

This research did not involve experiments with human participants or the collection of personal or sensitive data. Therefore, ethical approval and informed consent were not required.

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1. Introduction

Manufacturing is undergoing a rapid digital transformation known as Industry 4.0 (I4.0), which evolves the third industrial revolution's use of computers and automation by incorporating autonomous, data-driven, and intelligent systems (Klingenberg et al., 2018; Sharma & Singh, 2020). Integrating physical assets, human input, and smart machines, I4.0 enables decentralized decision-making based on real-time data, resulting in an agile, connected value chain (Kandarkar & Ravi, 2024).

Technological innovations in manufacturing have renewed interest in new or adapted operations management systems (Choi et al., 2022). Research highlights the benefits of digitalization and the integration of artificial



intelligence (AI) to enhance production planning and control (PPC) (Colombari et al., 2024). In operations management, the I4.0 perspective, by developing analytical capabilities in production systems, can allow for better analysis of demand patterns and fluctuations and significantly improve production planning and control (PPC) (Prashar, 2023). As an example, the benefits of machine learning (Esteso et al., 2023), Internet of Things (IoT) (Luo et al., 2023), and big data (Jahani et al., 2023) adoption in PPC and operations management activities are cited.

Recent research on management models has explored the impacts of Industry 4.0 technologies, emphasizing increased data access and the anticipated reduction in uncertainty these advancements bring. For example, there are initial studies on the potential implications of I4.0 for contemporary methods such as Lean Manufacturing (Kumar et al., 2024), Six Sigma (Wankhede et al., 2025), and Theory of Constraints (TOC) (Khakifirooz et al., 2024; Tsai & Lu, 2018).

Focusing on ensuring reliable and quick delivery with low costs since the 1980s, TOC evolved alongside manufacturing and information technology (IT), originating in production optimization software known as OPT (Optimized Production Technology) (Souza, 2005). For example, its approach to PPC, Drum-Buffer-rope (DBR), is cited as an efficient method for real-time updating of production schedules, fitting into the context of I4.0 (Saif et al., 2019). Also, Urban & Rogowska (2019) suggest that future TOC research could explore the transformation of its tools and instruments to facilitate application, with I4.0 technologies potentially having a significant impact.

While some studies address the application of specific technologies, such as AI (Khakifirooz et al., 2024) and IoT (Balaji et al., 2018), in the context of TOC, a comprehensive framework is still needed to examine how technologies can support TOC techniques and how TOC principles can, in turn, guide the implementation of I4.0 technologies. A systematic literature review was conducted to develop a framework for the relationship between TOC and I4.0. Previous reviews focused on identifying relevant research areas related to TOC (Ikeziiri et al., 2018; Urban & Rogowska, 2019); synthesizing research on Critical Chain Project Management (CCPM) (Luiz et al., 2019; Mirzaei & Mabin, 2018); and establishing comparisons between Lean and TOC (Pacheco et al., 2019).

While recent systematic reviews have summarized studies integrating lean manufacturing (Kumar et al., 2024), lean office (Santos et al., 2024), and lean six-sigma (Antony et al., 2023) with Industry 4.0, no similar systematic investigation has been conducted regarding the intersection of TOC and I4.0. This study aims to provide an overview of research connecting TOC principles and tools to I4.0. To achieve this, the PRISMA protocol was applied to outline the integrated research profile and propose a future research agenda.

This research contributes to the business and management literature by offering a comprehensive view of the mutual benefits between new digital technologies and TOC techniques. With its systemic, constraint-focused approach, TOC can guide technology implementation in smart environments (Acikgoz et al., 2024). Additionally, establishing cyber-physical systems can support key TOC management activities, such as buffer control (Kuo et al., 2021) or its thinking processes (Aljaž, 2024b). Importantly, this study also builds on recent contributions from the Brazilian TOC research community, such as Rays Filho et al. (2023), who explored TOC as a conceptual foundation for smart, data-driven decision-making supported by digital simulation. By extending this line of inquiry, the present work not only advances the development of the TOC, a field that has seen notable growth in Brazil, but also strengthens its relevance and applicability within the global context (Ikeziiri et al., 2018).

The article is organized into five sections. Section 2 introduces the main concepts of TOC and I4.0. Section 3 outlines the research method to ensure future reproducibility. Section 4 presents and discusses the results, highlighting two main areas: the contributions of TOC to the implementation and evolution of I4.0 and the contributions of I4.0 technologies to TOC practices. Section 5 proposes an integrated framework of TOC and I4.0. The article concludes by underscoring its main contributions and limitations and suggesting directions for future research.

2. Theoretical foundation

This section aims to define the theoretical basis that allowed the systematization of the literature collected for analysis and the development of an integrated framework. The discussion here does not intend to explore all aspects of the two main themes in detail, a task already carried out in the specific literature for each theme.

2.1. Theory of Constraints (TOC)

Initially applied in production management (Goldratt & Cox, 1990), TOC expanded to areas like project management, finance, and supply chain management (SCM). Its core concept revolves around constraints—factors

limiting system performance—and the improvement process is guided by the Five Focusing Steps (5FS): identify, exploit, subordinate, elevate, and prevent inertia (Bacelar-Silva et al., 2021). The 5FS has been integrated into what is known as the “Process Of On-Going Improvement (POOGI)” (Watson et al., 2007). This includes tools and techniques for identifying and managing constraints, such as the Thinking Processes (Khakifirooz et al., 2024). A general overview of POOGI is to answer three questions that guide the improvement process as a sequence of changes: What to change? What to change to? And how to cause the change? (Banerjee & Lowalekar, 2021).

