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Otimização Baseada em Simulação para o Planejamento Integrado de Estoque, Produção e Transporte

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Matheus Cardoso Pires

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O presente trabalho em nível de doutorado foi avaliado e aprovado por banca examinadora composta pelos seguintes membros:

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Certificamos que esta é a **versão original e final** do trabalho de conclusão que foi julgado adequado para obtenção do título de Doutor em Engenharia de Produção.

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Prof. Enzo Morosini Frazzon, Dr.-Ing.
Orientador

Florianópolis, 2023.

Este trabalho é dedicado à minha família, que acompanha minha caminhada a qualquer distância.

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“Nada é difícil se for dividido em pequenas partes” (Henry Ford)

RESUMO

O objetivo da presente pesquisa é propor uma abordagem de planejamento capaz de lidar com cenários complexos e compostos por variáveis estocásticas, abrangendo estoque de matéria prima, produção e entrega. Tal tipo de abordagem é necessário pois a visão de empresas trabalhando isoladamente evoluiu para uma visão holística, onde empresas atuam de forma integrada para manter sua competitividade no mercado. Para adquirir vantagem competitiva, o planejamento integrado pode aprimorar o desempenho global do sistema. A eficiência dos sistemas de manufatura depende da alocação adequada de recursos. Devido às interdependências existentes, a consideração integrada dos processos de produção, transporte e controle de estoque pode melhorar o desempenho geral do sistema produtivo. Atualmente, estudos atuais convergem para o desenvolvimento e validação de métodos de otimização mais eficientes computacionalmente e que consigam considerar um comportamento mais real das cadeias de suprimentos, incluindo comportamentos estocásticos e cenários mais complexos. Além disso, os conceitos e tecnologias introduzidos pela quarta revolução industrial apoiam a viabilização desses novos modelos de planejamento integrado. Para lidar com tal necessidade, é proposto um método de otimização baseado em simulação para o planejamento do estoque de matérias-primas, da produção e da entrega, capaz de lidar com sistemas complexos envolvendo grande número de elementos e variáveis, dentro de ambientes dinâmicos contendo diversas variáveis estocásticas. Os resultados obtidos mostram que a abordagem é capaz de lidar com a complexidade e estocasticidade dos sistemas de produção do mundo real, superando os métodos clássicos de planejamento e controle. Por último, o modelo de otimização baseada em simulação é testado e comparado a um caso real em uma indústria de equipamentos elétricos, onde o modelo demonstrou um desempenho superior ao obtido nas práticas clássicas de programação da produção, compra de matéria-prima e entrega.

Palavras-chave: Logística, Pesquisa Operacional, Otimização, Simulação, Planejamento.

ABSTRACT

The objective of this research is to propose a planning approach capable of dealing with complex scenarios composed of stochastic variables, covering raw material stock, production and delivery. This type of approach is necessary because the vision of companies working in isolation has evolved into a holistic vision, where companies act in an integrated manner to maintain their competitiveness in the market. To gain competitive advantage, integrated planning can improve overall system performance. The efficiency of manufacturing systems depends on the appropriate allocation of resources. Due to existing interdependencies, the integrated consideration of production, transportation and inventory control processes can improve the overall performance of the production system. Currently, current studies converge towards the development and validation of more computationally efficient optimization methods that are able to consider more real behavior of supply chains, including stochastic behaviors and more complex scenarios. Furthermore, the concepts and technologies introduced by the fourth industrial revolution support the feasibility of these new integrated planning models. To deal with this need, a simulation-based optimization method is proposed for planning raw material inventory, production and delivery, capable of dealing with complex systems involving a large number of elements and variables, within dynamic environments containing several stochastic variables. The results obtained show that the approach is capable of dealing with the complexity and stochasticity of real-world production systems, surpassing classical planning and control methods. Finally, the simulation-based optimization model is tested and compared to a real case in an electrical equipment industry, where the model demonstrated superior performance to that obtained in classic practices of production scheduling, raw material purchasing and delivery.

Keywords: Logistic, Operations Research, Optimization, Simulation, Planning.

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LISTA DE QUADROS

LISTA DE ABREVIATURAS E SIGLAS

IoT	Internet of Things
CPS	Cyber Physical Systems
RFID	Radio Frequency Identification
EWO	Enterprise Wide Optimization
MIP	Mixed Integer Programming
MINLF	Mixed Integer Non-Linear Formulation
MINLP	Mixed Integer Non-Linear Programming
IBFA	Integrated Bacteria Foraging Algorithm
FPBH	Five Phase Based Heuristic
DC	Distribution Center
PSO	Particle Swarm Optimization
DPSO	Discrete Particle Swarm Optimization
SC	Supply Chain
MDPD	Manufacturing Distribution Planning Decision
MOP	Multi Objective Programming
GHG	Greenhouse Gas
EOQ	Economic Order Quantity
LTL	Less Than Truck Load
TL	Truck Load
JIT	Just In Time
GA	Genetic Algorithm
LNS	Large Neighborhood Search
P-D	Production Distribution
SS	Safety Stock
SBO	Simulation Based Optimization
SCI	Supply Chain Integration
SD	System Dynamics
BWE	Bullwhip Effect
GVNS	General Variable Neighborhood Search

SUMÁRIO

1 INTRODUÇÃO

A entrega de um produto a um consumidor é precedida por diversas etapas executadas por diferentes setores e empresas. Tais participantes do processo, com o objetivo de simplificar o sistema e manter seus interesses individuais, trocam o mínimo de informações e tomam suas próximas decisões considerando ótimos locais e momentâneos, em geral. Consequentemente, considerando os sistemas como um todo, os resultados em nível de eficiência e eficácia tendem a ficar aquém do que poderiam. Portando, cada vez mais as indústrias estão tentando integrar seus processos de planejamento de produção e distribuição para otimizá-los simultaneamente, adquirindo melhores resultados (SCHOLZ-REITER *et al.*, 2011).

Como é possível ver em Scholz-Reiter *et al.* (2011), atualmente a coordenação entre os processos de planejamento de produção e programação da distribuição é simplificadamente embasada em pouquíssima informação trocada entre atores de uma cadeia de suprimentos, o que faz com que normalmente os modelos de tomada de decisão não consigam representar de forma satisfatória o ambiente dinâmico que realmente é uma cadeia de suprimentos. Sendo assim, novos conceitos no âmbito de comunicação se fazem necessários para melhor embasamento de métodos de otimização dos processos de produção e distribuição na cadeia de suprimentos. Chen (2004) por sua vez também reitera a importância da coordenação entre o planejamento de produção e distribuição e Chen e Vairaktarakis (2005) propõem um modelo de planejamento integrado da produção e distribuição. Mula *et al.* (2010) também discorre sobre tal importância e faz um levantamento sobre os modelos existentes de integração do planejamento da produção e dos transportes.

Além disso, a inovação tecnológica e as demandas dos clientes levaram o cenário industrial a vários desafios e oportunidades de avanços, e esse novo cenário foi considerado a nova Revolução Industrial, comumente abordada como Indústria 4.0 (BARRETO; AMARAL; PEREIRA, 2017). O nome baseia-se no programa do governo alemão para promover a informatização de indústrias, originalmente a *Industrie 4.0*. No entanto, vários outros países promoveram programas semelhantes, por exemplo, Estados Unidos da América, que nomearam esforços de digitalização como *Smart Manufacturing* e Japão e Coréia (THOBEN; WIESNER; WUEST, 2017). A nova revolução é impulsionada pela possibilidade de um nível mais alto de comunicação entre pessoas, máquinas e recursos, com base em três componentes principais: Internet das Coisas (IoT), Sistemas Ciber-Físicos (CPS) e Fábricas Inteligentes, todos eles possíveis através do uso de identificação por frequência de rádio (RFID), sensores, atuadores e redes de comunicação (HERMANN; PENTEK; OTTO, 2016).

Sistemas ciber-físicos são sistemas constituídos de entidades computacionais com forte conexão trabalhando de forma colaborativa dentro do mundo físico provendo e usando simultaneamente serviços de acesso e processamento de dados dentro de uma rede (MONOSTORI *et al*., 2016). De acordo com Lee, Bagheri e Kao (2015), a partir dos sistemas *cyber*-físicos máquinas conectadas a uma mesma rede conseguirão alcançar melhores desempenhos, colaborativos e resilientes. Sistemas ciber-físicos são comumente considerados como a porta para a quarta revolução industrial e podem ser a chave para a integração e sincronização de processos dentro da indústria e entre as indústrias em uma cadeia de suprimentos.

1.1 PROBLEMA DE PESQUISA

De acordo com Chopra e Meindl (2013), o inventário abrange todas as matérias-primas, produtos em processo e produtos acabados de uma empresa. Além dos objetivos de alta confiabilidade na data de vencimento, tempos de produção curtos e alta utilização de recursos, os baixos estoques representam o quarto objetivo importante do sistema de objetivos logísticos de Wiendahl (2014). Portanto, o objetivo do planejamento de estoque é determinar a quantidade certa de estoque para atingir o nível certo de capacidade de resposta com o menor custo possível. Para reabastecer estoques de matérias-primas ou produtos acabados, diferentes estratégias de pedidos podem ser aplicadas (CHOPRA; MEINDL, 2013). Essas estratégias determinam o tempo e a quantidade de pedidos. O tempo de reordenação pode ser periódico ou orientado a eventos, ou seja, quando o nível de estoque cair abaixo de um determinado valor mínimo (ponto de pedido). A quantidade da ordem pode ser um valor fixo ou a diferença entre o estoque atual e o nível de estoque desejado. Embora os estoques de produtos acabadas e o material em processamento sejam considerados pela atribuição de prazos para o planejamento da produção, o controle do estoque de matérias-primas geralmente não é considerado explicitamente nas abordagens de planejamento e controle da produção. Apesar de, tradicionalmente, o planejamento de estoque de matéria prima ser considerado uma tarefa individual separada do planejamento e controle da produção, existem abordagens para integrar as duas tarefas de planejamento (LEE, 2005; KIM *et al.,* 2006; MUNGAN *et al.,* 2010; SANA, 2011; YU *et al*., 2011; KUMAR *et al*., 2016). No entanto, essas abordagens se concentram nas decisões de planejamento de longo prazo e não permitem uma reação às mudanças dinâmicas em tempo real, estando aí uma oportunidade de englobá-la no planejamento integrado.

No entanto, a tentativa de englobar muitas organizações, operações e clientes leva a um cenário de alta incerteza de diferentes fontes (PEIDRO *et al*., 2009). Segundo Peidro *et al.* (2009), a incerteza surge de três fontes em uma cadeia de suprimentos: demanda, processo de transformação e suprimento. Dessa forma, modelos analíticos podem ser pouco adequados, uma vez que pode haver variações em tempos de entrega, tempos de processamento, refugos, disponibilidade de máquinas e até demanda. A incerteza de modelagem na modelagem da cadeia de suprimentos para planejamento e suporte a decisões impõe desafios. No entanto, isso deve ser considerado nas questões de planejamento e controle, a fim de obter políticas e planos robustos.

O problema de pesquisa então resume-se à inclusão do planejamento e controle do estoque de matéria-prima ao planejamento da produção e da cadeia de suprimentos como um todo, e ainda, como lidar com a inclusão de mais uma etapa da cadeia de forma simples, eficiente e eficaz, podendo lidar com a quantidade de incertezas geradas pelo extenso cenário considerado.

Para lidar com esse comportamento, a otimização baseada em simulação é uma abordagem que possui recursos para lidar eficientemente com um cenário estendido, levando em consideração a dinâmica dos sistemas, levando a soluções quase ótimas em um tempo possível (LIOTTA *et al*., 2016). Métodos baseados em simulação podem ser usados para desenvolver e avaliar sistemas complexos. Aspectos como configuração física ou regras operacionais de um sistema podem ser considerados. Suas aplicações cresceram em diversas áreas, auxiliando os gerentes no processo de tomada de decisão e permitindo uma melhor compreensão dos processos em sistemas complexos (SAKURADA; MIYAKE, 2009). Essas premissas são expressas em relações matemáticas, lógicas e simbólicas entre as entidades ou objetos de interesse do sistema. Dessa forma, as possíveis alterações do sistema podem primeiro ser simuladas para prever seu impacto no desempenho do sistema. Além disso, a simulação também permite ao tomador de decisão avaliar várias políticas de controle (PIRARD *et al*., 2011). Numerosas réplicas das simulações podem ser realizadas para avaliar a robustez do projeto implementado. Infelizmente, a simulação não garante um *design* ideal. No entanto, a desvantagem apresentada pode ser equilibrada com a integração de outras ferramentas, como a modelagem matemática.

A combinação de modelos de simulação e programação matemática em um esquema iterativo, visa avaliar os efeitos das decisões no desempenho de um sistema de manufatura. Assim, trabalhos nesse sentido concentram-se na integração de diferentes metodologias de modelagem, a fim de combinar as vantagens oferecidas por cada uma delas na solução de problemas complexos. Os modelos analíticos buscam soluções que avaliam os valores ideais das variáveis de decisão. No entanto, as soluções fornecidas são geralmente limitadas em seus campos de aplicação devido a premissas restritivas predeterminadas. Os modelos de simulação, por sua vez, são mais capazes de capturar o comportamento real do sistema, mas não são adequados para resolver problemas de otimização. A integração de modelos analíticos e de simulação, também chamados de modelos híbridos, leva a representar uma opção promissora para melhores resultados (LIN; CHEN, 2015). Assim, os modelos híbridos buscam combinar as vantagens e evitar as desvantagens de ambas as ferramentas (PEIDRO *et al.*, 2009).

1.2 OBJETIVOS

Considerando o problema de pesquisa apresentado, os objetivos gerais e específicos desse estudo são apresentados a seguir.

1.2.1 Objetivo Geral

O objetivo da presente pesquisa é propor um método de otimização baseado em simulação para o planejamento do estoque de matérias-primas, da produção e da entrega, capaz de lidar com sistemas complexos envolvendo grande número de atores e variáveis, dentro de ambientes dinâmicos contendo diversas variáveis estocásticas.

1.2.2 Objetivos Específicos

a) Identificar lacunas e oportunidades na área de planejamento integrado da cadeia de suprimentos bem como delimitar principais métodos/tecnologias de planejamento integrado da cadeia de suprimentos;
b) Propor um modelo conceitual de planejamento integrado de estoque de matéria-prima, produção e transporte utilizando otimização adaptativa

baseada em simulação e comparar os resultados do modelo proposto com o de modelos já validados na literatura;

c) Avaliar o desempenho do modelo proposto utilizando dados provenientes de uma aplicação real, analisando potenciais ganhos em termos de desempenho operacional em cenários envolvendo comportamentos estocásticos.

1.3 JUSTIFICATIVA E RELEVÂNCIA

Ao longo dos anos, prevaleceu a visão de uma empresa que trabalha não isolada, mas em conjunto com outras empresas (CHAE *et al*., 2014). Assim, estruturas da cadeia de suprimentos cada vez mais complexas em ambientes dinâmicos exigem capacidade de resposta e produtividade, nas quais os recursos existentes do sistema são empregados da maneira mais eficiente possível (EHM *et al*., 2015; FRAZZON *et al*., 2017). A Indústria 4.0 e sua ampla gama de conceitos e tecnologias podem contribuir para a materialização da produtividade e da capacidade de resposta (LASI *et al*., 2014). No entanto, conectar muitas organizações, operações e clientes leva a um cenário de alta incerteza de diferentes fontes (PEIDRO *et al*., 2009). No entanto, isso deve ser considerado nas questões de planejamento e controle, a fim de obter políticas e planos robustos.

Portanto, essa revolução na indústria certamente terá efeitos positivos em como gerenciar o fluxo de materiais e informações, estendendo os avanços à perspectiva da logística e da cadeia de suprimentos (BARRETO; AMARAL; PEREIRA, 2017). Maier, Korbel e Brem (2015) reforçam que a aplicação das tecnologias da Indústria 4.0 pode levar à inovação nas cadeias de suprimentos e resolver problemas como a assimetria de informação.

Chamada por Queiroz *et al*. (2017) de cadeia de suprimentos inteligente e por Büyüközkan e Göçer (2018) de cadeia de suprimentos digital, uma nova era para o cenário da cadeia de suprimentos está sendo construída com base em princípios e tecnologias da nova revolução industrial e impactará vários processos. Visando à competitividade, o planejamento da cadeia de suprimentos é uma chave importante para a eficiência e poucos autores já exploraram as oportunidades introduzidas pela quarta revolução industrial. Por exemplo, Ivanov *et al*. (2016) propõem um modelo dinâmico e um algoritmo para o agendamento da cadeia de suprimentos no contexto da Indústria 4.0.

A presente pesquisa tem o objetivo de ir ao encontro das bases da Indústria 4.0, extraindo os benefícios proporcionados pelas tecnologias que vem surgindo ao mesmo tempo que apresenta uma forma de lidar com o grande comportamento dinâmico e com os cenários complexos que surgem junto a tal revolução industrial. Tal pesquisa torna-se relevante primeiramente para comunidade científica, destacando as oportunidades de utilização da abordagem de otimização baseada em simulação para lidar com cenários complexos e estocásticos, bem como demonstra a oportunidade e viabilidade de trabalhar com planejamento integrado de estoque de matéria prima, planejamento da produção, e programação de entrega. Além disso, a pesquisa pode auxiliar gestores de cadeias de suprimentos a verem as possibilidades de se utilizar a abordagem, reiterando as oportunidades de se utilizar gêmeos digitais e simulação para o planejamento da cadeia de suprimentos.

