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The role of optimal control theory in the curricular proposal for dynamic supply chains in industrial engineering education

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1 Introduction

This research communication aims to present a curricular proposal to relate the importance of the application of optimal control theory for dynamic supply chains for industrial engineering students and practitioners. This is done by considering the role of model-based optimal control theory in management sciences, specifically for dynamic supply chains (DSCs) at the operational level, with emphasis on high-volume production systems.

In general, control theory relates the core idea of maintaining an equilibrium and a stable state with uncertainty and disturbance (Wiener, 1948). Moreover, a classical control system is rooted in the concept of feedback systems. A general goal of control systems is to minimize the level of error in the system, subject to some performance criteria. Mathematical modeling and analysis of control systems presents the following taxonomy: model-based control and data-driven control. In general, model-based control can be classified into the following sub-classes: optimal control, robust control, adaptive control, and intelligent control. Our aim in this research communication is to present the importance of optimal control theory, which is analyzed via the Pontryagin maximum principle, and evaluate its impact on improving the curricular proposal for DSCs for industrial engineering practitioners.

In the past, interest in investigating the dynamic behavior of management control systems has been growing (Connors and Teichroew, 1967). The mathematical description of a dynamical system is often in terms of difference or differential equations. A general theory exists that permits us to determine the optimal control of such a system according to suitable performance criteria. Necessary and sufficient conditions of optimality are derived from a class of optimal control problems. Our interest is to present conventional optimal control problems for linear time-invariant dynamical systems in the context of industrial engineering education. Applications of optimal control in management sciences and operations research are (1) pricing, (2) scheduling, (3) logistics networks, (4) optimal transfer of technology, and (5) optimal remanufacturing and recycling in closed-loop supply chains, among others. Therefore, decision-makers in management sciences and operations research use optimal control theory to map dynamic optimization methods to those suited to the complexity of the DSC system. In the following section, optimal control

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theory for DSCs is addressed, including the role of mathematical modeling, the calculus of variations, and optimal control theory applied to DSCs.

2 Optimal control theory for dynamic supply chains

Nowadays, supply chain management (SCM) refers to the cooperation process management of materials and information flows between supply chain partners (Sucky, 2005). From here, the principal components in generic manufacturing supply chain networks are suppliers, manufacturers, customers, logistics and distribution networks, and retailing centers (Kamble et al., 2020). As a general definition, "A supply chain is a network of suppliers that produce goods, both for one another and for generic customers" (Daganzo, 2003).

2.1 Mathematical modeling

Dynamic supply chains are important to minimize inventory and to allow the flow of raw material, cash, information, labor force, and energy while maximizing profits along the entire operation (Taboada et al., 2022). This DSC operation requires decision-making with synchronization. Mathematical modeling for optimal control theory, from engineering education perspective, justifies proper skills in ordinary differential equations (ODEs), which mainly are based on linear systems of first and second order in the DSC context (Zill, 2016). This is considering that the root of the applicability of OCT are the state-space formulation for the description of the evolution of the DSC system by considering the definition of inputs, states, and outputs for the dynamical system mathematical description. However, DSCs can be modeled via partial differential equations (Davizon et al., 2023). This type of mathematical modeling is out of the scope of our research communication.

Besides, while the main goal along the DSCs is to regulate inventory levels, which are present all along the DSCs, inventory control is a crucial activity by a company's management (Bieniek, 2019). Presenting appropriate inventory levels is a crucial task for an enterprise (Duan and Ventura, 2019), as fast customer response is associated with high inventory levels (which increase costs), while low inventory levels may lead to scarcity.

2.2 Calculus of variations

Calculus of variations (CV) has its roots in the 17th century, from classical optimization problems such as the brachistochrone; it was formalized by Euler and Lagrange, who developed the Euler–Lagrange equation. The problem of the calculus of variations emerges from mathematical analysis of functions (Komzsik, 2009). In general, CV is a mathematical discipline related to determining the function, curve, or surface that optimizes a given functional, typically expressed as an integral dependent on a function with proper derivatives. In practice, CVs expand classical calculus by finding entire functions, paths, or shapes that minimize or maximize a given physical or performance criterion. Furthermore, it connects mathematical modeling with physical intuition, preparing future engineers to approach interdisciplinary problems with a rigorous and systematic methodology. In essence, it offers a unified framework for understanding how natural and artificial systems evolve toward optimal configurations.