Each TOC application area has specific characteristics. Common areas include operations/production, finance, thinking processes, distribution and SCM, marketing, and ongoing improvement (Ikeziri et al., 2018). To support these applications, Goldratt introduced Thinking Process (TP) tools for problem structuring and conflict resolution, including the Current Reality Tree, Evaporating Cloud (Gomes et al., 2021), and Future Reality Tree (Mabin & Cavana, 2024).

The most recognized TOC application in PPC is Drum-Buffer-Rope (DBR), described in *The Goal* (Goldratt & Cox, 1990). The “Drum” represents the system constraint, the “Buffer” ensures protection against variability, and the “Rope” synchronizes production orders to the constraint’s pace (Mayo-Alvarez et al., 2024). A simplified version (S-DBR) adapts DBR to systems where market demand is the primary constraint (Lee et al., 2010).

In supply chain management, TOC employs pull-based distribution, replenishing stocks based on actual consumption and centralizing inventory at the source (Modi et al., 2019). For project management, Critical Chain Project Management (CCPM) focuses on the main chain of activities that defines project completion time, addressing biases that often lead to delays and budget overruns (Luiz et al., 2019).

TOC’s Throughput Accounting (TA) measures performance by focusing on throughput, material cost, and operating expenses, avoiding incentives that can harm overall performance (Myrelid & Olhager, 2019). Unlike traditional accounting, TA considers inventory a liability rather than an asset. However, limitations in handling long-term decisions and high variability led to the development of Throughput Economics, offering better support for decisions in uncertain environments (Schrageheim et al., 2019).

Goldratt also examined technology adoption in organizations through the book *Necessary But Not Sufficient* (Goldratt et al., 2000). The key question is: “When does a new technology bring value?” TOC suggests technology adds value when it reduces a system constraint. Goldratt proposed the Six Technological Questions to evaluate technology’s impact, focusing on its potential to eliminate limitations and drive behavioral changes. These questions are: 1. What is the power of the technology? 2. What limitation does it diminish? 3. What rules helped us accommodate the old limitation? 4. What new rules should we adopt? 5. What technological changes are needed to support the new rules? 6. How do we cause the change to happen? These questions could be applied to assess the ability to deliver its full potential value and/or be used to guide the development of the technology.

Coman & Ronen (1995) identified three types of interactions between TOC and Information Technology (IT): IT-constraints (applying TOC to identify and manage IT bottlenecks), IT-aiming (using IT to overcome organizational constraints), and Computer-Aided TOC (enhancing TOC applications through technology). These insights serve as a foundation for adapting TOC in I4.0 environments.

Overall, TOC provides a robust framework for identifying and managing constraints across various domains. By applying TOC principles, organizations can continuously improve, enhance productivity, and drive sustainable growth.

2.2. Industry 4.0

The rationale for adopting the framework proposed by Oesterreich & Teuteberg (2016) to support the systematization of the sample of articles in this review is threefold. First, unlike other frameworks that primarily emphasize technical aspects of I4.0, this framework provides a comprehensive and interdisciplinary perspective by clustering I4.0 technologies into three categories – Smart Factory, Simulation/Modeling, and Digitalization/Virtualization – while considering broader organizational and environmental implications. Second, this framework was developed through a rigorous triangulation approach combining a systematic literature review, content analysis, and case studies, strengthening its conceptual robustness and suitability as a basis for mapping the literature. Third, its holistic view aligns directly with the objectives of this study, which explores the mutual contributions of TOC and I4.0. By not limiting the analysis to purely technological dimensions, this framework facilitates investigating how digital innovations can enhance TOC applications and how TOC principles can guide the effective integration of I4.0 solutions within manufacturing systems. The emphasis on Smart Factory technologies makes it particularly appropriate for structuring the analysis in this review, given the manufacturing-centric focus of TOC operational improvements.

Smart factories represent a leap from traditional automation to a fully integrated and flexible system where real-time data is shared between resources, allowing adaptations to new demands (Osterrieder et al., 2020). Technologies already consolidated in previous industrial revolutions, such as Robotics and RFID, are combined in cyber-physical systems that integrate physical resources through networks (Oztemel & Gursev, 2020). What provides this connectivity is the so-called Internet of Things (IoT), which is the connection of machines and other physical resources of the system to the network, allowing the sharing of data generated by these resources (Malik et al., 2021). Additive manufacturing can also be described as a group of digital manufacturing technologies in which physical objects are made from digital models (Franco et al., 2020; Khajavi et al., 2014; Naghsineh, 2024).

Technological advances have not only improved physical transformation processes but are also allowing these processes to become digital or virtual (Alcácer & Cruz-Machado, 2019). Cloud Computing enables remote use of computing resources via the Internet, hosting various resources, programs, and information (Tao et al., 2019). With its portability, mobile computing facilitates access to computing in the production process (Aceto et al., 2019). The digitization of human activities has generated data at an unprecedented amount and speed, and this phenomenon is represented by the concept of big data (Sestino et al., 2020).