1.4 CONTRIBUIÇÃO E INEDITISMO

Pires, Parreira e Frazzon (2021) indicam que há lacunas de pesquisa referente ao planejamento integrado de compras, produção e entrega. Os autores ainda destacatam os potenciais pouco explorados das capabilidades da Indústria 4.0 nos modelos de planejamento para a cadeia de suprimentos, havendo então uma lacuna em modelos capazes de lidar com estocasticidade e cenários mais complexos envolvendo várias etapas da cadeia de suprimentos. Liotta *et al*. (2016) afirmam que a otimização baseada em simulação é uma estratégia para lidar com a incerteza na cadeia de suprimentos, e utiliza o método híbrido para transporte e produção sustentáveis em redes colaborativas. Frazzon *et al*. (2017) propõem abordagens de otimização baseada em simulação para lidar com sistemas complexos, que consistem em uma otimização baseada em simulação adaptativa, considerando programação da produção e transporte. No modelo conceitual do método proposto pelos autores em Frazzon *et al*. (2017), os dados em tempo real alimentam a otimização baseada em simulação, que gera cenários, executa estratégias de otimização local e fornece feedback para aprimorar a simulação. A simulação pode representar melhores ambientes dinâmicos com comportamento estocástico, enquanto as estratégias de otimização podem gerar soluções com baixos custos computacionais. Kück *et al*. (2017) desenvolveram uma abordagem de otimização baseada em simulação adaptativa e orientada a dados para determinar regras de despacho adequadas para controle de produção em um aplicativo da fabricação de semicondutores. Esse método foi estendido por uma estrutura de troca de dados para obter a capacidade de reagir a mudanças dinâmicas em tempo real. Uma avaliação em um cenário de um fabricante brasileiro de componentes mecânicos para a indústria automotiva mostrou melhor desempenho operacional em comparação com o procedimento anteriormente aplicado pela empresa e em comparação com as regras de despacho estático (FRAZZON *et al.*, 2017). Como pode ser observado em Pires *et al.* (2020), a utilização de otimização baseada em simulação é uma oportunidade de lidar com as lacunas necessárias do campo de planejamento da cadeia de suprimentos, mas há inedistismo em lidar simultaneamente com a etapa de compras de matéria prima, produção e distribuição de produtos acabados.

1.5 DELIMITAÇÕES

Para tornar os objetivos do presente trabalho factíveis de serem alcançados, será necessária uma delimitação do escopo da pesquisa, maximizando a eficiência e qualidade da solução atingimento das lacunas encontradas.

Primeiramente, em se tratando da revisão sistemática da literatura, foram consideradas as palavras-chaves: "*Supply Chain*", "*Integrated*", "*Planning*", "*Control*", "*Supplier Selection*", "*Material Inventory*", "*Production*", "*Scheduling*", "*Transportation*", "*Distribution*", "*Routing*", "*Sales and Operations*". A estrutura lógica pode ser vista na íntegra na Fase 1 da pesquisa. As buscas também se limitaram às bases de dados *Web of Science*, *Scopus* e *Science Direct*, considerando apenas documentos escritos em língua inglesa.

Na Fase 2, a implementação se limitará a considerar estoque de matéria-prima, produção e transporte. Áreas adjacentes podem estar presentes na simulação, mas não serão consideradas nas variáveis de decisão. Ainda, o modelo proposto será comparado com um cenário de *benchmarking* que aplicará métodos clássicos da literatura para lidar com as áreas.

Na fase final, de implementação de caso teste, aspectos de sigilo serão limitantes em alguns pontos, por tanto, a implementação do modelo será em grau médio de abstração, com custos detalhados e listas técnicas não disponibilizadas.

1.6 ESTRUTURA

O presente documento está organizado como segue. No Capítulo dois será apresentada metodologia das pesquisas e suas características, como o procedimento de pesquisa e a classificação da mesma. No capítulo de metodologia de pesquisa será abordado também as particularidades da estrutura do compêndio de artigos, feito com base na Resolução 001/PPGEP/2018, de 07/11/2018, da Universidade Federal de Santa Catarina (UFSC), opção de execução da presente tese. No presente modelo escolhido, as macro etapas da pesquisa, que serão apresentadas no Capítulo 2 junto a metodologia de pesquisa, são oficializadas por artigos publicados ou submetidos a periódicos ou conferências, sendo cada etapa então revisada por pares e resultando em um artigo, nesse documento apresentado em forma de capítulos. Objetivando trabalhar com a comunidade científica global, os artigos resultantes de cada etapa da pesquisa foram confeccionados e submetidos na linguagem inglesa.

Após a metodologia, no Capítulo 3 será apresentada a primeira fase da pesquisa, correspondente a identificação de lacunas e principais correntes de pesquisa relacionadas ao planejamento integrado da cadeia de suprimentos. No Capítulo 4, será apresentada a segunda fase da pesquisa, onde um modelo conceitual é proposto objetivando o preenchimento das lacunas identificadas na primeira etapa. Ainda na segunda etapa, uma aplicação teste hipotética é implementada no modelo conceitual, para a verificação da factibilidade e convergência do modelo proposto. Na etapa final da pesquisa, apresentada no Capítulo 5, o modelo conceitual é aplicado virtualmente em um caso teste existente na realidade, com o intuito de gerar um comparativo de desempenho entre o estado atual de uma indústria e os resultados do modelo proposto. Por sua vez, o Capítulo 6 traz uma síntese da pesquisa como um todo e suas contribuições, bem como discussões dos seus resultados. Finalizando, no Capítulo 7 são apresentadas as conclusões da pesquisa.

Ainda com relação a formatação específica do modelo Compêndio de Artigos, alguns aspectos individuais do modelo devem ser ressaltados:

- Conforme formalizado na resolução supracitada, os Capítulos 1, 2, 6 e 7 foram escritos em língua portuguesa, enquanto os Capítulos 3, 4 e 5 foram mantidos na língua inglesa, preservando os documentos submetidos originalmente;
- As referências, figuras e demais componentes seguem o formato ABNT (Associação Brasileira de Normas Técnicas) nos capítulos 1, 2, 6 e 7;
- Os capítulos 3, 4 e 5 mantém a formatação do documento publicado ou submetido, incluindo suas referências;

- As referências dos Capítulos 1, 2, 6 e 7 são apresentadas em uma única lista encontrada ao final do presente documento;
- As referências das etapas em língua inglesa se encontram diretamente no final de cada capítulo, pois fazem parte do documento submetido em formato de artigo;
- Os documentos originais das etapas já publicadas podem ser acessados através do Identificador de Objeto Digital (*Digital Object Identifier, DOI*) disponível em seu respectivo capítulo.

2 PROCEDIMENTOS METODOLÓGICOS

Neste capítulo é apresentada a metodologia para desenvolvimento da tese, sendo dividida em (i) procedimento metodológico, no qual são apresentados os relacionamentos entre as fases (artigos) e (ii) enquadramento metodológico, o qual apresenta a relação entre as fases (artigos) e os objetivos específicos.

2.1 CLASSIFICAÇÃO DA PESQUISA

A pesquisa desenvolvida será no formato da composição de coletânea de artigos, sendo composta por três fases, as quais constituem a solução do problema de pesquisa. O Quadro 1 apresenta o resumo das três fases da pesquisa, incluindo suas respectivas classificações metodológicas. Cabe salientar que, o objetivo de cada fase está alinhado com os objetivos específicos da pesquisa, sendo que cada fase será relatada por meio de um artigo científico.

Quadro 1 - Objetivos de cada fase e métodos

	OBJETIVOS	QUESTÃO DE PESQUISA	MÉTODO DE PESQUISA
FASE 1	Identificar na literatura as principais correntes de estudos em planejamento da cadeia de suprimentos bem como as oportunidades de pesquisa	O que se tem desenvolvido em planejamento da cadeia de suprimentos e quais as limitações dos modelos atuais?	Pesquisa Teórica Qualitativa 1. Revisão da Literatura

FASE 2	Propor um modelo conceitual para o planejamento da cadeia de suprimentos que lide com as limitações dos modelos atuais bem como a implementação do modelo e sua comparação com modelos clássicos	Como lidar com as atuais limitações dos modelos de planejamento das cadeias de suprimentos? Qual o desempenho do modelo proposto?	Pesquisa Teórica Qualitativa e Modelagem e Simulação Quantitativas 1. Modelo conceitual 2. Modelo Científico 3. Benchmarking
FASE 3	Implementar o modelo com dados reais de uma empresa de manufatura	Qual a contribuição do modelo proposto em uma empresa de manufatura brasileira?	Modelagem e Simulação Quantitativa 1. Coleta de dados 2. Entrevistas não estruturadas 3. Grupos focais 4. Prospecção de cenários

Fonte: Elaborado pelo autor (2023).

Silva e Menezes (2000) propuseram uma classificação de pesquisa dividida em quatro categorias, em relação à natureza da pesquisa, abordagem, objetivos propostos e procedimentos técnicos adotados pelo pesquisador. Em relação à sua natureza, a presente proposta de pesquisa é uma pesquisa aplicada que pretende gerar conhecimento para orientar a solução de problemas específicos. Em relação à sua abordagem, trata-se de um trabalho quantitativo, uma vez que o resultado do procedimento proposto é avaliado de acordo com o desempenho medido por indicadores a serem definidos, através de uma simulação. Em relação aos seus objetivos, essa pesquisa é exploratória, pois oferece uma visão mais próxima do problema, proporcionando uma melhor compreensão geral. Em relação ao procedimento técnico, este trabalho emprega pesquisa bibliográfica e pesquisa experimental. O procedimento bibliográfico é usado para compreender conceitos, avanços e oportunidades de pesquisa, enquanto a experimentação (através de um modelo de simulação) é utilizada para verificar a aplicabilidade do procedimento proposto. Os métodos de modelagem matemática e simulação serão utilizados tanto para a descrição quanto para a solução do problema.

2.2 PROCEDIMENTO METODOLÓGICO

O procedimento de aplicação da presente pesquisa será divido em três etapas, cada etapa resultando em pelo menos uma entrega parcial no formato de artigo científico e visando o cumprimento de um objetivo específico anteriormente apresentado. Os passos e objetivos estão dispostos como segue e são apresentados graficamente na Figura 1.

Na primeira etapa, uma revisão sistemática da literatura será realizada com o objetivo de verificar a tendência do volume de pesquisa sobre o tema, bem como autores mais influentes, palavras-chaves relacionadas, direções de pesquisa existentes bem como subsidiar uma classificação de trabalhos mais importantes sobre os tópicos. A partir dessa classificação e de filtros posteriormente estabelecidos, um volume representativo de artigos será selecionado para a leitura de conteúdo. A leitura de conteúdo tem como objeto expor os principais conceitos, métodos e modelos que estão sendo considerados, e principalmente tornar possível a identificação de oportunidades de pesquisa. Essa primeira etapa teve como resultado a submissão de um trabalho científico no periódico *International Journal of Integrated Supply Chain Management* com o nome "*Integrated Operational Supply Chain Planning In Industry 4.0*".

Por sua vez, na etapa dois, com o uso dos métodos e ferramentas resultantes da etapa anterior, um modelo conceitual será inicialmente proposto como forma de desenvolvimento na direção das oportunidades de pesquisa anteriormente selecionadas. O modelo conceitual foi implementado com dados hipotéticos e resultou em um artigo para a conferência CIRP CMS (*Conference on Manufacturing Systems*). A partir do modelo conceitual validado na conferência, o próximo passo dentro dessa etapa tem como objetivo verificar a eficiência do modelo ante aos diferentes modelos existentes na literatura. Para tal processo, alguns casos e modelos existentes na literatura serão reproduzidos, e uma análise de benchmarking será feita para comparar os modelos. O resultado parcial referente a essa etapa será um artigo científico de provável nome "*An Approach for an Adaptive Simulation Based Optimization for Integrated Production and Logistics Planning*" o qual foi submetido como versão preliminar para a *Manufacturing Modelling, Managing and Control Conference* (MIM) e como versão estendida será submetido a uma revista a definir.

Na terceira e última etapa, a implementação do modelo conceitual será feita em um caso real com dados reais, para averiguar os potenciais ganhos na aplicação de tal modelo. Como resultado da pesquisa, um artigo científico foi submetido para publicação no *Journal of Manufacturing Systems*.

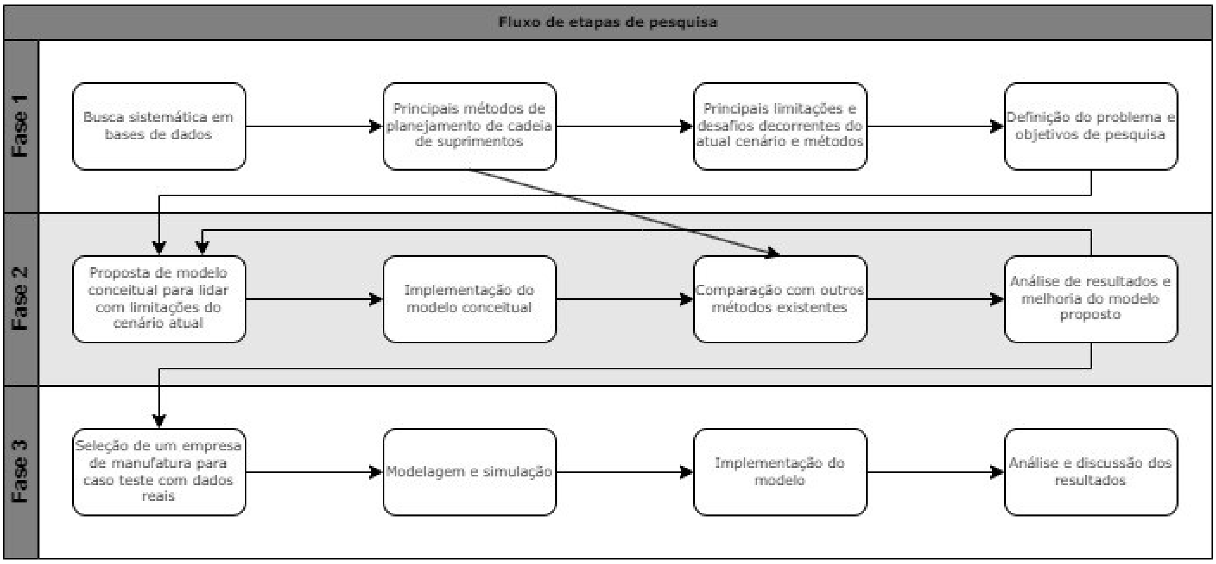
Conforme informado anteriormente e evidenciado no Apêndice A, os resultados das pesquisas realizadas em cada uma das fases foram ou estão sendo publicados em artigos científicos, os quais compõem esta tese de doutorado na forma de coletânea de artigos. No caso da Fase 1, a busca sistemática na base de dados teve como objetivo identificar os principais métodos e tendências sobre planejamento em cadeia de suprimentos, bem como suas principais limitações e oportunidades. Dessa etapa foi elaborado o problema e objetivos de pesquisa, apresentados e validados em formato de artigo e publicado no *Integrated Supply*

Chain Management com o nome "*Integrated Operational Supply Chain Planning In Industry 4.0*". Como resultado, foram obtidos cinco fluxos de pesquisa predominantes: (i) abordagens para lidar com a complexidade, (ii) consideração de incerteza, (iii) controle de estoque de matérias-primas e processos de compras, (iv) necessidade de considerar impactos ambientais, (v) e modelos específicos para lidar com produtos com vida útil limitada. Oportunidades comuns de pesquisa futura mencionadas: (i) incluindo comportamento estocástico e dinâmico nos modelos, (ii) estendendo os modelos para incluir uma rede maior, mais variáveis ou estendendo os casos de teste para avaliar o modelo em maior escala e (iii) desenvolver abordagens de solução mais eficientes.

Com as oportunidades de pesquisa encontradas na Fase 1, na Fase 2 foi proposto um modelo conceitual de otimização baseada em simulação, para lidar com as oportunidades e limitações supracitadas. O modelo conceitual foi aplicado em um caso teste hipotético e comparado com abordagens clássicas da literatura. Os resultados obtidos mostram que a abordagem é capaz de lidar com a complexidade e cenários estocásticos dos sistemas de fabricação do mundo real, superando os métodos clássicos de controle.

A partir do teste de desempenho obtido na Fase 2, é interessante então verificar a aplicabilidade do modelo em um cenário real. Na Fase 3 então, o modelo é replicado com base em um cenário real na indústria de equipamentos elétricos, onde o modelo se mostra aplicável e com um desempenho superior ao obtido no cenário real, ainda que o melhor resultado do sistema obtido pelo método não seja a soma dos melhores desempenhos observados por área (estoque, produção e entrega).

Figura 1 - Procedimento Metodológico



Fonte: Elaborado pelo autor (2023).