2.3 The Pontryagin maximum principle: optimal control theory

In general, optimal control theory requires a mathematical model to apply Pontryagin's maximum principle. An optimal control is defined as an admissible control that minimizes a functional objective. Based on this, given a dynamical system with initial condition x_0, which evolves in time according to the state space equation $\dot{x} = f(x, u, t)$, to find an admissible control and make the functional objective achieve its maximum.

A general mathematical form for the optimal control problem is:

$$\begin{aligned} \min_{u} J(u) = \frac{1}{2}\int_{to}^{tf} F(x,u,t)dt + S\left[x\left(t_f\right)\right] \\ \text{s.t.} \\ \dot{x} = f(x,u,t) \\ x(t_0) = x_0, x \in X, u \in U \end{aligned} \tag{1}$$

Therefore, optimal control methods require: (1) a performance index; (2) dynamical systems to optimize; and (3) constraints on states, inputs, and outputs.

2.3.1 Minimum time-optimal control

Consider the following optimal control problems for a linear system.

$$\begin{aligned} \min_{u} J(u) = \int_{to}^{tf} 1dt \\ \text{s.t.} \\ \dot{x} = Ax(t) + Bu(t) \\ x(0) = x_0, x(T) = x_f \ (fixed) \\ u \in U \end{aligned} \tag{2}$$

This is called a minimum time optimal control problem based on the context that the objective is to transfer the state x from a fixed initial point x_i to a fixed final point x_f in a minimum time, which implies a time-optimal way. In supply chain systems, minimum-time optimal control improves coordinated and efficient transitions between inputs, states, and outputs, from production setups to logistics reconfiguration.

2.3.2. Minimum fuel optimal control

The minimum-fuel optimal control problem enables sustainable, energy-efficient, and low-emission supply chains by optimizing transportation, production, and network operations to balance economic and environmental tradeoffs, such as positive and negative externalities in the minimum fuel optimal control approach.

The general form of the minimum fuel performance index is:

$$\min_{u} J(u) = \int_0^T |u|\, dt \quad \text{s.t.} \quad \dot{x} = Ax(t) + Bu(t), \quad x(0) = x_0, x(T) = x_f\ (\textit{fixed}), \quad u \in U \tag{3}$$

2.3.3. Minimum energy optimal control

The minimum-energy optimal control problem improves supply chain performance by minimizing energy consumption across transportation, production, and logistics processes, promoting the equilibrium between economic efficiency and environmental goals. For a minimum energy optimal control problem, the performance index is:

$$\min_{u} J(u) = \frac{1}{2}\int_0^T u^2 dt \quad s.t. \quad \dot{x} = Ax(t) + Bu(t), \quad x(0) = x_0, x(T) = x_f\ (\textit{fixed}), \quad u \in U \tag{4}$$

2.4 The curricular proposal for OCT in DSCs

2.4.1 Optimal control in dynamic supply chains

Optimal control theory justifies its application in DSCs by enabling time-dependent decisions that optimize inventory, production, and distribution. Additionally, it supports practices with real-time, automated systems, making DSCs more optimal, adaptive, and robust from a systems theory perspective.

Optimal integrated ordering and production control in a supply chain for finite-capacitated warehouses is analyzed in Song (2009). In Kogan et al. (2010), address a differential game where the effect of information asymmetry is present under stochastic demand. Considering the dynamic nature of goods flow processes, efficient inventory management in production–inventory systems is presented in Ignaciuk and Bartoszewicz (2010). In Ignaciuk and Bartoszewicz (2012), a control theory approach presented to the problem of inventory control in systems with perishable goods. The applicability of optimal control theory to supply chain management is analyzed by Ivanov et al. (2012) is which is based on the fundamentals of control and systems theory. Furthermore, the problem of supply chain coordination by a robust schedule coordination approach, applying optimal control theory, is addressed in Ivanov et al. (2016). In Dolgui et al. (2018), a survey on optimal control applications to scheduling in production, supply chain, and Industry 4.0 systems via the deterministic maximum principle is presented. An optimal control model is present for a class of low-carbon supply chain systems, as depicted in Yu et al. (2020). In Raritàa et al. (2021), supply chains are modeled by partial and ordinary differential equations.