For example, Building Information Modeling (BIM) enhances construction project management by consolidating planning data and providing detailed information accessible to all parties (Mantravadi et al., 2023). Digital twins and augmented/virtual reality are often linked to simulation in I4.0. A digital twin is a virtual replica of a physical object or process, enabling real-time monitoring. (Tao et al., 2019). While augmented reality allows for the insertion of digital information into the real world view, virtual reality allows the user to be immersed in a simulated virtual environment (Gichane et al., 2025).

3. Research method

In order to assess the mutual contribution of I4.0 and TOC, a systematic cross-literature review of the topics was conducted (Paul et al., 2023). This process was designed to be rigorous, transparent, and replicable, following the PRISMA 2020 protocol (Page et al., 2021). The research process unfolded in four main stages. The study began with *(1) planning and scoping*, involving the definition of research objectives focused on exploring the intersection of I4.0 and the TOC, alongside a review of existing literature to refine the scope and ensure relevance. This was followed by *(2) structured search and sampling*, in which two sets of search terms, developed based on prior systematic reviews on I4.0 and TOC, were applied to the Scopus and Web of Science databases to identify articles published up to February 2025, with objective filters restricting the selection to English-language journal articles; subsequently, a subjective screening of titles and abstracts was conducted to ensure alignment with the research theme. Next, *(3) content analysis* was carried out, where the full texts of the final sample were systematically coded using theoretically grounded frameworks—specifically, the framework by Oesterreich & Teuteberg (2016) for I4.0 and the classification proposed by Ikeziri et al. (2018) for TOC—following the recommendation by Seuring & Gold (2012) to employ categorization schemes with predefined categories and clear definitions to enhance reliability; the first author initially performed coding and then validated through discussions with the second and third authors. Finally, *(4) synthesis* was performed, drawing on techniques discussed by Ermel et al. (2021), whereby thematically similar excerpts were grouped to form the structure of the Results and Discussion section, supporting the construction of the theoretical framework proposed by this study. These steps are summarized in Figure 1.

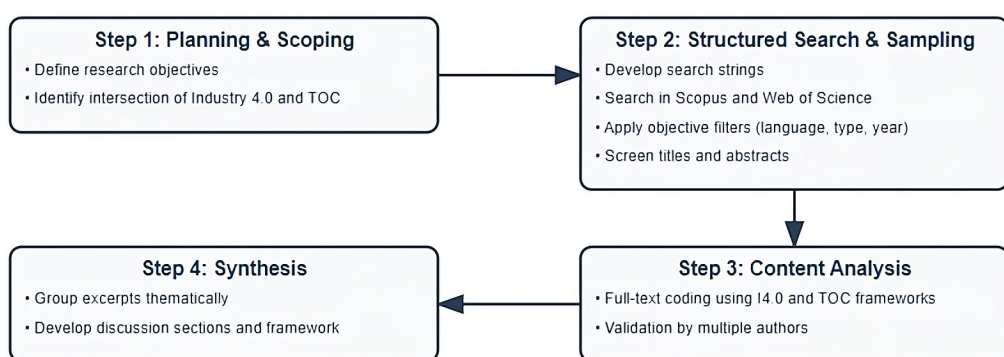


Figure 1. Research process steps.

To enable the review to be carried out objectively and rigorously, the steps provided in the PRISMA 2020 protocol were followed, using the flow diagram for new systematic reviews, which included searches of databases and registers only (Page et al., 2021). Figure 2 describes the steps undertaken, indicating the sample size after each round of evaluation and document exclusion.

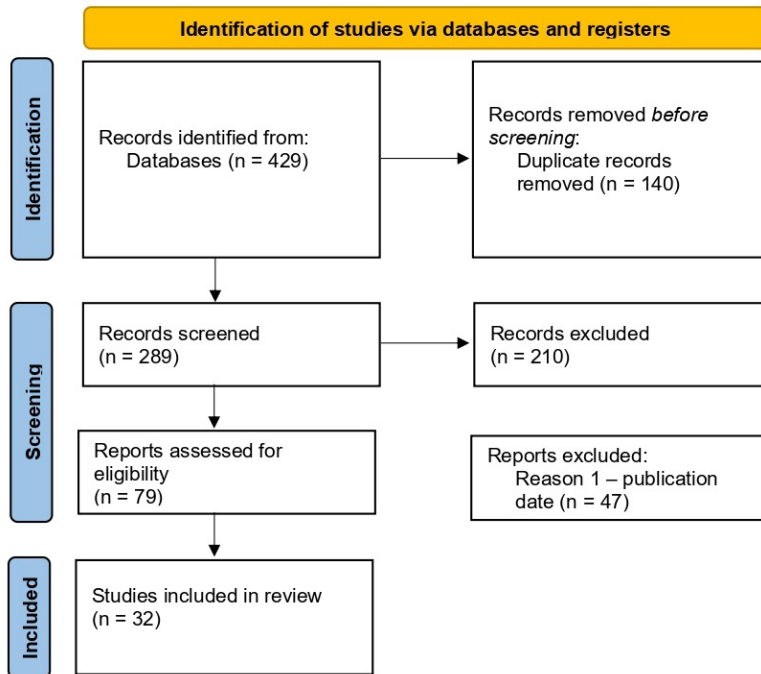


Figure 2. Review process according to PRISMA 2020 guidelines. Source: Page et al. (2021).