3 INTEGRATED OPERATIONAL SUPPLY CHAIN PLANNING IN INDUSTRY 4.0

Este capítulo apresenta o conteúdo do primeiro artigo[1], sendo este o resultado da primeira fase da pesquisa. Nessa etapa uma revisão sistemática da literatura abrangendo o planejamento integrado de cadeia de suprimentos é realizada com o objetivo de verificar as tendências de pesquisa sobre o tema, bem como autores mais influentes, palavras-chaves relacionadas e direções de pesquisa existentes. A partir de filtros posteriormente estabelecidos, um volume representativo de artigos é selecionado para a leitura de conteúdo. A leitura de conteúdo tem como objeto expor os principais conceitos, métodos e modelos que estão sendo considerados, e principalmente tornar possível a identificação de oportunidades de pesquisa.

3.1 INTRODUCTION

Supply chains embrace multiple material and information processes, linking the supply, production and distribution of products or services, crossing organizations' boundaries, adding value for customers and other stakeholders (Frazzon, 2009; Monostori et al., 2016). Over the years, the vision of a company working isolated has been substituted for a vision of a company being a piece of a complex network that should work with coordination and synchrony to stay competitive and guarantee market share (Chae, Olson, and Sheu, 2014). Thus, increasingly complex supply chain structures within dynamic environments require responsiveness and productivity, in which existing system resources are employed as efficiently as possible (Ehm et al., 2015; Frazzon et al., 2017). As a natural evolution, derived from an increasingly competitive environment, companies must interact, plan and act beyond their internal processes (Khan, Jaber, and Ahmad, 2014)

Furthermore, technological innovation and customer demands has led the industrial scenario to several challenges and opportunities of advances, and this new scenario has been considered the new Industrial Revolution, commonly addressed as Industry 4.0 (Barreto, Amaral, and Pereira, 2017). The name is based in the German government program to promote computerization of industries, originally Industrie 4.0, however, several other

[1] PIRES, MATHEUS; PARREIRA, R. M.; FRAZZON, E.M. Integrated Operational Supply Chain Planning in Industry 4.0. Int. J. of Integrated Supply Management, v. 14, p. 28-49, 2021. https://doi.org/10.1504/IJISM.2021.113566

countries promoted similar programs, for instance United States of America, which named such efforts on digitalization as Smart Manufacturing, and Japan and Korea (Thoben, Wiesner, and Wuest, 2017). The new revolution is driven by the possibility of a higher level of communication among people, machines and resources, based in three key components: Internet of Things (IoT), Cyber-Physical Systems (CPS) and Smart Factories, all of them made possible through the use of RFID, sensors, actuators and communication networks (Hermann, Pentek, and Otto, 2016).

Therefore, such revolution in the industry will certainly have positive effects on how to manage materials and information flow, extending the advances to logistics and supply chain perspective (Barreto et al., 2017; Queiroz, Telles, and Machado, 2017). (Maier, Korbel, and Brem, 2015) reinforces that the application of Industry 4.0 technologies can lead to innovation in supply chains and solve problems such as information asymmetry.

Either called Smart Supply Chain (Queiroz et al., 2017) or Digital Supply Chain (Büyüközkan and Göçer, 2018) a new era for the supply chain scene is being built upon principles and technologies from the new industrial revolution and it will impact several processes. Aiming for competitiveness, supply chain planning is an important key for efficiency and few authors have already explored the opportunities introduced by the fourth industrial revolution. For instance, Ivanov et al. (2016) propose a dynamic model and an algorithm for supply chain scheduling in the industry 4.0 context.

Although some research papers introduce the opportunities Industry 4.0 and Smart Manufacturing can provide to the supply chain scenario, it is not clear if the supply chain planning research are already considering the new capabilities from the supply chains' network to be explored in the proposed models or if the state-of-the-art models could be improved by considering such capabilities. Some questions arise about the topic: (1) Are new supply chain planning researchers considering the new supply chain capabilities introduced by Industry 4.0? (2) Are all the areas of supply chain planning addressed equally? Which methods are currently being applied? (3) Which are the most frequent problems addressed by the authors? And how do they cope with them? (4) What are the main opportunities for future research identified by the authors? In this paper, a systematic literature review aims to address these questions.

The paper is organized as follows: section two presents the research procedure to be utilized in the systematic review. Section three presents the numerical results and discussions over the research questions. To finalize, conclusions present the general idea of the paper, comparing the objectives to the results, and summarizing the main findings.

3.2 RESEARCH PROCEDURE

Literature reviews are the backbone of the academic literature, such condensed overviews can base the search for the state-of-the-art and desired scientific contribution (Seuring and Gold, 2012). However, studies have evaluated the quality of review reports and conclude all of them could not meet all quality criteria, thus a systematic procedure is necessary to guarantee the study reproducibility and clarity to identify its strengths, weaknesses and findings (Moher et al., 2009). The present paper utilizes a mixed approach composed by guidelines and procedures presented by Seuring and Gold (2012) and by Moher et al. (2009) to base the systematic literature review here reported. The procedure applied consists in four main steps: Paper gathering, Paper selection, Data Collection, Content Analysis.

3.2.1 Paper Collection

The first step is to collect the topic related papers from representative scientific databases. The selected databases cover the main journals in engineering and supply chain areas and are: Scopus (www.scopus.com), Science Direct (www.sciencedirect.com) and Web of Science (www.webofknowledge.com) (Uhlmann and Frazzon, 2018)

In order to reach all the suitable papers and, two different searches were executed in each database. The first utilizes the following strings and boolean operators: (TITLE("Supply Chain") AND TITLE(integrated) AND TITLE(planning OR control)) AND DOCTYPE(ar OR re). The second utilizes the following strings and boolean operators: (TITLE(planning OR control) AND TITLE(integrated) AND TITLE("Supplier Selection" OR "Material Inventory" OR "Production" OR "Scheduling" OR "Transportation" OR "Distribution" OR "Routing" OR "Sales and Operations")) AND DOCTYPE(ar OR re). Supply Chain Planning has a high volume of publications. However, several studies do not use the term clearly right in the title nor in the abstract. Those papers are still important for the analysis, and for this reason, several keywords identifying processes along the supply chain were included. This inclusion results in an enormous number of papers and to ensure only closely related were provided, only the Title section was analysed at this step. The document type was also limited to Article and Review Paper, for being the focus of the review.

3.2.2 Screening

The number of papers collected in the first step was naturally large. However, not all of them needed to be included in the review process, only the closest related and high impacting ones. To select them, screening processes were executed to decide which papers matched the proposed criteria. In order to clarify the inclusion and exclusion criteria, a table adapted from Liao et al. (2017) and Uhlmann and Frazzon (2018) was elaborated and presented in Quadro 2, where the criteria are carefully described.

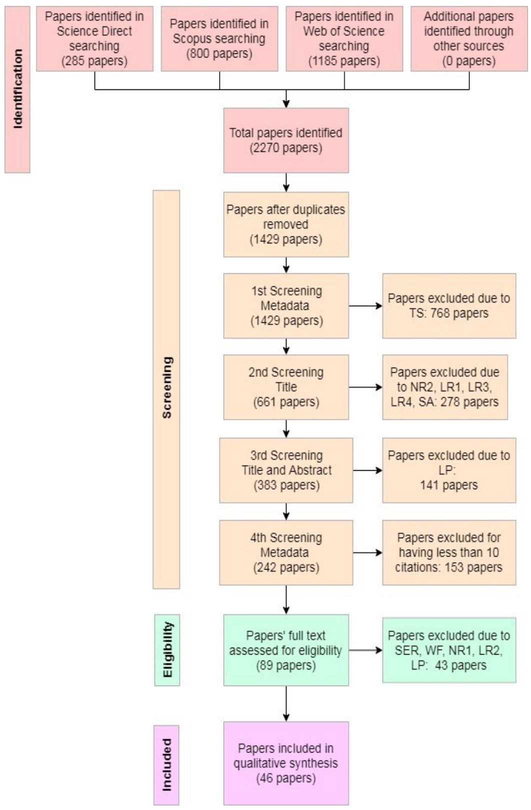
Quadro 2 - Inclusion and exclusion criteria

Action	Criteria	Criteria explanation
Inclusion	Closely related (CR)	• Research efforts of the paper are explicitly and specifically dedicated to integrated supply chain planning; • Time Span: from 2011 to December 2018; • Subject area: Engineering; • Document Type: Article or Review Paper; • Source Type: Conference Proceedings or Journals; • Language: English.
Exclusion	Search engine reason (SER)	Paper does not have its full text written in English.
	Without full text (WF)	Full text not available.
	Time span (TS)	Paper published before 2011.
	Non-related (NR)	NR1: The paper is not an academic article. Example: editorials, conference reviews, contents, or forewords; NR2: The paper is not aligned with "integrated supply chain planning".
	Loosely related (LR)	The paper does not focus on the discussion, or problem solving of production rescheduling. LR1: Integrated supply chain planning is only used as an example or context; LR2: Integrated supply chain planning is only cited in future research opportunities; LR3: Integrated supply chain planning is only mentioned; LR4: Integrated supply chain planning is only used in keywords and/or references;
	Specific Area (SA)	Paper addresses areas not related with production. Example: disaster logistics.
	Level of Planning (LP)	Paper does not consider operational level.

Fonte: Elaborado pelos autores (2021).

Before starting with the screening process, a software tool was utilized to eliminate possible duplicate papers, since it is very likely to find the same paper in different databases. Thus, the first screening was applied by checking the papers' metadata and excluding the papers published before 2011. Since the concept of Industry 4.0 started being disseminated in 2011, the present work will focus in the integrated supply chain planning area after this event. During the second screening, the titles of the papers were analysed in order to identify loosely related and non-related papers, as well as other specific areas that are not in the scope for the present work. In the third screening, the abstracts were also read and the papers that addressed only strategic and tactical levels were excluded. In the fourth and last screening, the metadata was evaluated and papers with less than 10 citations were excluded. The number of citations per paper was chosen according to the Pareto Principle, or 80/20 rule, where the selected papers are responsible for, exactly, 82,70% of the total citations in the database on the beginning of the fourth screening. The papers published in the year of the searches, 2018, were not considered during this step. Furthermore, in the eligibility step, the papers' full text was analysed and papers without full text available or without the full text in English were eliminated, as well as unrelated papers, loosely related or papers that only consider strategic or tactical planning. The result of the eligibility process provided the final database of papers to be thoroughly read and analysed. Details of each process can be found on Figura 2.

Figura 2 - PRISMA Flow



Fonte: Elaborado pelos autores (2021).

3.2.3 Data Collection

At first glance, the papers were evaluated in order to identify the desired characteristics. Four elements were considered: (I) the objective of the paper (Model, Framework, Literature Review and so on), (II) the processes along the supply chain that the paper considers (as decision variable), (III) the solution method utilized by the authors, and (IV) if the authors explore the Industry 4.0 capabilities and/or its technologies capabilities to enhance the model or framework proposed or if they at least recognized the fourth industrial revolution and the technological advances as a trend in supply chain planning.

3.2.4 Synthesize results

After carefully evaluating all the papers, a summary of their content was elaborated, highlighting key points such as contextualization, explored research gap, method, limitations and future research opportunities. Together with the data collected in the previous step, all the information was organized in spreadsheets, tables and graphics in order to provide a better visualization and identification of the target characteristics.

3.3 RESULTS

The procedure described resulted in 46 papers to be included in the present review. Their characteristics are presented in Table 2, where M stands for Model, F for Framework, R for Review and M for Method.

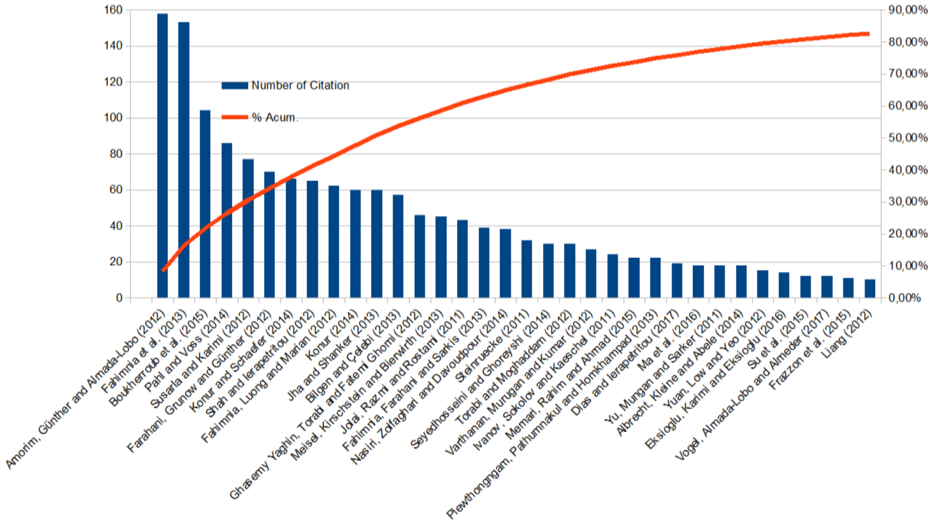
Quadro 3 - Selected papers' characteristics

	Type	Procurement	Material Inventory	Production Planning	Production Scheduling	Finished Goods Inventory	Distribution	Transportation Routing/Scheduling	MIP	Simulation	Simulation Based Optimization	Analytycal/Exact	Dynamic Models	Heuristic/Meta-Heuristic	Stochastic/Probabilistic Models	I4.0 Mention
Shah and Ierapetritou (2011)	M			x	x	x	x		x							
Meisel, Kirschstein and Bierwirth (2013)	M			x		x	x		x			x		x		
Farahani, Grunow and Günther (2012)	M				x	x	x		x					x		
Jolai, Razmi and Rostami (2011)	M				x	x	x		x					x		
Seyedhosseini and Ghoreyshi (2014)	M			x			x		x					x		
Hossain and Hossain (2018)	M			x		x	x		x							
Torabi and Moghaddam (2012)	F			x		x	x		x							
Ghosh and Mondal (2018)	M			x	x	x	x	x	x							
Amorim, Günther and Almada-Lobo (2012)	M			x		x	x		x							
Darvish and Coelho (2018)	M			x		x	x		x					x		x
Piewthongngam, Pathumnakul and Homkhampad (2013)	M			x		x	x	x	x					x		
Konur (2014)	M		x				x		x					x		
Choi et al. (2018)	M	x	x	x					x							
Konur and Schaefer (2014)	M	x	x									x				
Jha and Shanker (2012)	M			x		x	x							x		
Varthanan, Murugan and Kumar (2012)	M			x		x	x		x		x			x		
Steinrücke (2011)	M			x	x	x	x	x	x					x		
Pahl and Voss (2014)	R															
Susarla and Karimi (2018)	M		x	x	x	x	x		x							
Das (2018)	M			x		x	x		x							
Fahimnia et al (2013)	R															
Tabrizi (2018)	M	x	x		x				x					x		
Nasiri, Zolfaghari and Davoudpour (2014)	M			x		x	x		x					x		
Bilgen and Çelebi (2013)	M				x	x	x		x	x						
Liu, Wang and Leung (2018)	M	x		x		x	x		x							
Ivanov, Sokolov and Kaeschel (2011)	M			x		x	x		x				x			
Dias and Ierapetritou (2017)	R															
Boukherroub et al (2015)	Me/M	x		x		x	x		x							
Ma et al (2016)	M			x		x	x		x					x		
Liang (2012)	M			x		x	x		x						x	
Frazzon et al (2015)	F				x	x	x		x			x				x
Su et al (2015)	M	x		x		x	x		x					x		
Eksioglu, Karimi and Eksioglu (2016)	M			x		x	x		x							
Yuan, Low and Yeo (2012)	M			x		x	x		x							
Sel et al (2015)	M			x		x	x		x							
Fahimnia, Farahani and Sarkis (2012)	M			x		x	x		x					x		
Yu, Mungan, and Sarker (2011)	M	x	x			x						x				
Ghasemy Yaghin (2018)	M			x		x			x					x		
Ghasemy Yaghin, Torabi and Fatemi Ghomi (2012)	M			x		x									x	
Memari, Rahim and Ahmad (2015)	M			x		x	x		x					x		
Rafiei, Safaei and Rabbani (2018)	M		x	x		x	x		x							
Fahimnia, Luong and Marian (2012)	M			x		x	x		x					x		
Chen (2016)	M			x	x	x			x					x		
Orbegozo et al (2018)	R															
Brahimi, Aouam and Aghezzaf (2015)	M			x		x			x					x		

Fonte: Elaborado pelos autores (2021).

In this set of papers, a representative sample of the current supply chain planning concerns is expected to be found. This set of papers is composed by the highest cited papers in the research area, and all of them together are responsible for almost the totality of the citations among the related papers, as it is shown in Figura 3.