2.4.2 The curricular proposal methodology

In industrial engineering, real-world problems, such as allocating resources, scheduling production, or managing inventories so that costs are minimized or revenue is maximized, involve decision-making within a certain time horizon. Optimal control theory develops mathematical modeling, optimization, and systems engineering as an essential part of industrial engineering education. It trains future engineers to think dynamically, make informed decisions, skills that are mandatory in modern industry and automation-driven, at the operational level, for high-volume production systems. In industrial engineering, these principles are applied to problems such as production scheduling, inventory management, and process automation. By integrating mathematical modeling, systems analysis, and decision-making, optimal control theory advances the development of critical

TABLE 1 Syllabus scheduling for the course "Optimal control principles for dynamic supply chains."

Course topic	Course scheduling per week: "optimal control principles for dynamic supply chain"														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Introduction to DSC	■														
Mathematical modeling		■	■												
State-space formulation			■	■	■										
Calculus of variations						■	■	■							
Optimal control: PMP									■	■	■	■			
Case study 1												■	■		
Case study 1														■	■

competencies for designing and managing industrial systems at the operational level.

Based on this, a suitable curricular proposal is mandatory to address the application of optimal control theory in dynamic supply chains; this is by means of the context of feedback systems and proper analogy applied in a Gantt diagram. Refer to Table 1 for the syllabus design of an undergraduate-level course entitled “Optimal control principles for dynamic supply chains.”

This syllabus scheduling is based on a regular course of 15 weeks, which are divided into serial topics such as: (1) introduction to dynamic supply chains, (2) mathematical modeling, (3) state-space formulation, (4) the calculus of variations, (5) PMP in engineering education, (6) case study 1: high-volume DSCs, and (7) case study 2: time-delayed DSCs.

Optimal control theory plays an important role in industrial engineering education, providing students with the analytical and computational tools to model, optimize, and regulate DSCs. The principles of the calculus of variations provide a systematic platform for determining time-dependent control strategies that achieve optimal performance under given constraints, as we previously presented.

3 Discussion

In dynamic supply chains, operations and production planning processes enable decision-makers to make convenient and suitable decisions, validate their hypothesis about which decisions incorporate more profit while reducing costs in enterprise operations. Based on this, inventory management plays an important role in the DSC analysis. In future studies, we will incorporate optimal control theory into industrial engineering curricula to enhance students’ capacity to address real-world challenges through rigorous, optimization-based approaches. Engineering education faces difficulties due to misunderstandings that obstruct students from comprehending core scientific concepts (Guerra and Meneses, 2025). Moreover, optimal control for DSC application aligns with emerging paradigms such as Industry 4.0 and smart manufacturing, where adaptive and data-driven control strategies are of interest to explore in practical case studies.

Finally, the analysis and optimization of DSCs are enabled by mathematical modeling, CV, and optimal control, all of which are critical components of engineering education. and successfully integrated mathematical theory with engineering practice for future industrial engineering practitioners, strengthening analytical thinking and the capacity to build effective systems and technologically sophisticated solutions for processes.

Author contributions

YD: Methodology, Conceptualization, Writing – review & editing, Writing – original draft. JS-L: Resources, Project administration, Methodology, Conceptualization, Writing – review & editing, Funding acquisition. ES: Writing – original draft, Funding acquisition, Methodology, Validation, Conceptualization. NS: Writing – original draft, Resources, Funding acquisition, Methodology, Validation, Conceptualization, Writing – review & editing.

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Conflict of interest

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The author(s) declared that generative AI was not used in the creation of this manuscript.

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