The first stage consisted of sampling: searching, identifying, and filtering publications presenting thematic elements of TOC and I4.0. Regarding the search terms, two initial sets of keywords were developed based on literature reviews published in journals on I4.0 and TOC. Data was collected from the Scopus and Web of Science databases, with the sample covering searches conducted up to February 2025. The applied search strings are presented in Table 1. An initial filter was also applied to include only publications in English and from journal sources.

Table 1. Search queries employed in database screening.

Research themes	Search strings
Theory of Constraints	"buffer management" OR ccpm OR "constraint buffer" OR "critical chain project management" OR "current reality tree" OR "drum buffer rope" OR "five focusing steps" OR goldratt OR "make to availability" OR "Theory of Constraint*" OR "Theory of Restrictions" OR "thinking process*" OR "throughput accounting" OR "throughput economics"
Industry 4.0	"3D printing" OR "4° industrial revolution" OR "4th industrial revolution" OR "additive fabrication" OR "additive manufacturing" OR "artificial intelligence" OR "augmented reality" OR "autonomous car" OR "autonomous guided" OR "autonomous vehicle" OR "big data" OR "cloud computing" OR "cloud manufacturing" OR "connected industry" OR "cyber physical system" OR "digital intelligence" OR "digital manufacturing" OR "digital technolog*" OR digitalization OR digitization OR "driverless car" OR "driverless vehicle" OR "fourth industrial revolution" OR "human-computer interaction" OR "human-machine interaction" OR iiot OR "Industrie 4.0" OR "Industry 4.0" OR "intelligent factories" OR "intelligent factory" OR "intelligent manufacturing" OR "intelligent product*" OR "internet of services" OR "internet of things" OR iot OR "machine learning" OR "machine-to-machine communication" OR "manufacturing execution system" OR "mixed reality" OR "mobile computing" OR "mobile tech*" OR "production 4.0" OR "radio-frequency identification" OR "rapid prototyping" OR "real-time factory" OR "real-time manufacturing" OR rfid OR "robot car" OR "robotic car" OR scada OR "self driving car" OR "self driving vehicle" OR "smart factories" OR "smart factory" OR "smart industry" OR "smart manufacturing" OR "smart product" OR "smart production" OR "smarter manufacturing" OR "Supervisory Control and Data Acquisition" OR "ubiquitous factories" OR "ubiquitous factory" OR "ubiquitous manufacturing" OR "virtual reality" OR virtualization

The initial search resulted in 154 files on the Web of Science and 275 articles on Scopus. The *bibliometrix* package of R statistical software was used to compile and remove sample redundancies. 140 duplicates were found and removed, resulting in a sample of 289 documents. The title and abstract were screened to exclude articles misaligned with the review's theme. Common exclusion reasons included misuse of TOC-related terms, lack of focus on I4.0 technologies, and unrelated contexts for concepts like DBR, CCPM, or throughput accounting. Articles without access to abstracts, full texts, or authorship were also removed. After applying these filters, 79 articles remained for full reading. Publications prior to 2010 were disregarded, given that I4.0 was formally introduced in 2011 (Kagermann, 2015).

Ultimately, the full texts of the 32 articles selected for the sample underwent a systematic content analysis, guided by the frameworks of Oesterreich & Teuteberg (2016) for I4.0 and Ikeziri et al. (2018) for TOC, which provided the theoretically grounded categorization schemes and clear definitions recommended to enhance reliability in content analysis (Seuring & Gold, 2012). Initially, excerpts related to the application of intelligent systems in manufacturing were labeled as *Smart Factory*, those addressing modeling, simulation, or digital twins were coded as *Simulation*, and aspects concerning the transformation of traditional processes into digital ones—including management processes—were categorized under *Digitalization*. This coding was performed by the first author and validated by the second and third authors.

Subsequently, drawing on synthesis techniques as discussed by Ermel et al. (2021), the content was organized thematically, with excerpts grouped to form the basis of each section in *Results and Discussions* (Section 4). A second layer of analysis examined the interaction between TOC and I4.0 technologies through the lens of Coman & Ronen (1995), who identified three modes of interaction between TOC and IT: managing IT bottlenecks, using IT to overcome organizational constraints, and enhancing TOC applications via IT. Building on these insights, excerpts were initially coded into two overarching categories: (i) *TOC principles and tools supporting the adoption and use of I4.0 technologies* and (ii) *technological support provided by I4.0 for management processes and TOC applications*. After team validation and discussion, the content of the first category was reorganized in the final framework into two main themes: (i) how TOC tools identify and improve constraints while assessing the value of new technologies and guiding their implementation, and (ii) how TOC principles facilitate the deployment of I4.0 technologies. Based on the findings presented in the results and discussion section, this theoretical framework was thus developed to synthesize and illustrate how TOC and Industry 4.0 mutually reinforce each other.

4. Results and discussions

The review identified 32 articles meeting the inclusion and exclusion criteria outlined in Section 3, which explore the relationship between TOC and I4.0. A summary of the sampled articles and their contributions is presented in Appendix A. This section discusses the findings organized into two major areas: (i) the contributions of TOC to the implementation and evolution of I4.0, and (ii) the contributions of I4.0 technologies to TOC practices. The results are also analyzed according to the “Smart Factory”, “Simulation”, and “Digitalization” dimensions, following the framework of Oesterreich & Teuteberg (2016).