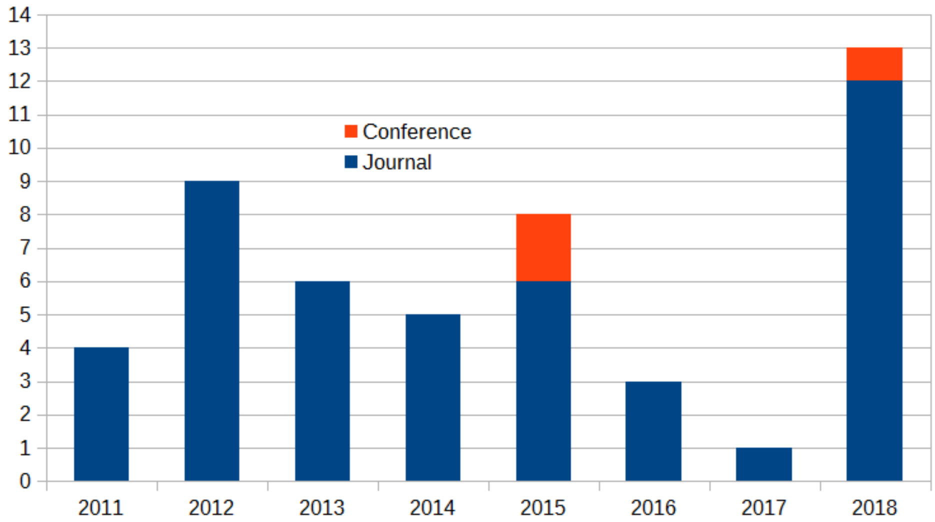
Figura 3 - Citation per paper



Fonte: Elaborado pelos autores (2021).

The time plot presented on Figure 4 shows the publication volume per year of the 46 papers analysed. It is possible to notice a major increase on the number of papers one year after the presentation of the concept, while after then to the present time; this number has been steady within a margin. The year of 2017 might show a smaller amount due to the citation criteria applied, which might have been more impacting on more recent papers. 2018 presents a higher amount because the citation criteria were not applied to this year. From the set of papers, only three of them were presented in conferences, they are Memari, Rahim and Ahmad (2015), Choi et al. (2018) and Frazzon et al. (2015).

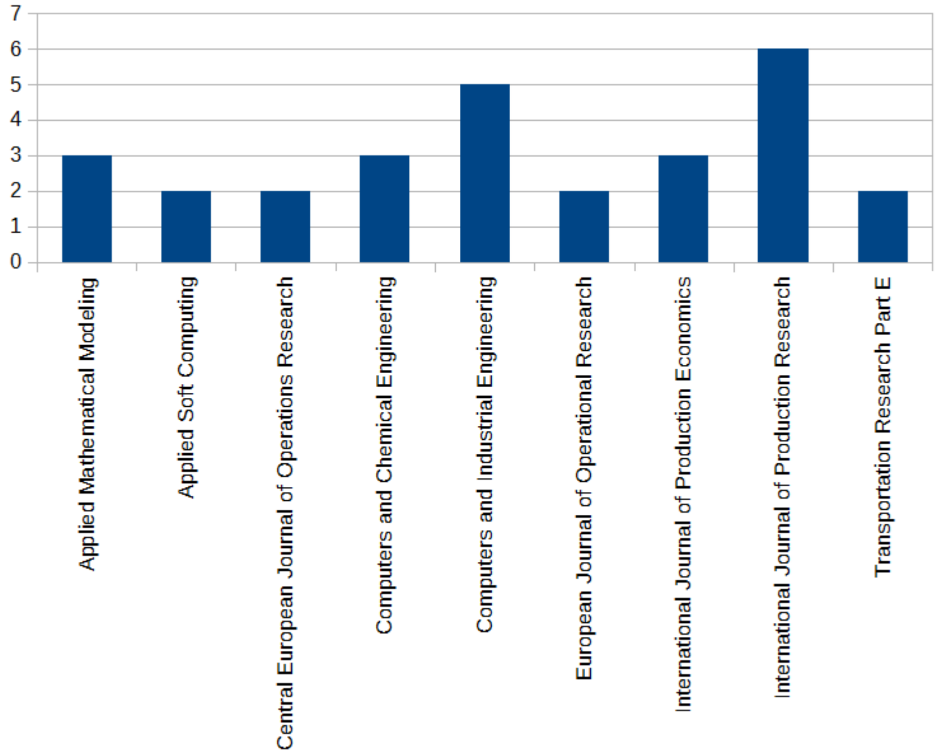
Figura 4 - Volume of publication per year



Fonte: Elaborada pelos autores (2021).

Figura 5 presents the 9 journals that published more than one paper from the present set of papers. This set of 9 papers is responsible for 65% of the journal papers in this collection. The others 15 journals published on paper each.

Figura 5 - Publication per journal



Fonte: Elaborada pelos autores (2021).

3.3.1 Are new supply chain planning researchers considering the new supply chain capabilities introduced by Industry 4.0?

Despite the proportions and opportunities provided by industry 4.0 concept, only two of the 46 papers collected have addressed somehow the industry 4.0, smart manufacturing, or its technologies.

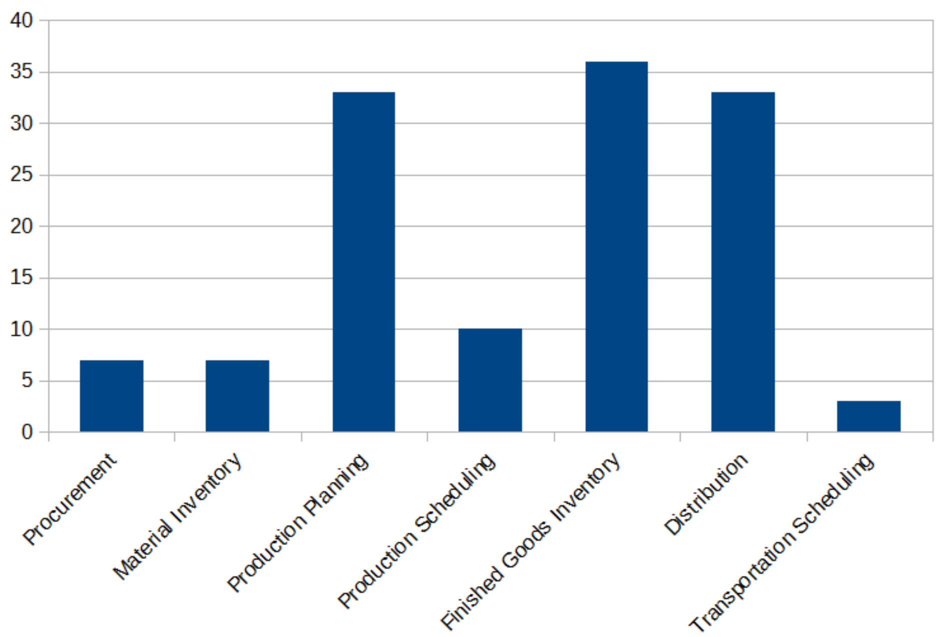
Frazzon et al. (2015) proposed a hybrid approach (simulation and optimization) to cope with the current dynamic and complex scenario of supply chains' integrated control and schedule of production and logistics processes. The author merges the capabilities of both simulation and optimisation to generate a decision support tool able to deal with complexity and stochastic behaviour and still be capable of being implemented for real-time scheduling.

Darvish and Coelho (2018) state that integrated optimization of production, location, inventory control and distribution can be more beneficial than sequential individual optimization, once a global optimum can be better for the network and for the synergy of a global strategy. The authors then propose both a metaheuristic and an exact approach for the integrated optimization. Computational experiments showed advantage for the integrated approach, either metaheuristic or exact. To base their research, the authors affirm collaboration and flexible network integration are synchronized with the premises of the industry 4.0 movement.

3.3.2 Are all the areas of supply chain planning addressed equally? Which methods are currently being used?

A supply chain planning can address several planning areas along several tiers in real life. However, research papers tend to simplify them in fewer processes they want to emphasize. Figura 6 presents the number of papers that have addressed the planning area on their scope, considering aspects from the area in their decision variables. It is easy to notice there is a major focus on production planning and transportation planning. Finished goods inventory distinction is a consequence of the fact that most of the reviewed papers consider the integration of both production and distribution, thus, the interface of both processes is always considered to keep mass equilibrium.

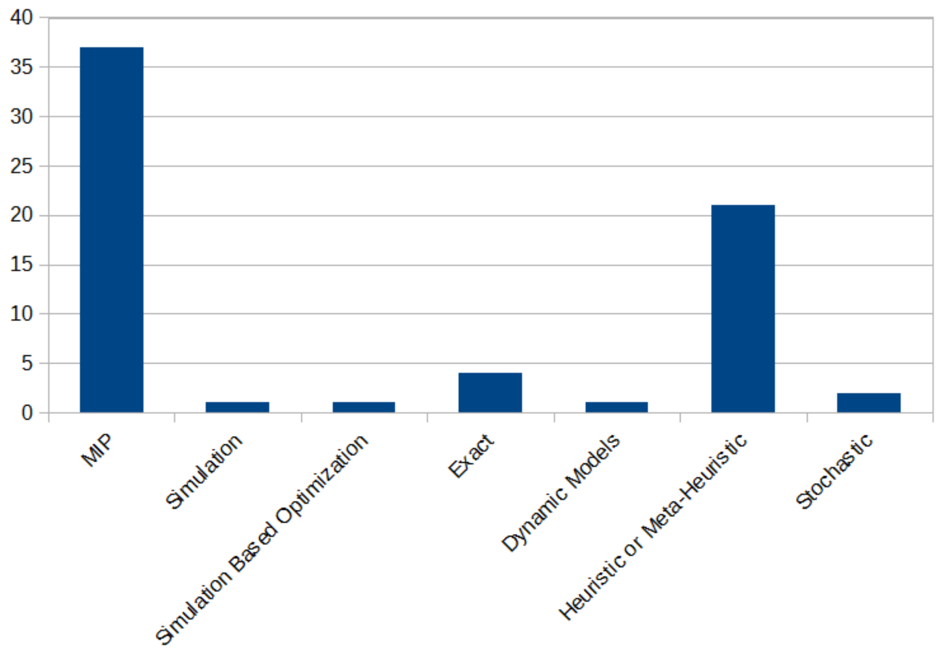
Figura 6 - Processes addressed in the papers



Fonte: Elaborada pelos autores (2021).

When it comes to characteristics of the models, mixed integer programming is present in nearly every paper, as it can be seen in Figura 7. However, solution methods may vary. While linear and small problems are easy to tackle with exact solution, a considerable amount of the presented problems is: (i) too complex to be solved in feasible time or (ii) non-linear. Meta heuristics and algorithms to decompose large problems are usual tools to reach satisfactory results. However, few models are capable of dealing with stochastic and dynamic behaviours.

Figura 7 - Aspects from the models



Fonte: Elaborada pelos autores (2021).

3.3.3 What are the most frequent problems addressed by the authors? And how do they tackle them?

Integrated supply chain planning aims at obtaining competitiveness by embracing several decision variables and finding a global optimum. However, these decision variables extended to multiple time periods (planning horizon) and the requirement of respecting several constrain lead to a very demanding problem with high complexity. To cope with such complexity and large problems, several authors have been addressing approaches to deal with these problems efficiently. Shah and Ierapetritou (2012) deals with the so called Enterprise Wide Optimization (EWO), an equivalent of supply chain optimization, but focusing on production, although not neglecting inventory and transportation. Such wideness of optimization leads to an enormous complexity, thus the authors utilize mathematical decompositions and Lagrangian relaxation to cope with the MIP, obtaining faster solution times. Brahimi, Aouam, and Aghezzaf (2015) proposes a time based relax-and-fix heuristic and an order based relax-and-fix heuristic to solve efficiently large instances of the production planning problem considering outbound logistics. Fahimnia, Luong, & Marian (2012a) present mixed integer non-linear formulation (MINLF) for a complex production-distribution plan and formulated a genetic algorithm procedure for the optimisation of the developed mathematical model, since meta-heuristics provide satisfying solutions in feasible time. Fahimnia, Luong, and Marian (2012) reinforces the potential but complexity of integrated supply chain planning, and proposes a memetic algorithm to deal with a MINLP model formulation. Piewthongngam, Pathumnakul, and Homkhampad (2013) proposes a heuristic based solution for the production-distribution planning for the food supplying to pig farming, obtaining a solution slightly deviated from the optimal, but in a dramatic declined computational time. Steinruecke (2011) proposes relax-and-fix heuristics to deal with production-transportation planning and scheduling in a real-life global aluminium supply chain. Experiments demonstrate that the heuristics can find nearly optimal solutions along with drastically reduced computation times. Liu, Wang, and Leung (2018) propose a novel integrated bacteria foraging algorithm (IBFA) embedding a five-phase based heuristic (FPBH) to deal with cellular manufacturing in supply chain considering facility transfer and production planning. Experiments conducted to verify the performances of the IBFA, modified bacteria evolution operators and the FPBH. The results indicate that with the modified operators and the FPBH, the IBFA performs better than without them, and the IBFA frequently outperforms the heuristic based genetic algorithm and the heuristic based simulated annealing within the same running time. Ma et al., (2016) presented a bi-level integrated production-distribution control considering conflicts on coordination. The approach is hierarchical, the core firm minimize its costs on tactical decision, afterwards, production and distribution optimize their processes respecting tactical decisions. To tackle the model a hybrid priority-based two stage genetic algorithm with a fuzzy logic controller algorithm is developed. Su et al. (2015) suggests an optimization model and a hybrid algorithm which combines particle swarm optimization and genetic algorithm with learning scheme to deal with integrated partner selection and production–distribution planning problem considering multi-product, multi-stage, multi-production route, multi-machine, and multi-period manufacturing environment. Experiments have shown that the hybrid algorithm can outperform the conventional genetic algorithm, the particle swarm optimization and the genetic algorithm with learning scheme. Jolai, Razmi and Rostami (2011) develops a multi-objective linear programming to integrate production and distribution considering a supply chain composed of a manufacturer, with multiple plants, products, distribution centres (DCs), retailers and customers. To cope with the complexity of the problem, the authors propose a genetic algorithm, particle swarm optimization (PSO) algorithm with a new fitness function, and an improved hybrid genetic algorithm.

While complexity defines the size and computational effort required to solve, another challenging aspect of supply chain planning models is to deal with uncertainty. Traditional production and distribution planning problems are usually solved by considering deterministic parameters and ignoring flexibility (Hossain & Hossain, 2018). The authors present a fuzzy multi-objective linear programming model to simultaneously minimise the total production cost, distribution cost and delivery time for multi-product and multi-time period under multiple uncertainty. Furthermore, flexibility in formulating production–distribution strategies to overcome demand uncertainties is crucial for the success of such industries, yet mathematical modelling does not represent the reality of the supply chains, while simulation has a limited capacity to optimize supply chain planning problems (Varthanan, Murugan, & Kumar, 2012). The authors proposed a novel heuristic based discrete particle swarm optimization (DPSO) algorithm, used with simulation approach for determining the solutions for the stochastic demand cases. Das (2018) highlights that supply chains (SCs) are exposed to several unpredictable disaster situations that lack historical data to base their planning, thus, they must strive to develop resilient systems capable of mitigating the caused effects while still achieving their planned objectives. Thus, the authors propose a MIP for the integrated supply chain planning considering disruptions and risks. Ivanov, Sokolov, and Kaeschel (2011) propose an integrated model of production and transportation planning in the SC based in optimal control theory concepts, allowing them to cope with non-stationary processes caused by structure dynamics. Liang (2012) proposes a method for solving the integrated manufacturing/distribution planning decision (MDPD) problems with multiple imprecise goals in supply chains under an uncertain environment.

Material inventory and procurement are critical to supply the manufacturing business, yet few models addressed these areas. However, in the present set of papers is possible to find works that also include such tasks. Fully integrated models can result in a challenging problem due to its size, to avoid such unlikely complexity Choi et al. (2018) proposes a two-stage hierarchical integrated procurement and production planning but including weight factors to avoid sub-optimality. The author quantifies the weight factors and as a result proposes a Mixed Integer Non-Linear Programming (MINLP) model for the procurement planning model integrated with production system. For Susarla and Karimi (2018) pharmaceutical companies are becoming more aware of the importance of optimizing their supply chain operations to gain competitiveness, despite its fame of slow adapters of new technologies. An important aspect of typical pharmaceutical supply chain is the high material inventories. The authors propose a Mixed Integer Programming (MIP) model for multiperiod enterprise-wide planning in a multisite, multiechelon pharmaceutical company. The model addresses, among other decision variables, the inventory levels and inter facility material transfers. Boukherroub et al. (2015) also address procurement in their sustainable supply chain planning model. The authors propose a Multi-objective Mathematical Programming (MOP) to determine the volume of wood to harvest in the forests and the volume of wood to source from forest contractors, integrated with manufacturing, finished goods inventory, transportation and employment decisions. Yu, Mungan, and Sarker (2011) proposes a non-linear model to determine an optimal economic lot size model for raw material procurement, production setup and finished goods delivering under an infinite planning horizon and develop two algorithms to solve the model. Tabrizi (2018) and Rafiei, Safaei, and Rabbani (2018) also use MIP to integrated supply chain planning addressing raw material inventory decisions. The first integrates project scheduling to procurement considering environmental impacts, while the second targets an integrated production-distribution planning in a competition-based four-echelon supply chain.

Environmental concerns are also addressed among the set of papers collected. In Konur and Schaefer (2014) is possible to conclude that greenhouse gas (GHG) emissions are threatening the earth's ecology, and the sustainability of supply chains are getting more important every day. Their study analyses integrated inventory control and transportation planning problem with carbon emissions regulations. The authors use EOQ (Economic Order Quantity) model to reach retailer's optimal order quantity in a range of parameters, comparing less-than-truckload (LTL) and truckload (TL) carriers. In addition, intermodal transportation provides potentials for relieving congested road infrastructure, for reducing greenhouse gas emissions, and for achieving economies of scale from jointly shipping large volumes of cargo. Meisel, Kirschstein, and Bierwirth (2013) propose a MIP model considering output volumes of plants, cargo consolidation at intermodal terminals, and capacity bookings for road and rail transports, and suggests two approaches to solve the problem: one exact approach and one heuristic approach. Memari et al. (2015) states most mathematical production and distribution models only focus on cost reduction while neglecting environmental influences. To cope with these conflicting objectives, the authors propose a multi-objective mathematical model within a supply chain network using just-in-time (JIT) logistics. The author writes the problem as a MIP and proposes a genetic algorithm (GA) to solve it. The objective of the model is to minimize the costs of production, distribution and stocking as well as minimizing carbon emission in the logistics network.

Products with limited lifetime are a special concern in supply chain planning, since lead time must be strongly reduced while costs still should be minimized. Several papers addressed perishable products scenario. Sel et al. (2015) considers the integrated planning and scheduling of the dairy industry. A MILP is proposed to integrate tactical and operational decisions considering product shelf life. To cope with the model, a heuristic is proposed to decompose the problem. Pahl and Voss (2014) show that a study conducted for the International Congress ‘‘Save Food!’’ states that 1.3 billion tons of food per year are wasted on a global scale: around one-third of all food produced worldwide for human consumption is wasted. The authors present a survey on the state-of-the-art on supply chain planning with lifetime constrains in production. Amorim, Günther, and Almada-Lobo (2012) also address perishable products and propose a model that explores, through a multi-objective framework, the advantages of integrating production and distribution at an operational level. The authors formulate models for the case where perishable goods have a fixed and a loose shelf-life (i.e. with and without a best-before-date). Ghosh and Mondal (2018) uses a (MILP) model to formulate the production-distribution problem in an Indian milk industry, aiming to maximise the overall profit contribution of the business. Farahani, Grunow, and Guenther (2012) reinforce the importance and singularity of working with perishable foods. The authors use two stage hierarchical planning, where the production scheduling is solved by a mixed-integer linear programming and the distribution by a large neighborhood search algorithm (LNS). Bilgen and Çelebi (2013) complements that dairy food industry is a major industry in most developed and developing economies of the world. the authors propose a MILP addressing production and distribution planning to optimize shelf-life dependent pricing component and costs such as processing, setup, storage, overtime, backlogging, and transportation costs. To considerate the dynamic behaviour of real-world system, the authors also explore a hybrid approach, where simulation tests adjust the optimization model. Seyedhosseini and Ghoreyshi (2015) proposes a new integrated production and distribution planning model for perishable products. The authors divided the problem into a production submodel and a distribution submodel. The production submodel is solved using LINGO, and a particle swarm heuristic is developed to tackle distribution submodel.

3.3.4 What are the main opportunities for future research identified by the authors?

One of the main suggestions of improvement mentioned by the authors is the inclusion of stochastic behaviour and dynamic events in their models. Meisel, Kirschstein and Bierwirth (2013) say that one of the main limitations of their model is the lack of uncertainty in customer demand. Ghosh and Mondal (2018) mention the consideration of various stochastic parameters as a possibility of improvement for their model. Fahimnia et al. (2013) conclude at the end of their systematic review, among other things, that the development of dynamic, probabilistic and stochastic P-D models was, at the time, explored by few researchers and that the volatility and uncertainty of the key input parameters should be addressed in future P-D models. Another six papers suggested including dynamic and stochastic behaviours (Fahimnia, Luong and Marian, 2012; Konur and Schaefer, 2014; Ghasemy Yaghin, 2018; Yu, Mungan and Sarker, 2011; Bilgen and Çelebi, 2013; Ghasemy Yaghin, Torabi and Fatemi Ghomi, 2012)

Several papers suggested extending their own models to include more complexity by adding more facilities, decision variables, dynamic events and stochastic behaviour. Ma et al. (2016) suggests the inclusion of more participants in the SC considered. Ghasemy Yaghin, Torabi and Fatemi Ghomi (2012) also conclude from their research that the increase in complexity of their model is an opportunity for future research and a way of making the model closer to a real-world situation. Steinruecke (2011) consider the inclusion of several transportation modes between SC stages including different transportation costs and transportation times as adaptations for specifics industries. The consideration of set up times and costs are also frequently mentioned as possible inclusions for future models of future research. Pahl and Voss (2014) consider aspects like sequence-dependent setup times and costs to be gaps that need to be filled in future research. Another 6 papers suggested including complexity and uncertainty to their models (Fahimnia et al., 2013; Liu, Wang, and Leung, 2018; Ma et al., 2016; Frazzon et al., 2015; Tabrizi, 2018; Ivanov, Sokolov, and Kaeschel, 2011; Brahimi, Aouam and Aghezzaf, 2015).

The third and last most recurrent opportunity for future research is the search for faster or closer to optimal solving methods. Fahimnia, Farahani and Sarkis (2013) suggest evaluating different optimization approaches and assumptions to further fine-tune the solution methodology used by them. Ghasemy Yaghin, Torabi and Fatemi Ghomi (2012) have also proposed the development of an efficient new algorithm to solve the non-linear model and reaching efficient solutions. Orbegozo et al. (2018) propose the development of new effective optimization algorithms that can obtain good quality solutions in reasonable running times. Another three papers suggest improving solving methods (Brahimi, Aouam, and Aghezzaf, 2015; Sel et al, 2015; Nasiri, Zolfaghari and Davoudpour, 2014).

In addition to the set of papers collected from the systematic review, in (Dolgui et al, 2019a) and (Ivanov et al, 2018) is possible to notice the importance and opportunities of short-term production scheduling and control in supply chain and Industry 4.0 systems. From them, a stream of study can be highlighted: the study of short-term, real-time optimization in supply chain, where the supply chain planning converges to the real-time operational scheduling, considering long-term impacts. Furthermore, the technologies related to the digital transformation may provide positive impacts on supply chain disruptions and on supply chain risks (Ivanov, Dolgui and Sokolov, 2019). Moreover, new technologies and methods such as machine learning and blockchain may be used to optimize certain tasks of supply chain, for instance, supplier selection and smart contract design (Dolgui et al, 2019b; Cavalcante et al, 2019).

3.4 CONCLUSION

The present paper presented a systematic literature review on integrated supply chain planning, resulting in a 46 papers data set, with the purpose of identifying current research efforts, approaches to tackle the main challenges, future research opportunities, and specially to verify how Industry 4.0 concepts are being considered. The systematic analysis demonstrated that: (i) production planning and distribution planning are the main research focus, (ii) MIP, heuristics and meta-heuristics are the most frequent modeling approaches, and (iii) only two research papers are oriented to Industry 4.0 concepts and technologies.

The in-depth analysis highlighted addressed topics and future research opportunities. For the most addressed topics, it is possible to highlight six of them: (i) the large complexity of supply chain problems requiring more efficient solving approaches; (ii) the necessity of considering real life uncertainty along the processes in the models; (iii) the incipient but highly important consideration of raw material inventory control and procurement processes;

(iv) the evident necessity of considering environmental impacts; (v) the particular models for dealing with limited lifetime products and perishable foods; and (vi) the convergence of supply chain planning and control for operational and short-term decision which need to take into consideration long-term impacts. In regard to future research opportunities, authors converge to four directions: (i) including stochastic and dynamic behaviour into their models to approximate them to the real life scenarios, (ii) extending their models to include a larger network, more variables or extending their test cases to assess the model in larger scale, (iii) developing faster solving approaches or approaches capable of obtaining results closer to the optimal, and (iv) addressing short-term operational decision as supply chain planning drivers, concomitantly with the analysis of medium to long-term impacts.

The present paper should be read under the light of a few limitations: the database set was limited to three main databases, the language was limited to only English, and the systematic procedure excluded papers non-related related to the interest area or to the planning level addressed.

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4 SIMULATION-BASED OPTIMIZATION FOR THE INTEGRATED CONTROL OF PRODUCTION AND LOGISTICS: A PERFORMANCE COMPARISON

Este capítulo apresenta o resultado da segunda etapa de pesquisa, formalizada no segundo artigo[2] aqui apresentado. A segunda etapa a compor a pesquisa tem como objetivo propor um modelo conceitual de otimização baseada em simulação para o controle integrado da produção, compra de matéria-prima e entrega de produto acabado, atuando na direção das lacunas de pesquisa identificadas na etapa anterior do trabalho. Nesse capítulo, o modelo conceitual é apresentado e seu desempenho é comparado com métodos clássicos de controle em um caso hipotético para a validação da sua eficiência.

4.1 INTRODUCTION

Supply chains embrace multiple material and information processes, linking the supply, production and distribution of products or services, crossing organizations' boundaries, adding value for customers and other stakeholders (Frazzon, 2009). Over the years, the vision of a company working not isolated but jointly with other companies has prevailed (Chae et al., 2014). Thus, increasingly complex supply chain structures within dynamic environments require responsiveness and productivity, in which existing system resources are employed as efficiently as possible (Ehm et al., 2015; Frazzon, Albrecht, et al., 2018). As a natural evolution, derived from an increasingly competitive environment, companies must interact, plan and act beyond their internal processes (Khan et al., 2014). However, software systems are commonly divided into modules for the planning of basic schedule (Enterprise Resource Planning Systems) and the control of processes on the operational level (Machine Execution Systems). The scheduling and control of production processes has a significant influence on the performance of manufacturing systems.

After determining a set of production orders based on demand forecasts or customer orders, the scheduling and sequencing of job processing with several machines must be conducted optimizing performance indicators (Schuh et al., 2017). There are two different methods to define a suitable job sequence, either generating a production schedule in advance

[2] PIRES, MATHEUS C.; FRAZZON, ENZO M.; QUADRAS, DJONATHAN; Broda, Eike; FREITAG, MICHAEL. Simulation-Based Optimization for the Integrated Control of Production and Logistics: A Performance Comparison. IFAC-PAPERSONLINE, v. 53, p. 10639-10644, 2020. https://doi.org/10.1016/j.ifacol.2020.12.2824

or using dispatching rules to continuously be determining the priorities of jobs waiting to be processed by the resources. Computing a whole new schedule can be very time-consuming. Moreover, schedules can become unreliable if they are not robust enough and the production processes are subject to stochastic effects, such as fluctuating processing times (Frazzon et al., 2018a).

In addition, while finished goods inventories and work-in-process are considered by assigning due-dates for production planning, raw material inventory control is generally not considered explicitly in production planning and control. Despite the fact that, traditionally, inventory planning is considered as an individual task separated from production scheduling and control, there are approaches to integrate both tasks (Kumar et al. 2016). However, these approaches focus on long-term planning decisions and do not allow for a reaction to dynamic changes in real-time.

Moreover, on the operational decision level, recent studies show that the integration of production and transport in supply chains provides potential to decrease costs, to enhance the on-time delivery of customer orders and consequently to improve supply chain competitiveness (Ehm et al., 2015).

Industry 4.0 and its wide range of concepts and technologies (Lasi et al., 2014) can contribute to the materialization of both productivity and responsiveness. In an ideal digital factory environment, computers, sensors and software, can collect data and compute the materials required for the manufacturing processes. This new industrial phase is characterized by the use of Internet of Things (IoT) data. It has led to a growth in the quantity of acquired data along the production processes through the communication of different equipments of a manufacturing system. In this environment with a high volume of data, more accessible technologies from digital factories could be further developed order to achieve the goal of intelligent and self-learning manufacturing (Lee et al. 2014).

However, connecting many organizations, equipment generating data, operations and clients leads to a scenario of high uncertainty from different sources (Peidro et al., 2009). According to (Peidro et al., 2009), uncertainty arises from three sources in a supply chain: demand, process/manufacturing and supply. In this sense, uncertainty in supply chain modelling for planning and decision support imposes challenges, and it has to be considered in planning and control issues, in order to obtain robust policies and plans. In addition, the availability of real-time data regarding several areas of the systems enables real-time optimization, creating a convergence to the most operational level task, i.e., the production controlling strategies.

To cope with such behaviour, simulation-based optimization is an approach that holds capabilities to deal efficiently with a large scenario taking into account the dynamics of the systems, leading to nearly optimal solutions in a feasible time (Liotta et al., 2016). Simulation-based methods can be used to both develop and to evaluate complex systems. Aspects such as physical configuration or operating rules of a system can be considered. Its applications have grown in several areas, assisting managers in the decision-making process and allowing a better understanding of processes in complex systems (Sakurada and Miyake, 2009). These assumptions are expressed in mathematical, logical and symbolic relations between the entities or objects of interest of the system. In this way, potential system changes can first be simulated in order to predict their impact on system performance. Moreover, simulation also allows a decision-maker to evaluate various control policies (Pirard et al., 2011). Numerous replications of the simulations can be performed in order to evaluate the robustness of the implemented design. Unfortunately, the simulation does not guarantee an optimum design. However, the presented disadvantage can be balanced with the integration of other tools, such as mathematical modelling.

The combination of simulation and mathematical programming models in an iterative scheme aims to evaluate the effects of decisions on the performance of a manufacturing system. Thus, such works are focused on the integration of different modelling methodologies in order to combine the advantages offered by each of them for solving complex problems. Analytical models look for solutions evaluating optimal values of decision variables. However, the provided solutions are generally limited in their fields of application because of predetermined restrictive assumptions. Simulation models, in turn, are better able to capture the real behaviour of the system but are not adequate to solve optimization problems. The integration of analytical and simulation models, also called hybrid models, leads to representing a promising option for better results (Lin and Chen, 2015). Thus, hybrid models seek to combine the advantages and avoid the disadvantages of both tools (Peidro et al., 2009).

Liotta et al. (2016) state that simulation-based optimization is a strategy for dealing with uncertainty in the supply chain. Frazzon et al. (2018) propose a simulation-based optimization approach to deal with complex systems, which consists of an adaptive simulation-based optimization. In the conceptual model of the method proposed by the authors, real-time data feeds the simulation-based optimization, which generates scenarios performs local optimization strategies and provides feedback to enhance the simulation. Simulation can represent better dynamic environments that have stochastic behaviour, while optimization strategies can generate solutions with low computational costs. Kück et al. (2017) developed a data-driven and adaptive simulation-based optimization approach to determine suitable dispatching rules for production control in an application from semiconductor manufacturing. This method was extended by a data-exchange framework to achieve the capability of reacting on dynamic changes in real-time. In Frazzon et al. (2018b) an evaluation within a scenario of a Brazilian manufacturer of mechanical components for the automotive industry showed better operational performance compared to the procedure previously applied by the company as well as in comparison to static dispatching rules. However, the literature about simulation-based optimization lacks experiments in addressing material inventory planning and control, production planning and control and transportation planning and control, all integrated in one model. The model aims to be easier to develop and to deliver better fitting parameters for real scenarios.

This work proposes the application of a data-driven simulation-based optimization approach to cope with integrated production and logistics control in uncertain scenarios, i.e. scenarios with stochastic behaviour and dynamic events, addressing material inventory, production and transportation. The proposed approach is intended to be use by companies aiming to synchronize the production with the delivery and the raw material inventory, being able to generate satisfying solution under uncertainty. The approach is tested using a use case and its performance is compared to a literature benchmark. The paper is organized as follows: Section 2 presents the problem to be addressed, the benchmark approach and the proposed simulation-based optimization. Section 3 highlights and discusses the main results. Finally, the conclusion section summarizes the paper objectives, findings and results.

4.2 SIMULATION-BASED OPTIMIZATION FOR MATERIAL INVENTORY, PRODUCTION AND DELIVERY CONTROL

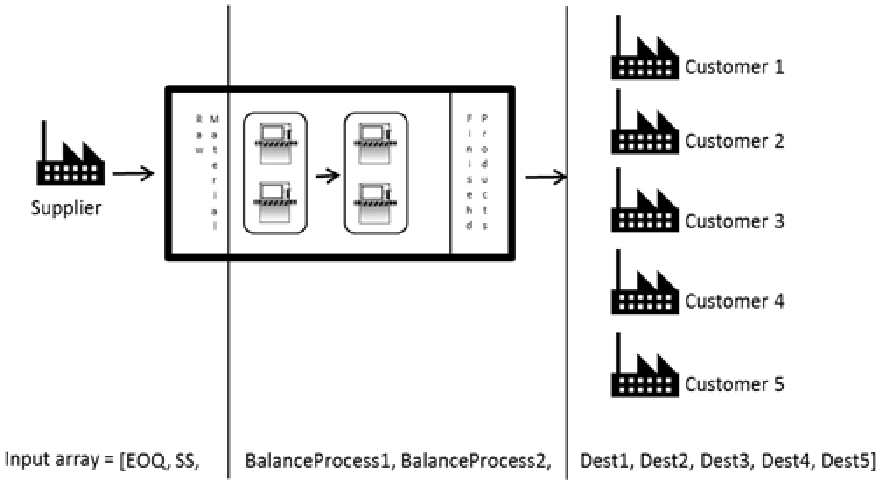
This section proposes and evaluates the performance of a simulation-based optimization approach for integrated material inventory, production and transport planning and control in a simple supply chain scenario. At first, the supply chain scenario is described.

Subsequently, the benchmark approach and the simulation-based optimization approach are described and their performance evaluated.