4.1. Contributions of TOC to Industry 4.0

The TOC literature on operations frequently discusses Smart Factory technologies, especially in manufacturing. A key point is TOC's ability to enhance operational flexibility through mass customization, integrated with approaches like lean manufacturing (Peralta-Abarca et al., 2024). However, Stump & Badurdeen (2012) note that TOC may be less effective in mass customization due to constantly changing bottlenecks (Golmohammadi, 2015). TOC has also contributed to optimizing production processes with various technologies: DBR reduces scrap (Hilmola & Gupta, 2015), while TOC-based modularization improves production design (Eidelwein et al., 2018).

Thinking Process tools like CRT and FRT help identify conditions and actions for improvement (Aljaž, 2024a, b), establishing the relationship of causes and effects that generate undesirable effects, and the Future Reality Tree (FRT) to identify conditions and actions that generate desirable effects. Advances in I4.0, such as modularization, can be used as “injections” to solve root causes (Mabin & Cavana, 2024).

TOC's approach to uncertainty in production is also highlighted. DBR has been effective in environments with fluctuations and resource interdependence (Hilmola & Gupta, 2015), and TOC's adaptability in supply chain management is discussed (Silva Stefano et al., 2024). System modularization, facilitated by TOC, helps reduce uncertainty (Eidelwein et al., 2018). The TOC-based Continuous Improvement Process, cited in various studies,

supports production technology implementation (Balaji et al., 2018; Noh et al., 2017). Saif et al. (2019) use DBR-based heuristics to plan IoT implementation, enhancing shop floor data management.

Additionally, TOC provides guidelines for Digitalization efforts. TOC supports effective implementation of digital technologies by focusing improvements on constraints. For instance, Groop et al. (2010) explore mobile technology in healthcare to improve constraint productivity, using TOC to focus on critical points. TOC has also been applied to cloud computing to prevent customer memory shortages while aligning with financial goals (Chang et al., 2017). This ability to resolve conflicts between I4.0 stakeholders' objectives highlights TOC's potential.

4.2. Contributions of Industry 4.0 to TOC

On the other hand, Industry 4.0 technologies strengthen TOC practices by offering new ways to monitor, analyze, and respond to system constraints.

In the Smart Factory dimension, IoT and sensors aid TOC by monitoring systems and detecting constraints (Helfer et al., 2024), while RFID and simulation improve agility in uncertain conditions (Chou et al., 2016). IoT applications can be cost-effective when guided by TOC principles (Balaji et al., 2018; Saif et al., 2019). This creates a cycle where TOC supports IoT, generating data for TOC applications. Robotics also plays a role, with TOC applied to improve robotic production systems (Noh et al., 2017). Additionally, digital and mobile devices support data collection for TOC applications (Groop et al., 2010), and biometric sensors enable data collection without handheld gadgets (Kumar et al., 2020).

Regarding simulation, this is the least explored of the proposed clusters in TOC literature, with most studies focusing on research methods rather than practical applications in operations management (Rays Filho et al., 2023; Silva Stefano et al., 2024; Hilmola & Gupta, 2015). Nonetheless, key contributions highlight using data analytics and AI to support decision-making. Simulation has been applied to analyze TOC supply chain replenishment in real cases (Silva Stefano et al., 2024). Li et al. (2022) proposed a data-driven approach for buffer sizing in CCPM using support vector regression and Monte Carlo simulation. Costas et al. (2023) developed an agent-based simulator to evaluate uncertainty costs in production systems, demonstrating how DBR effectively accommodates variability. Future research should investigate when AI-based algorithms outperform traditional approaches and how to integrate them, as illustrated by optimization models that combine ABC and TOC costing with advanced MES systems (Tsai, 2023; Tsai & Su, 2024). However, TOC scholars often resist complex mathematical models, favoring simplicity and "good enough" solutions over purely optimal ones (Naor et al., 2013).

Gaps remain in integrating simulation with I4.0 technologies like digital twins and virtual reality in TOC contexts. Augmented reality could aid visual management of production orders and buffer consumption. Moreover, no studies connect TOC with BIM, which is widely used in construction for cost and time estimates (Oraee et al., 2025). Future research should explore its relationship with CCPM, as seen in lean management (Aburumman et al., 2024).

In the Digitalization cluster, digitizing production with sensors and big data enables continuous feedback for TOC-based production planning (Tsai et al., 2024a) and real-time monitoring of capacity utilization (Saif et al., 2019). Monitoring WIP and plant status is relevant in buffer-based TOC control tools. Deep learning with temporal data is now being explored to predict task bottlenecks in digital enterprises, using network structures to capture spatio-temporal dependencies and enhance prediction accuracy (Yin et al., 2025).

A key gap is the absence of studies on social media's connection to TOC. Integrated with CCPM, social media could enhance collaboration and communication. Future research might explore integrating social platforms with TOC TP tools, which also prioritize collaboration (Mabin & Cavana, 2024). Furthermore, future studies may target TOC application areas not identified in this review, such as Finance, Marketing, Sales, and People Management. Notably, articles on CCPM are absent, even though research directly discusses I4.0 technologies in project management (Jauhar et al., 2023).