4.2.1 Scenario Description

The simulation-based optimization for integrated material inventory, production and transportation planning and control approach is tested in the supply chain represented in Figura 8, in which one supplier provides a single material to an original equipment manufacturer that processes the material and turns into a product to be delivered to five customers. The present supply chain structure aims to represent a frequent observed yet simple design among supply chains, comprising the three partners.

Figura 8 - Test case scenario



Fonte: Elaborada pelos autores (2020).

The production facility analyzes its material inventory every day. If it is below the safety stock (SS), it orders a fixed amount given as the economic order quantity (EOQ). Both safety stock and EOQ are decision variables.

The supplier tries to produce the ordered amount and delivers on the next day. No backlogging is allowed. The supplier production is considered as a single machine with a capacity for one product per time. In the production facility each job consists of two processes before being delivered. For each of these processes, two parallel machines are available, and the distribution of jobs between these machines is a decision variable for each process. This balance is defined as the percentage of products being allocated to the first parallel machine. The second machine produces the remaining products. Each one of the four machines has a single processing time determined by triangular distributions. The minimum and maximum processing times are: for machine 1 from process 1 = [10, 15], for machine 2 from process 1 = [5, 30], for machine 1 from process 2 = [10, 25], for machine 2 from process 2 = [15, 19].

The delivery takes place every day, right after receiving the daily demand from five customers. One truck is available to do the delivery. The truck is loaded every day at the middle of the day and loads at maximum, if available, the sum of the daily demands. At each stop, the truck delivers the largest amount possible, as the price of the products is the same for every customer. Once the truck is empty, it returns to the production factory. The unserved demands are lost since no backlogging is allowed. The daily demand for each client is determined by a singular triangular distribution, varying from 0 to 30, 15, 15, 60 and 30 for Customer 1, Customer 2, Customer 3, Customer 4 and Customer 5 respectively. The route to be travelled every day by the truck is the last decision variable. Each customer has a geographical position, and all travel links have different lengths. For each travel link travelled, the travel time is determined by the length of the link divided by a stochastic speed, also determined by a triangular distribution with minimum equals to 10 and maximum equals to 20. In the present work, the use of triangular distribution was chosen in order to obtain a high variability in the stochastic variable by only determining the range of possible values.

Thus, the objective consists of determining the safety stock, the economic order quantity, the products distribution between machines in each process (in percentage) and the delivery route to be applied every day. The solution was represented as an array of nine positions, as shown in the bottom of Fig. 1, where: the first two values represent the supplier, giving the EOQ and the SS as integers. The third (BalanceProcess1) and fourth position (BalanceProcess2) show the percentage of products allocated to the first of the parallel machines each. Finally, the last five positions (Dest1, Dest2, Dest3, Dest4 and Dest5) are the sequence of customers to be served. Such a test case already provides several sources of uncertainty. The stochastic behaviour occurs due to the supplier production time, the processing time in each one of the four individual machines from the production facility, where each has its own probability distribution and therefore capacity, the travel time for each link travelled by the truck, and the demand of each one of the clients.

The performance of a control strategy is measured by the profit made by the production facility in ten days. The revenue is composed only by the sum of the products' prices that are successfully delivered to the clients. Each unit successfully delivered represents $200 of revenue. The expenses are the sum of the following costs: The ordering costs are composed by a fixed ordering cost plus the individual cost of each product ordered. Inventory holding cost in the production facility are calculated every day. The production costs, which are different for each machine, are calculated by the amount of products processed in machine m times the cost of processing one product in machine m. For the delivery the utilized route cost is summed up, that are proportional to the realized travel times.

4.2.2 Benchmark Approach

The benchmark approach is used to evaluate the simulation-based optimization approach performance. Its control approaches were selected to mimic classical and empirical approaches commonly utilized on the daily routine of production and logistics control. On the material inventory control, the Economic Order Quantity (EOQ), calculated with the expression (1), and Minimum Safety Stock (SS), calculated with the expression (2), were adopted. Where D stands for average demand, S for the order placement cost, H for the inventory holding cost per unit, σ_d is the standard deviation of the demand, l is the lead time for delivery, and z is the inverse distribution function of a standard normal distribution, here assumed as 3 for the desired service level (99,87%).

$$EOQ = \sqrt{\frac{2 \cdot D \cdot S}{H}} \tag{1}$$

$$SS = z \cdot \sigma_d \cdot \sqrt{l} \tag{2}$$

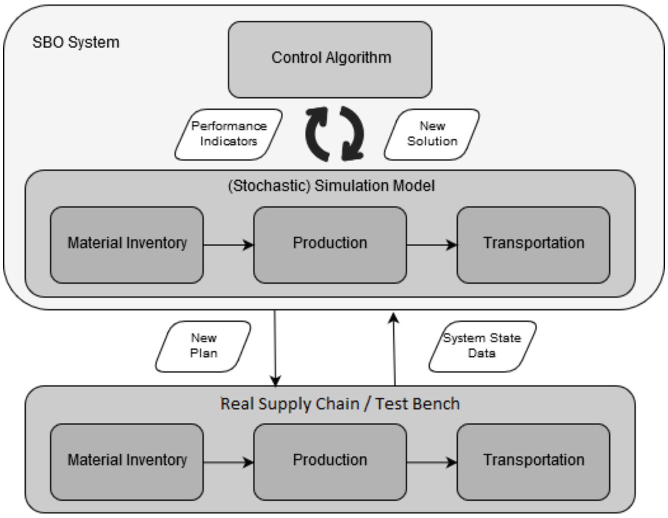
On the production, the optimization algorithm Jaya is implemented. The algorithm optimizes an objective function f(x) (i.e., minimizing the total cost of the production) through a series of interactions that changes the values of x at each interaction according to the equation (3), where x is the quantity of products to be produced in each machine at each echelon (Venkata Rao, 2016). For transportation control the Clarke and Wright saving algorithm was implemented (Clarke and Wright, 1964). The heuristic starts from a solution in which each of the n customers is visited in a separate tour. The cost of this solution is equal to twice the sum of the travel costs between the depot and all customers. For each customer pair, the algorithm then determines the saving that would result from connecting these customers directly. The algorithm then creates a savings list by sorting these n(n-1)/2 savings in decreasing order (Sörensen et al., 2019). The simulation was implemented in AnyLogic software, and the optimization algorithms were implemented using Java programming.

$$X'_{j,k,i} = X_{j,k,i} + r_{1,j,i}\left(X_{j,best,i} - \left|X_{j.k.i}\right|\right) - r_{2,j,i}\left(X_{j,worst,i} - \left|X_{j.k.i}\right|\right) \quad (3)$$

4.2.3 Simulation-based Optimization Approach

The simulation-based optimization (SBO) approach is presented in Figura 9. At each iteration a solution is generated by a control algorithm. Then, this solution is tested in the simulation model, which replaces the objective function and describes in a better way reality since it incorporates the stochastic and dynamic behaviour observed in reality.

Figura 9 - Simulation Based Optimization Approach



Fonte: Elaborada pelos autores (2020).

To cope with faster convergence, some constraints were added in the control algorithm. For the economic order quantity, the generated value should be positive and close to the expected capacity of the supplier. The safety stock should also be positive and not much bigger than the maximum daily processing capacity of the production facility. The machines job distribution may vary between zero and one. The route destinations are mapping the five customers, so the values are between 1 and 5, but for each customer can only be assigned once. Each generated solution is tested through a simulation that represents ten days of the supply chain operations.

The control algorithm is based in the simulated annealing metaheuristic (SA) and implemented in Matlab. Küçükoğlu and Öztürk (2014) define SA as a stochastic method for solving combinatorial problems inspired by the metallurgy annealing process. SA resembles a process where a metal is heated to a high temperature and then cooled by a defined rate. The algorithm used in this work reads a first feasible solution specified by the user and evaluates it, entering a loop. At each iteration, it generates a new solution and compares it with the main solution. If the new solution is better than the main solution, the new solution is assigned as the new main solution; if it is not, the algorithm computes a probability as proposed by Küçükoğlu and Öztürk (2015), allowing it to escape from local optimums (Ropke and Pisinger, 2006). After each iteration, the temperature of the system is reduced by a defined rate. As the temperature reduces, the probability of the system accepting a "bad solution" as the main solution reduces too. The process continues until the temperature gets close to zero.

A new solution is generated by changing one of the nine parameters (safety stock, economic order quantity, the two distributions between machines in each process, and the sequence of clients to serve represented by five parameters) of the main solution to a random value within a defined range (to assure the solutions feasibility).

The evaluation of each solution is performed by running a simulation model within AnyLogic. The Matlab algorithm writes the variables' values of the current solution in a spreadsheet file and calls the AnyLogic model. An instance of AnyLogic is opened and runs the model with the values from the spreadsheet file. At the end of the run, the program exports the results (the profit found in the simulation) to a text file and tells Matlab that the simulation has finished. Matlab then reads the exported value and assigns it as the objective functions value for the current solutions parameters.

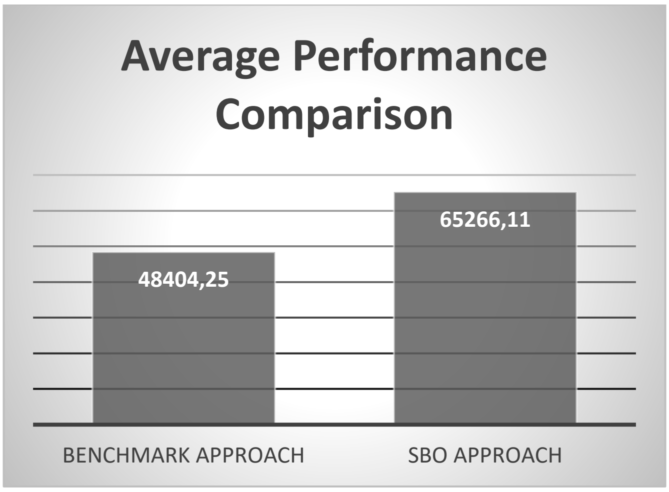
4.3 RESULTS AND DISCUSSION

Both approaches were run in a 10-days scenario to evaluate the profit obtained during this period and were executed ten times to evaluate the behaviour under stochasticity. Since the performance of the control strategy is measured by the profit, Figura 10 shows the results regarding the Average Performance Comparison in financial units. The Benchmark

Approach resulted in an average profit below the SBO approach, as presented in Figura 10, the profit was 35% higher for the SBO approach.

Through this analysis, it can be verified that the benchmark approach obtained considerably lower profit. This may have occurred because its costs are generally higher due to the bigger number of orders defined by the selected method.

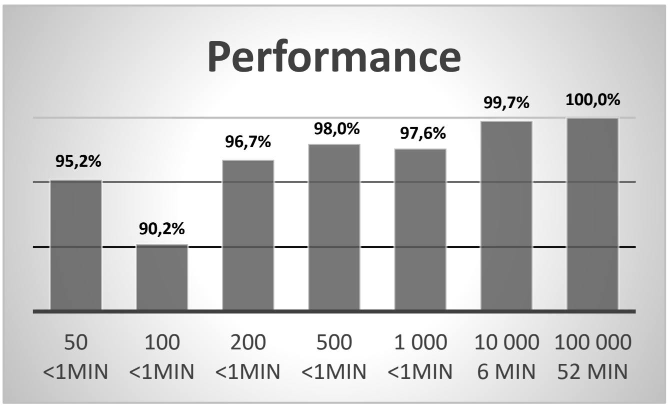
Figura 10 - Average Performance Comparison between approaches



Fonte: Elaborada pelos autores (2020).

In summary, the SBO approach provided satisfying results compared to the benchmark approach. The proposed approach kept bigger orders, seizing the low inventory holding cost and making savings in the number of orders. The approach also enabled the control algorithm to anticipate the opportunity of lower inventory costs and avoid the high order placement costs. Moreover, it was possible to select a more efficient delivery route for the demand uncertainty scenario. Therefore, the SBO approach showed a better ability to make good use of the scenario characteristics while responding to the uncertainties.

Figura 11 - Experiment performance compared to the best solution generated



Fonte: Elaboradao pelos autores (2020).

Moreover, further experiments presented a fast convergence to a satisfying result. Figura 11 presents the percentage of the best solution found by the experiment. Each bar represents an experiment, where the upper number in the label represents the number of iterations, and the lower number, the execution time. As presented, the simulation-based optimization was able to achieve more than 95% of the best solutions found with less than 1 minute running, for the test case applied, with the exception of the experiment with 100 iterations, which can be considered an outlier. Such cases may occur due to the random generation of solutions.

However, some further studies are recommended for a more in-depth evaluation of the approach. The first opportunity is to explore different qualities of the initial solution to evaluate the convergence when the initial solution is far from a good solution. Second, a study with parameters variations can clarify more aspects, such as sensitivity analysis. In addition, other approaches can be selected as benchmark approaches to evaluate the performance of the SBO compared to state-of-the-art approaches. Finally, the approach can be implemented in an adaptive way, to respond to dynamic events, such as a machine breakdown.

4.4 CONCLUSION

Supply chain structures are becoming more complex and dynamic. Such a transformation requires decision support tools, which are able to consider these characteristics. While Industry 4.0 concepts bring technologies that enable real-time data availability, decision support tools must be designed to consider this transparent dynamic behaviour better.

The present work reported a simulation-based optimization approach to simultaneously deal with material inventory, production and transportation processes control. Indeed, the concern of considering uncertainty and the dynamic behaviour of the supply chains has led to the proposal of hybrid approaches as simulation-based optimization by several authors. The presented approach obtained satisfying results significantly better than the benchmark approach.

However, it is desirable to extend the application of this approach to more complex scenarios in order to evaluate its behaviour. As future research, the development of improved heuristics should provide faster convergence. In addition, the performance of one simulation-based optimization relies on the accuracy of the implemented models, such as the simulation model and control algorithms, especially when dealing with uncertainty modelling. Thus, a test case in a real scenario is necessary to evaluate the complexity of obtaining such accuracy.

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5 INTEGRATED SIMULATION-BASED OPTIMIZATION OF INVENTORY, PRODUCTION AND DELIVERY PLANNING IN AN ELECTRICAL EQUIPMENT INDUSTRY

Este capítulo apresenta o conteúdo do terceiro artigo, resultado da terceira etapa da pesquisa, sendo o mesmo submetido ao *Journal of Manufacturing Systems*. O objetivo da terceira etapa da pesquisa é verificar a factibilidade da aplicação do modelo em um caso real, analisando resultados comparados ao executado atualmente na indústria bem como seu tempo de execução frente ao horizonte de planejamento. Nesse capítulo, a abordagem proposta é implementada em um cenário teste baseado em uma indústria brasileira de equipamentos elétricos.

5.1 INTRODUCTION

Supply chains comprise multiple flows of materials and processes across organizational boundaries, joining supply chains, production, and distribution of products and services, to add value to consumers and stakeholders (Frazzon 2009). Over the years, the vision of an isolated company has been transformed into one where companies work together (Chae, Olson, and Sheu 2014). The concept of supply chain integration is characterized by the company's collaboration with its partners in the supply chain, in an intra-organizational and inter-organizational scope, to make all flows within the chain more effective and efficient (Flynn, Huo, and Zhao 2010; Zhang et al. 2015). Considering the operational level, recent studies show that the integration of production and transportation has the potential to reduce costs, increase the number of on-time deliveries and increase the competitiveness of the chain as a whole (Ivanov, Sokolov, and Pavlov 2013; Ehm et al. 2015). Likewise, an increase in profit margins is noticeable when integrating purchasing and production planning (Siemon, Schiffer, and Walther 2021).

Although the integration between manufacturing and logistics along supply chains is advantageous, this approach increases the complexity of the decision-making process, which requires the use of new models, methods, and tools for decision-making (Reiter et al. 2011). This complexity is even more accentuated by the characteristics of growing demand and dynamic requirements of modern industrial systems, which require efficient and flexible control of machines and devices (Avventuroso et al. 2017; Ivanov et al. 2016). Real-time adaptation to changes in the supply chain is proven to be a competitive advantage (Barbieri et al., 2021; Takeda Berger et al., 2019; Espíndola et al., 2012).

Corroborating this idea, Pires, Parreira, and Frazzon (2021) analysed the impacts of 4.0 technologies in the context of the supply chain and presented the need for more efficient methods to solve many complex problems as well as the use of models that consider the uncertainties inherent in real-life processes. The authors suggest that some opportunities for future research are the inclusion of stochastic behaviour in the models, and the development of new approaches capable of achieving results close to optimal.

In this context, exact optimization models might be inadequate for the representation of productive systems due to their inherent complexity in these systems (M. Kuck et al., 2017). Frequently, supply chain problems with stochastic behaviour are addressed in the literature (Espíndola et. al., 2012). Simulation, on the other hand, is a more adequate tool to consider a system's stochastic behaviour, but it is not capable of delivering efficient optimization results when one or more objectives are established. Because real systems are subject to random events during their operation, simulation-based optimization approaches are recommended to deal with these uncertainties (Juan et al. 2021; Trigueiro de Sousa Junior et al. 2019). Simulation-Based Optimization (SBO) is an approach that combines the strengths of the two techniques: evaluates different system configurations through simulation and uses a meta-heuristic to determine nearly optimal configurations of parameters for the simulation (Fu, 2002). Shakibayifar et al. (2019) states that Adaptive Simulation-based Optimization (ASBO) is the ideal tool as it considers the stochasticity of the problem, providing solutions that are aligned with the real scenario through a simulation and optimizing the desired variables. Kück et al. (2017) and Ermolieva (2005) corroborate that an ASBO is capable of optimization by adjusting to system real life modifications. In addition, a supply chain digital twin is a real-time data-driven network model and enables real-time adaptation and optimization of the network (Frazzon et. al., 2021)

The SBO approach has been used to solve different problems related to supply chain planning. In the context of transport and logistics, Alrawabdeh (2021) used the approach to determine the optimal order quantity to satisfy the stochastic demand of all ages such that shortages and expirations are minimized in a context of extremely short shelf-life inventory and considering an age-discriminated stochastic demand. Aiassi et al. (2020) applied a simulation-based optimization approach to balance the trade-off between logistics cost and customers' experience level to achieve efficient management and integration of industrial restrictions and sales. Turan et al. (2020) compare the application of applying SBO with the use of isolated dispatching rules.