5. Proposition of a framework integrating TOC and I4.0

We propose a framework that integrates TOC with I4.0 technologies, as shown in Figure 3. This integration adapts the three interaction modes between TOC and IT (Coman & Ronen, 1995) to the I4.0 context: i) TOC tools identify and improve constraints while assessing the value of new technologies and guiding their implementation; ii) TOC principles support the implementation of I4.0 technologies; and iii) I4.0 technologies enhance TOC applications.

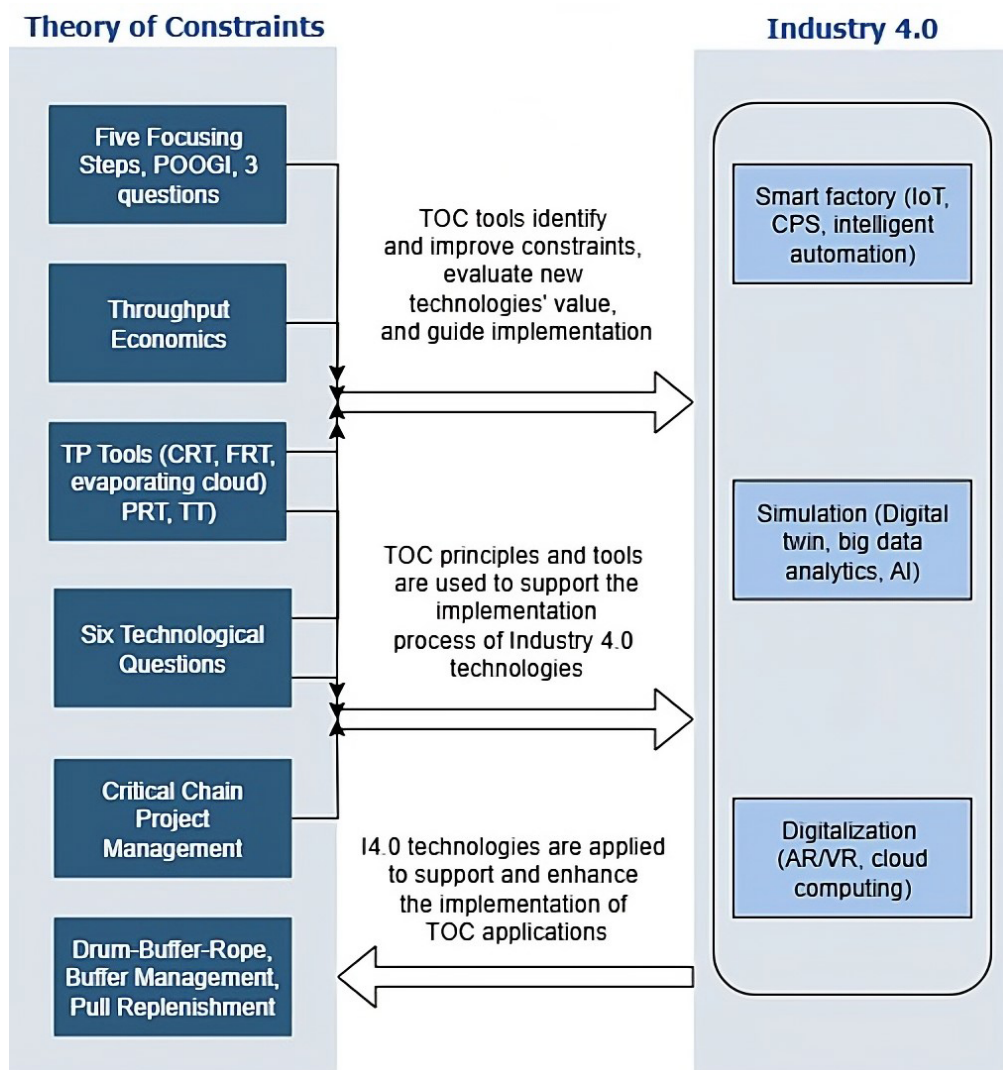


Figure 3. TOC and I4.0 Integration Framework.

5.1. Systems analysis and the need for I4.0 technologies

TOC provides systemic analysis tools to identify and improve constraints while assessing the potential value of adopting new technologies and guiding their implementation. The Five Focusing Steps and the three key questions for ongoing improvement (Cox III, 2019) –“What to change?”, “What to change it into?” and “How to cause the change?”– offer a holistic view of which I4.0 technologies should be applied and where, whether in specific workstations, departments, or broader operational contexts.

The six technological questions help assess the capacity of I4.0 technologies to eliminate existing barriers, considering current rules, policies, and behaviors (Goldratt et al., 2000). This structured approach allows managers to understand the challenges, opportunities, and requirements for a successful digital transformation, ensuring that technology adoption is not just a trend but a necessary and sufficient driver of meaningful improvements.

TOC analyzes the organizational context through its TP tools to pinpoint system constraints and determine where and how to apply technologies effectively (Mabin & Cavana, 2024). This analysis is reinforced by the six technological questions, which serve as a structured guide for targeted technological interventions (Goldratt et al., 2000). Additionally, throughput economics supports selecting I4.0 technologies based on managerial insights that genuinely enhance operational performance, preventing adoption driven solely by trends and allowing for a better evaluation of potential side effects (Rota & Souza, 2021).

Logical trees such as the Current Reality Tree (CRT), the Evaporating Cloud, and the Future Reality Tree (FRT) provide a framework for identifying undesirable system effects (Mabin & Cavana, 2024), uncovering the policies and behaviors that sustain them, and assessing the role of I4.0 technologies in driving the necessary transitions.