Alharkan et al. (2020) proposed a simulation-based model for optimizing order quantity and reorder point that minimizes the total inventory costs in a two-echelon supply chain, a distributor, and a supplier. Badakhshan et al. (2020). integrated system dynamics (SD) simulation and genetic algorithms to determine the optimal values for the inventory, supply line, and financial decision parameters. Their objective was to decrease both the bullwhip effect (BWE) and the cash flow bullwhip by applying a simulation-based optimisation approach. Quadras et al. (2022) applied simulation-based optimization to improve a production line's makespan and execution time in two different concepts: the first one considering the dispatch rule as the decision variable, and the second one utilizing a rule-free sequencing array as the decision variable. Both demonstrated satisfying results, with the second one returning a slightly better performance on both indicators. Wieczorek and Ignaciuk (2018) implemented a hybrid approach in a case study of a multi-period, multi-echelon, and multi-product production and distribution problem to identify the optimal production-distribution plan. Avci and Selim (2018) developed a multi-objective model based on mixed-integer programming. The proposal has three objectives: minimize the total cost of transportation and the costs associated with the use of intermediate nodes; minimize the risks of product losses in transportation; minimize the environmental impact of CO2 emissions produced by transportation and storage operations. Zhao and Wang (2018) presented a hybrid approach to support decisions for supply chain network design using a combination of analytical and discrete-event simulation models based on iterative procedures until the difference between subsequent solutions satisfies the pre-determined termination criteria. Heidary, Aghaie, and Jalalimanesh (2018) proposed an integrated production planning and inventory management model for the forest products industry to maximize the net annual profit of the forest industry under demand and supply uncertainty.

In addition to the research interest in using the SBO approach for problems related to transport and logistics, it is possible to find in the literature studies in which the approach is used to solve problems related to production planning and scheduling. Völker and Gmilkowsky (2003) presented a generalised method for creating reduced simulation models that facilitate simulation-based optimisation for medium-term production scheduling. Ehrenberg and Zimmermann (2012) proposed a simulation-based optimization approach that relies on coupling simulation and optimization through a relaxation-based schedule generation procedure, employing a mixed-integer programming model. Kück et al. (2017) proposed an adaptive simulation-based optimization approach to select individual dispatching rules for production control that can react quickly to dynamic changes. Purohit et al. (2017) proposed an approach for integrating production and maintenance planning considering the cost of rejection that allows joint optimization of batch allocation decision, batch sequencing decision, and PM decision to minimize overall operations cost. Kumar and Lad (2017) simultaneously addressed the lot sizing and job-sequencing problem that is solved by applying a Genetic Algorithm in a case study using simulation-based optimization to minimize the makespan time. Takeda Berger, Zanella and Frazzon (2019) proposed a new conceptual model for predictive-reactive scheduling combining machine learning and data-driven simulation-based optimization considering inventory availability. The authors highlight the relevance of the integration of machine learning and simulation-based optimization for the development of a reactive approach. Heinzl and Kastner (2020) included a multi-objective production scheduling problem, considering energy consumption as one of the factors. The authors used General Variable Neighbourhood Search (GVNS) as an optimization heuristic and the fitness evaluation is based on a hybrid discrete/continuous simulation model.

Despite research on the application of SBO in production, transportation, and logistics contexts, Cardoso et al. (2021) pointed out the incipient but highly important consideration of raw material inventory control and procurement processes. They indicated an opportunity to address short-term operational decisions as supply chain planning drivers, concomitantly with the analysis of medium to long-term impacts. The integration of different manufacturing systems and supply chain tasks needs to consider production planning, scheduling and control, transportation and logistics planning, scheduling and control, inventory planning and warehouse management and operations, manufacturing systems operations, as well as coupled services and technologies which can lead to improved performance.

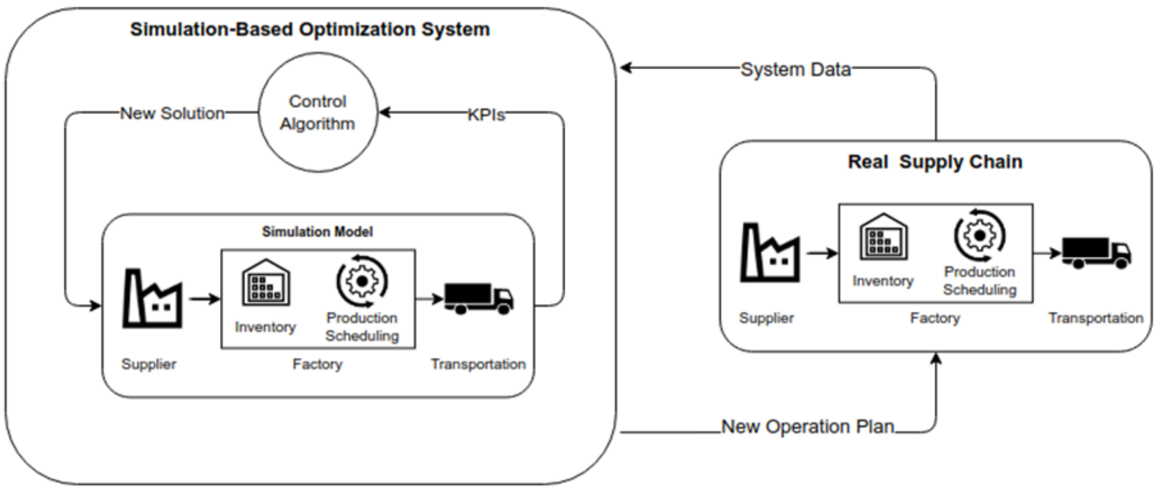
Considering the presented industrial challenges, this work proposes a simulation-based optimization approach aiming to improve raw material purchase, production planning, and transportation schedule. We applied the method in a Brazilian electric motor manufacturing industry test case, defined by uncertain scenarios and stochastic behaviour. The approach provides improved solutions considering the integrated system within a short time, allowing rescheduling if necessary.

The remainder of this manuscript is organized as follows: Section 2 presents the proposed conceptual model utilized later in this work. Then, in section 3, a test case scenario is defined based on a real case to apply the proposed conceptual model. Section 4 describes the application of the conceptual model applied in the test case. In section 5 the results are discussed comparing them to the performance of the current state scenario. Finally, section 6 presents the conclusions obtained with the application of the proposed model.

5.2 CONCEPTUAL MODEL PROPOSAL

The representation of a supply chain with multiple suppliers, and several production plants serving a large number of customers is a problem with a very large number of variables and high complexity. Then, it is necessary to use alternative methods that are capable of providing good solutions in appropriate processing time for use in practice, while considering the stochasticity of this system. The proposed conceptual solution procedure aims to overpass all these difficulties by applying a simulation-based optimization approach that addresses raw material purchase, production scheduling, and transportation considering stochastic factors from a real supply chain.

Figura 12 - Simulation-based optimization procedure



Fonte: Elaborada pelos autores (2023).

In the proposed procedure, presented in Figura 12, the real system provides the state data of the system, e.g., processing times and lead times, and inputs to the simulation-based optimization model. This data exchange can occur once, when the planning is needed, or can be triggered and occur every time a disruption happens (e.g., machine failure, last-minute urgent demand, or changes in supply parameters) and is based on several statuses distributed by the whole system such as probability distributions of delivery and processing times, inventory levels, machine states, repair times, and costs, among others. The simulation-based optimization, the left block of the conceptual model, is the core of the model, where the optimization occurs, and it is composed of an optimization method (e.g., heuristics, machine learning or other solution generation mathods) integrated into a simulation environment that represents the real-world scenario. The simulation plays the role of the objective function and allows solutions to be exposed to an environment of uncertainty similar to the real one. The SBO will work in loop. First, the loop is triggered by and event (network modification, for example) or by specified date and time. The real-word scenario will send the input parameters to the simulation model to be updated. The control algorithm will generate an initial solution (routes, rules, reorder points or others) and send to the simulation model. The simulation model will be executed and at the end it will return the performance of the model (total cost for example), assuming the role of an objective function. The control algorithm will evaluate the solution, and if no stop criteria is reached, new solution will be generated and sent to the simulation. Finally, the SBO returns to the real world the best solution that will be implemented.

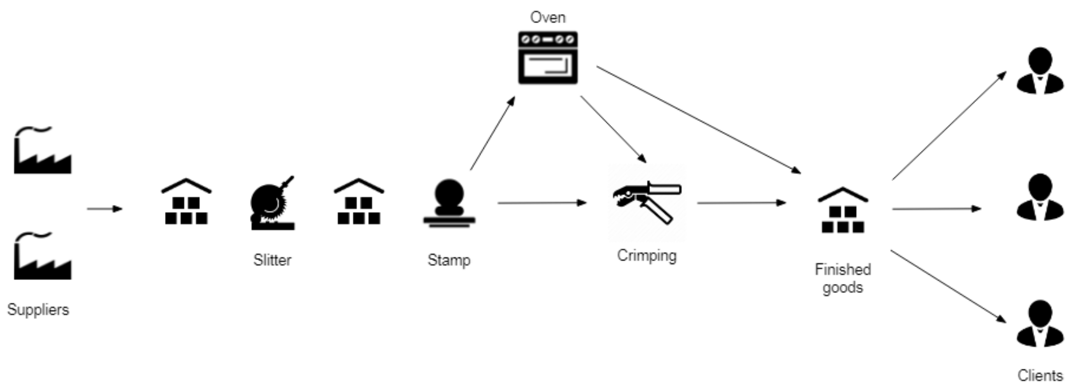
This methodology does not aim to find the best solution for each part of the system individually. It prioritizes finding a balance between supply, production, and transportation to achieve the best global solution with the minimum cost for the entire supply chain.

Also, this approach can be generalized to be included in the context of Industry 4.0. The connection between all parts of the chain can facilitate the exchange of real-time data between the real scenario and the simulation model. This data exchange is possible through the use of the sensor in cyber-physical systems, a fundamental concept of Industry 4.0. This technology enables the exchange of real-time data between real and digital systems, turning it possible to develop simulation models similar to its real correspondent. In addition, this exchange property gives the system greater responsiveness and flexibility. In theory, it would be a practical way to get around one of the problems explored by many authors, which would be the dynamism of supply chains.

5.3 TEST CASE DESCRIPTION

The test case for the application of the proposed procedure has as background an electrical equipment industry. The finished goods to be considered are unwounded stators and rotor sheets, each one with several variations of size and variations in raw material. To produce these products, three types of coil steel are purchased from two suppliers, each one of the suppliers with a stochastic lead time. After purchasing the raw material, the coil steel, the coils are sliced in a single machine to turn the coil into straps with the right width. Lately, the straps are used in three similar stamping machines, with stochastic producing time, to be transformed into stator sheets and rotor sheets. Products made with one particular raw material, semi-processed steel, are necessarily forwarded to an oven, with deterministic time. While rotor sheets are considered to be finished goods in the test case, stator sheets are still needed to be crimped in the last process. To finalize, one truck makes the delivery of the daily orders every day to six customers. The supply chain is summarized in Figura 13.

Figura 13 - Supply chain structure



Fonte: Elaborada pelos autores (2023).

5.4 APPLICATION ON TEST CASE

The objective of the optimization addresses three parts of the presented supply chain: raw material purchasing, order dispatching, and vehicle routing. The array of decision variables is composed of 12 variables:

Quadro 4 - Decision Variables

Decision Variable	Type	Range
Economic Order Quantity for Steel Type A	Integer	{250000, 4750000}
Economic Order Quantity for Steel Type B	Integer	{20000, 380000}
Economic Order Quantity for Steel Type C	Integer	{1500, 28500}
Reorder Frequency for Steel Type A	Integer	{2, 30}
Reorder Frequency for Steel Type B	Integer	{2, 30}
Reorder Frequency for Steel Type C	Integer	{2, 30}
Priority Rule for Job Dispatching	Integer	{1, 7}
First Customer to be Attended	Integer	{1, 5}
Second Customer to be Attended	Integer	{1, 5}
Third Customer to be Attended	Integer	{1, 5}
Fourth Customer to be Attended	Integer	{1, 5}
Fifth Customer to be Attended	Integer	{1, 5}

Fonte: Elaborado pelos autores (2023).

For the first part, the objective is to define the ordering frequency and the economic order quantity that satisfies the demand while reducing the stock cost of raw materials. The stock cost of each raw material (three types of steel) is calculated every day as the value of its material in stock (as raw material) and how much it could profit in a standard Brazilian financial application, i.e., opportunity cost (5,25% by year). For production, the objective is to define the best dispatching rule for the system, reducing setup costs and delays. The setup cost was obtained directly from the company represented on the test case and it occurs every time the tooling of the machine must be switched due to final product modification, according to the daily demands, and variates for each machine. Delay costs were also included to avoid the model to produce nothing at no cost. The delay cost was also calculate using the Brazilian opportunity cost (cost of the material that should have been delivered multiplied by the Brazilian standard interest rate, 5,25%). The considered Dispatching Rules are based on Kück et al. (2017): FIFO (First In, First Out), LIFO (Last In, First Out), EDD (Earliest Due Date), MDD (Modified Due Date), ODD (Operation Due Date), FASFS (First Arrival in System, First Served), and SPT (Shortest Processing Time).

Finally, the routing objective is to define the shortest route for the vehicle to attend to the six clients every day. The cost of delivery is considered as the cost per kilometer of a truck, including the fuel ($ 0,29 per km) and a driver driving at an average speed of 15km/h ($ 0,06 per km). Thus, the objective function is to minimize the total cost, defined as the sum of raw material stock costs, setup costs, and delivery costs. The final costs considered in the test case are summarized below.

Quadro 5 - Parameters

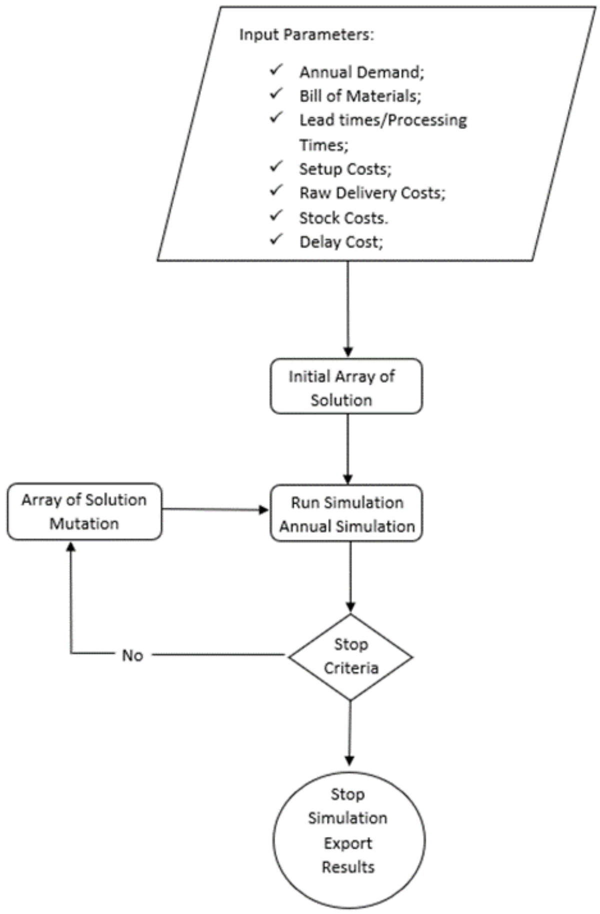
Object	Price	Unit
Steel Type A Price	$ 921,00	Per Ton
Steel Type B Price	$ 570,00	Per Ton
Steel Type C Price	$ 984,00	Per Ton
Steel Type A Stock	$ 0,13	Per Ton Per Day
Steel Type B Stock	$ 0,08	Per Ton Per Day
Steel Type C Stock	$ 0,14	Per Ton Per Day
Machine 1	$ 9,03	Per Setup
Machine 2	$ 6,25	Per Setup
Machine 3	$ 6,25	Per Setup
Delivery	$ 0,35	Per Km

Fonte: Elaborado pelos autores (2023).

To illustrate the proposed procedure, Figura 14 shows the steps that compose the optimization process. First, the input parameters are provided to elaborate the simulation model, where the annual demand is given, as well as the bill of materials of the demanded products, the lead times and processing times, the setup costs for each machine, the cost of each raw material for purchasing as well as the daily stocking cost, the delay cost for each material, and finally, the cost of each transportation arch to be included in the route.