5.2. Implementation of I4.0 guided by TOC principles and tools

Additional logical trees derived from TOC's TP tools play a crucial role in driving change and can guide the implementation of I4.0 within a specific organizational context. The Prerequisite Tree (PRT) helps plan and prioritize the necessary actions to achieve the desired outcomes outlined in the Future Reality Tree (FRT) by breaking down complex objectives into actionable steps (Mabin & Cavana, 2024). Meanwhile, the Transition Tree (TT) maps out potential actions and consequences, supporting strategic planning by identifying various pathways and optimizing processes (Mateen & More, 2013).

Furthermore, through Critical Chain Project Management (CCPM), TOC can directly support the execution of projects to implement selected technologies (Luiz et al., 2019). The connection between CCPM and I4.0 applications represents one of the most significant gaps identified in this research. Future studies could empirically assess the advantages and limitations of TOC-based approaches for managing I4.0 implementation projects.

5.3. Technological support of I4.0 in TOC activities

Technology can significantly enhance the implementation of various TOC applications. The most well-documented contributions are in manufacturing (Kuo et al., 2021), where real-time process monitoring and improved data accuracy support constraint identification, buffer sizing, and control.

The literature already highlights the use of generative AI to support TOC's TP tools (Aljaž, 2024a, b). Other applications include the development of digital twins for dynamic monitoring and adjustment of constraints (Ghobakloo, 2018), the integration of RFID and simulation for bottleneck identification (Rohit et al., 2025), and the deployment of AGVs and automated supermarkets to supply the drum in DBR- and JIT-managed manufacturing cells (Rüttimann & Stöckli, 2020).

Future research can explore additional applications, such as big data analytics, AI-based agents, and digital twins, to support DBR, Buffer Management (BM), pull replenishment, and CCPM, among other TOC activities. In summary, the proposed framework suggests a bidirectional relationship between both domains: TOC assists in selecting and implementing technologies, while these technologies, in turn, enhance the application of TOC principles.

6. Conclusion

This article is the first to highlight points of intersection between adopting emerging technologies from I4.0 and the tools and principles of TOC. A systematic and reproducible procedure was used to obtain a sample of 32 articles. The analysis of this sample showed a two-way relationship between the two themes. The current literature describes TOC as a guide for implementing technologies subordinated to the search for better operational performance, allowing a more careful and impartial selection of these solutions. This review also brings several examples of uses of technologies that improve TOC applications, with special mention to those that improve the quality and speed of data used in these applications.

This research contributes to managers adopting I4.0 technologies and TOC practitioners, as many TOC adopters remain unaware of the technological solutions discussed. For academics, it identifies research opportunities at the intersection of TOC and I4.0, highlighting unexplored areas of TOC in the context of new technologies. Educational programs in TOC and I4.0 could integrate these findings into their curricula. Limitations include common biases in systematic reviews, such as subjectivity in filter and keyword choices and result analysis.

Future research could consult experts to deepen the relationships proposed in the framework. Additionally, multi-criteria methods and empirical research could be applied to identify which technologies are more prioritized for TOC applications, as well as to examine how these uses would unfold following the principles of TOC in a systemic way. Empirical research to raise barriers and drivers for implementing the technologies discussed here in TOC environments is welcome.

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Data availability

Research data is only available upon request.

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Author Contributions

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Appendix A. Summary of the sample articles analyzed.

Title	Reference	Contribution
Applying the theory of constraints to health technology assessment	Groop et al. (2010)	Use of a TOC approach to assess mobile technologies applied to health.
Integrating lean and other strategies for mass customization manufacturing: a case study	Stump & Badurdeen (2012)	The research evaluates how TOC can be integrated with lean for production environments with mass customization.
On the strategy of supply chain collaboration based on dynamic inventory target level management: A theory of constraint perspective	Tsou (2013)	The author explores TOC-based supply chain collaboration strategies from data mining techniques.
Throughput accounting and performance of a manufacturing company under stochastic demand and scrap rates	Hilmola & Li (2016)	They propose a simulation for product mix problems under stochastic demand and scrap rates. The model employs DBR and Throughput Accounting approaches.
A practical multiple-tool-set approach for increasing agile response in overhaul production with limited resource requirement visibility	Chou et al. (2016)	Integration of RFID, simulation, and bottleneck identification methods to increase agile response in low visibility of resource requirements.
Real-time scheduling based on optimized topology and communication traffic in distributed real-time computation platform of storm	Li et al. (2017)	A TOC-based algorithm is proposed for real-time programming on a cloud computing platform.
A schedule of cleaning processes for a single-armed cluster tool	Noh et al. (2017)	TOC is used to program the frequency of robotic tool self-cleaning.
Applying theory of constraints-based approach to solve memory allocation of cloud storage	Chang et al. (2017)	This article proposes a TOC-based approach to solving cloud storage memory allocation.
Green Production Planning and Control for the Textile Industry by Using Mathematical Programming and Industry 4.0 Techniques	Tsai (2018)	An integrated approach of TOC-based mathematical models and real-time sensing and detection systems is applied.
A Framework of Production Planning and Control with Carbon Tax under Industry 4.0	Tsai & Lu (2018)	A mathematical programming model integrating activity-based costing (ABC) and TOC using carbon rates, big data, RFID, and MES to control the shop floor.
Green Production Planning and Control Model with ABC under Industry 4.0 for the Paper Industry	Tsai & Lai (2018)	A model based on TOC and ABC is applied in the pulp and paper industry. Aspects of cyber-physical and IoT systems are discussed.
Exploratory Analysis of Modularization Strategy Based on the Theory of Constraints Thinking Process	Eidelwein et al. (2018)	The authors analyze the adoption of modularization strategies by companies using TOC thinking processes.
Smart Manufacturing through TOC based Efficiency Monitoring System (TBEMS)	Balaji et al. (2018)	This article deals with implementing TOC concepts combined with IoT, aiming to increase the speed of technology implementation.
Drum buffer rope-based heuristic for multi-level rolling horizon planning in mixed model production	Saif et al. (2019)	The research investigates the multilevel planning problem in producing mixed models using a heuristic algorithm based on DBR, which helps implement IoT and I4.0.
Analysis of production activity control mechanisms for Industry 4.0	Costa et al. (2019)	The authors use simulations to analyze the performance of several production control methods, including DBR, in the context of I4.0.
From Batch & Queue to Industry 4.0-Type Manufacturing Systems: A Taxonomy of Alternative Production Models	Rüttimann & Stöckli (2020)	The article deals with the transition from traditional manufacturing systems to I4.0 and describes a JIT manufacturing cell based on the DBR approach.
Industry 4.0 enabling manufacturing competitiveness: Delivery performance improvement based on theory of constraints	Kuo et al. (2021)	Buffer control for work-in-process management in due date control, involving machine-to-machine (M2M) communication.
Data-driven project buffer sizing in critical chains	Li et al. (2022)	Project buffer sizing in CCPM using a data-driven approach with Monte Carlo simulation and support vector regression.
An agent-based simulator for quantifying the cost of uncertainty in production systems	Costas et al. (2023)	Use of the DBR mechanism to manage uncertainty in product-mix problems, improving system robustness to variability in demand volume and mix.
Balancing Profit and Environmental Sustainability with Carbon Emissions Management and Industry 4.0 Technologies	Tsai (2023)	I4.0 enhances TOC by integrating real-time sensing, ERP data analysis, and optimization models to improve production efficiency, carbon management, and waste reuse.
Sustainable Digitalization in Pharmaceutical Supply Chains Using Theory of Constraints: A Qualitative Study	Shashi (2023)	Use of digital enablers to identify constraints, optimize processes, and build sustainable, resilient, and agile systems
Revolutionizing Textile Manufacturing: Sustainable and Profitable Production by Integrating Industry 4.0, Activity-Based Costing, and the Theory of Constraints	Tsai et al. (2024b)	Integration of real-time sensing, ERP systems, and mathematical programming to optimize production, reduce waste, and balance profitability with sustainability

Title	Reference	Contribution
Value stream mapping and theory of constraints in a screw company: generating ways for the implementation of Industry 4.0	Helfer et al. (2024)	Application of sensing technologies and VSM to identify bottlenecks and improve profitability at scale.
Enhancing Retail Operations: Integrating Artificial Intelligence into the Theory of Constraints Thinking Process to Solve Shelf Issue	Aljaž (2024a)	Integrating AI into TP tools to identify root causes, optimize inventory management, and improve supply chain efficiency.
Leveraging ChatGPT for Enhanced Logical Analysis in the Theory of Constraints Thinking Process	Aljaž (2024b)	Integrating AI into the TP tools, improving decision-making, root cause analysis, and logical structuring while reducing bias and increasing efficiency.
Lean Office Approach for Continuous Improvement Identification in the Admission Process of University Students	Peralta-Abarca et al. (2024)	I4.0 enhances Lean and TOC in higher education by applying digitalization, sensor networks, and process improvement tools.
A Dynamic Approach to Sustainable Knitted Footwear Production in Industry 4.0: Integrating Short-Term Profitability and Long-Term Carbon Efficiency	Tsai & Su (2024)	Integrating carbon emission costs into a comprehensive model, optimizing profitability and sustainability in knitted shoe manufacturing.
Synergizing ChatGPT and experiential learning: unravelling TOC based production planning and control variants through the dice game	Gupta et al. (2024)	I4.0 enhances experiential learning in PPC by integrating AI with Goldratt's Dice Game to deepen understanding of DBR systems.
Solving business problems: the business-driven data-supported process	Rodgers et al. (2024)	Guiding businesses through the BDDS process, ensuring data is used effectively to identify performance gaps, uncover root causes, and generate actionable insights.
A Moderated Model of Open Innovation: An Integration of Theories of Constraint and Dynamic Capabilities	Hagan et al. (2024)	Digital transformation (DT) aligns with TOC and dynamic capability theories to explore how external constraints limit DT's impact on open innovation.
Theory of AI-driven scheduling (TAIS): a service-oriented scheduling framework by integrating theory of constraints and AI	Khakifirooz et al. (2024)	AI-driven scheduling framework, integrating continuous monitoring, lifecycle management, and adaptability.
Predicting task bottlenecks in digital manufacturing enterprises based on spatio-temporal graph convolutional networks	Yin et al. (2025)	This study introduces a deep learning-based model for predicting task throughput bottlenecks in digital manufacturing enterprises.