Thus, an algorithm generates a first solution, an array composed of the EOQ of each steel type, reordering frequency of each steel type, dispatching rule, and customer delivery sequence. The solution is applied to a one-year simulation of the scenario, and its performance is evaluated by the sum of the stocking costs, setup costs, and transportation costs. The parameter variation approach was applied as shown below. Dynamically, four parameters were varied. Three of these parameters represent the replenishment period for each of the three suppliers, ranging from six to thirty days, adding +2 days for each variation. The fourth parameter refers to the dispatch rule applied to the machines. This number ranges from one to six (adding +1 for each variation). In this way, it is guaranteed that all possible variations are analysed. The final product delivery order is randomly generated each round, regardless of parameter variation. In total, 23625 solutions were tested. Finally, the results are exported, and the outcome is explored in the Results section.

Figura 14 -Optimization flow

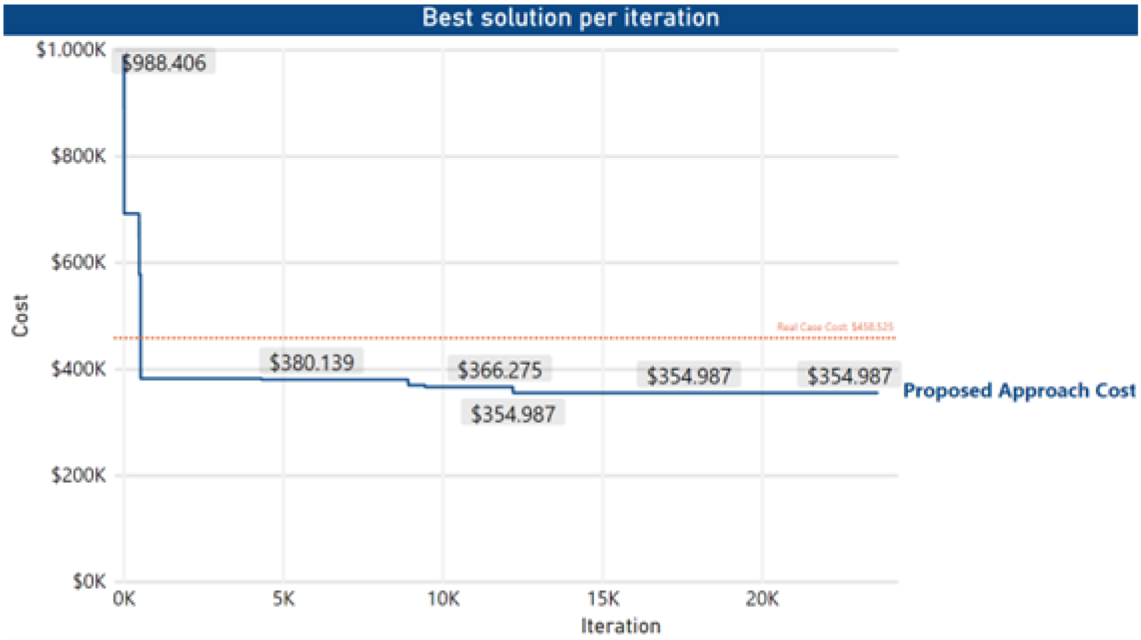


Fonte: Elaborada pelos autores (2023).

5.5 RESULTS

In this section, the results from the experiment described earlier are explored. To start the analysis, it is possible to compare the overall performance of both the SBO method and the current state, comparing the total cost obtained in both (the sum of stock cost, setup cost and delivery cost. As shown in Figura 15, it is possible to evaluate the convergence of the algorithm for the best solution. The blue line represents the total cost achieved on the best solution by the implemented SBO approach, while the orange dashed line shows the total cost on the current state as a reference. At the end of the more than twenty thousand iterations, the implemented SBO performed 22,1% lower costs than the current state, with a solution found at the 12234th iteration. However, at the 534th iteration, the implemented approach has already found a solution 16,7% better than the current state.

Figura 15 - Best solution per iteration



Fonte: Elaborada pelos autores (2023).

To drill down the overall performance, Quadro 5 presents the performance in each area of the three costs: the best overall solution from the proposed approach, the minimum cost of each area among all the solutions in the implemented SBO approach found individually in the simulations, and the cost for each area in the current state. The table results show that the global optimum among the solutions generated by the proposed procedure is not composed of the individual optimal obtained in each area in other solutions. This result raises two hypotheses: searching for more combinations of decision variables could bring better overall performances, combining the best solutions of each costing area, or the global optimum for the present problem is not the combination of local best solutions, as stated in several studies addressing supply chain problems. While some costing area can be competitive with each other, in this particular case the probability that one can impact the other, for example low stocks can lead to higher setups due to the scheduling with low raw material, is very unlikely due to the structure of the problem presented. Thus, it is likely that more iterations, or a better convergence supported by an evolutionary algorithm, may help to find even better solutions.

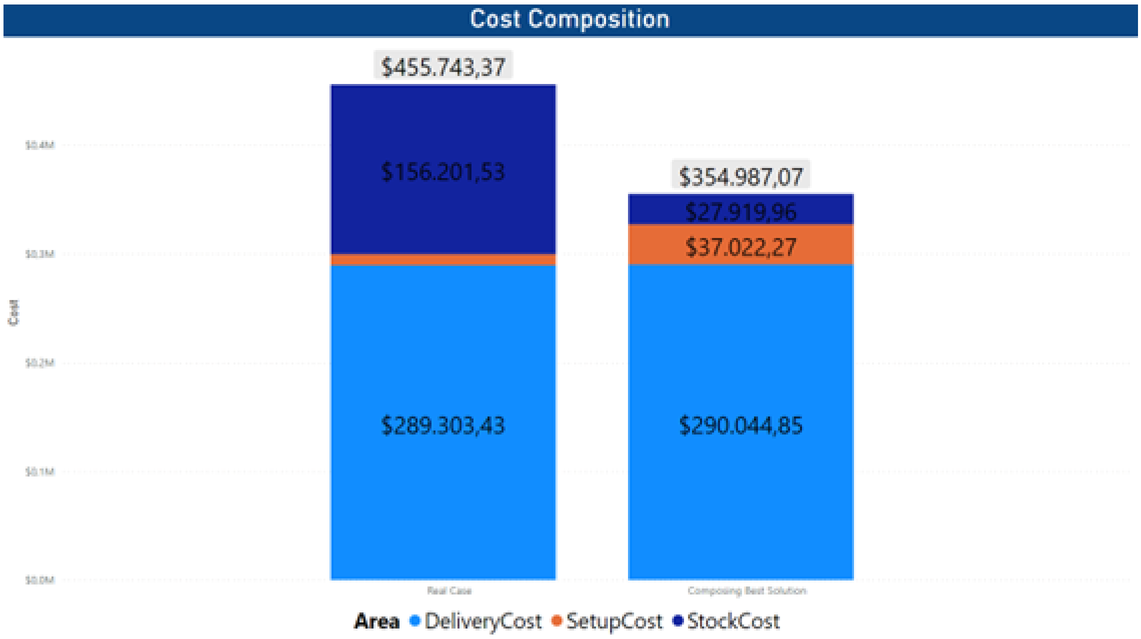
Quadro 6 - Costs by area and by approach

Approach	Cost			Total	Relative Performance
	Delivery Cost	Stock Cost	Setup Cost		
Proposed Overall Best	$ 290.045	$ 27.920	$ 37.022	$ 354.987	22,1%
Proposed Individual Best	$ 289.303	$ 9.005	$ 15.357	$ 313.665	31,2%
Current State	$ 289.303	$ 156.202	$ 10.238	$ 455.743	-

Fonte: Elaborado pelos autores (2023).

An overview of the cost composition of the scenarios is shown in Figura 16. In both proposed approaches overall best and current state, the delivery problem represents more than 60% of the total cost of the scenario. An expressive dominance on the delivery costs can lead the algorithm to prioritize the best solutions for the delivery problem and ignore less expensive and less sensitive problems, such as the setup cost. It is interesting in extension of the study to fix the delivery problem with the best solution found and solve the problem only for stock and setup, also analysing the dependence of the stock and setup problems for the delivery problem. However, the biggest gain concerning the current state was the stock cost, which had an 82% decrease on the application of SBO overall best solution and a 94% decrease in the minimum stock cost obtained. Therefore, stock costs were significantly smaller than the delivery cost in both application of SBO overall best and current state, but it was not ignored by the method. Setup cost, however, was already less than 3% of the cost of the current state, and did not perform very well in the proposed approach, neither in the overall best solution nor the individual best (50% more expensive, but still less than 8% of the final cost).

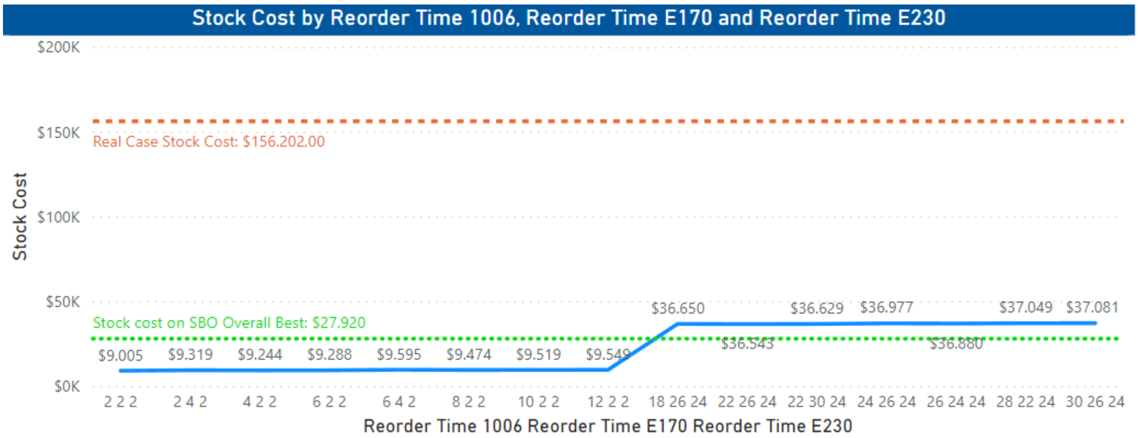
Figura 16 - Costs composition



Fonte: Elaborada pelos autores (2023).

Evaluating the chart in Figura 17 to look more closely at the stock problem, it is possible to see the stock cost per reorder time combination. As expected, the lower the reorder times the lower the stock costs, a consequence of the possibility to work with lower EOQs. Even though there was a fixed cost for order placing, it was better to work with lower EOQs and more frequent orders, due to the volume and price of the materials the stocking cost were significantly more important than the order placing cost. However, in the SBO overall best solution, the combination of reorder times was almost three times higher than the individual best found among the iterations, but still 82% lower than the current state.

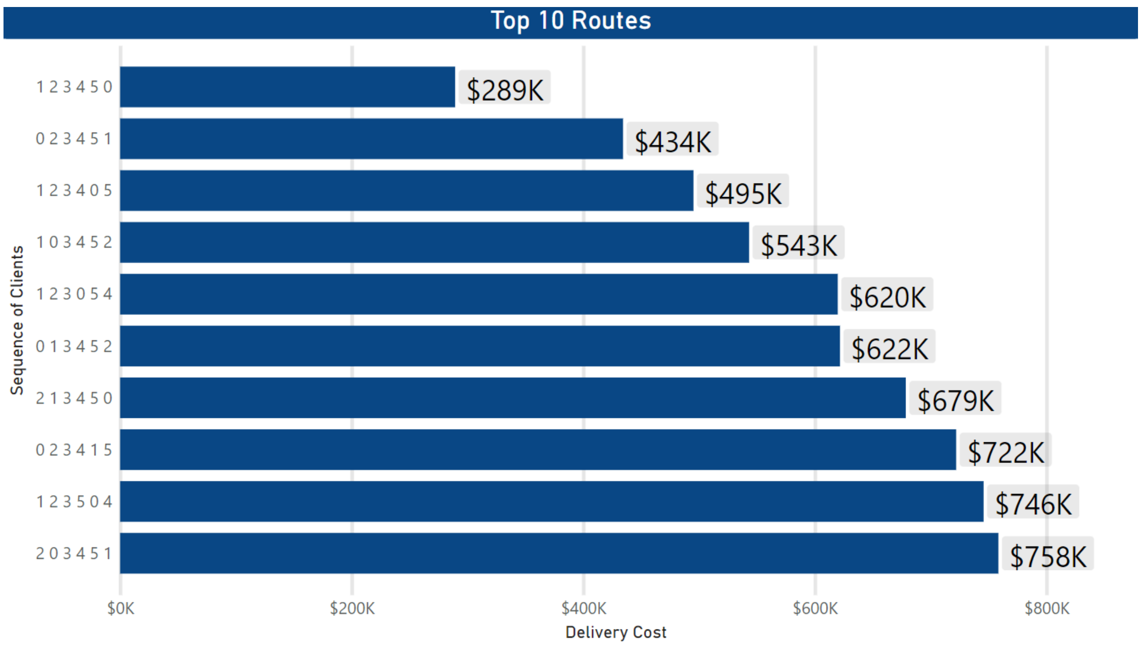
Figura 17 - Stock costs by reorder times



Fonte: Elaborada pelos autores (2023).

To analyse deeper the routing problem, Figura 18 presents the top 10 best routes and their final costing. Each bar represents the order of customers to be attended daily. For example, the best solution had the customer order [1, 2, 3, 4, 5, 0] and at the end of the year, the deliveries costed $ 290 045. It is possible to notice that a small change in the route can significantly increase the cost of the problem.

Figura 18 - Top 10 best routes

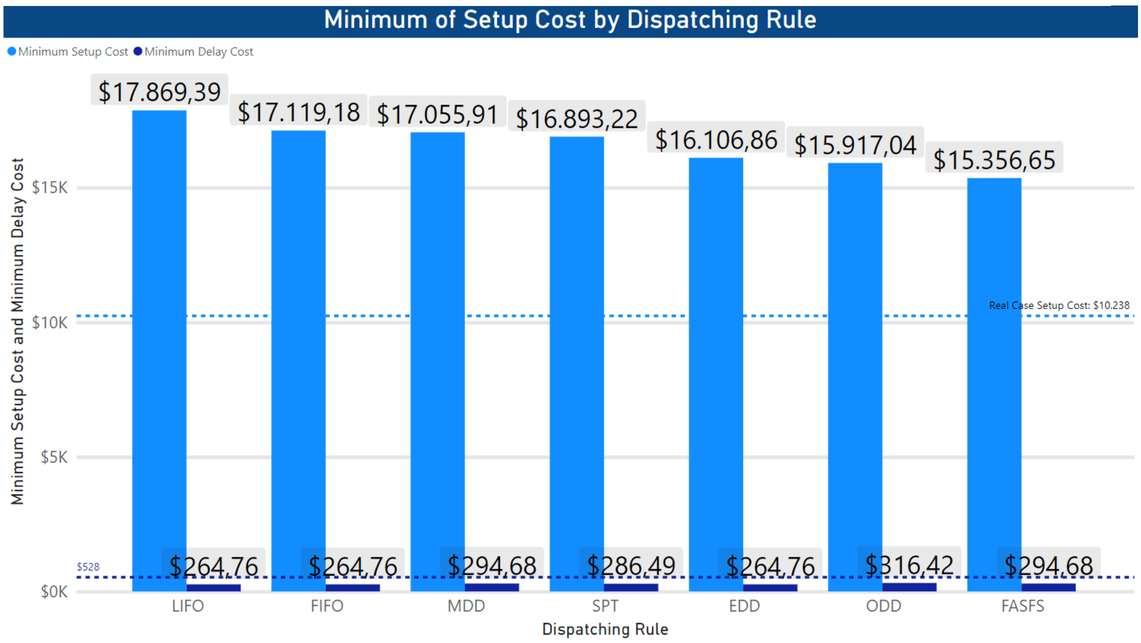


Fonte: Elaborada pelos autores (2023).

Therefore, Figura 18 explains the fast convergence to the best solution once the optimal route is reached. This problem only has 720 possible combinations, but the 10th better combination is already 162% more expensive than the optimal solution. Therefore, the dependence of the other problems about the routing must be analysed. One strategy to find a new overall best solution could be fixing the best solution found individually here and variating only the parameters of the other two problems.

Figura 19 compares the performance of each dispatching rule on the production line, where each light blue bar presents the minimum sum of setup costs along the year, and the dark blue bars present the minimum sum of delay costs along the year.

Figura 19 - Minimum Setup Costs and Average delay cost by dispatching rule



Fonte: Elaborada pelos autores (2023).

It is possible to notice that the dispatching rules have similar performance on the delay costs, indicating a balance in order quantity and machine availability. However, LIFO and FIFO presented lower delay costs, reaching almost half of the current state delay cost. Meanwhile FASFS had significantly lower setup costs, yet still significantly higher than the current state scenario. This indicates that dispatching rules are more capable of reducing delay cost, its main objective, than dealing with setup costs. The SBO Overall best was reached with MDD as dispatching rule, reaching $ 37 000 of stock cost and $ 5 148 of delay cost.

Therefore, the results indicated satisfying results obtained from the SBO application in an integrated supply chain planning. As indicated in literature review, the method must be capable of dealing with highly complex and stochastic systems. The proposed procedure took less than twenty hours in a regular computer to run more than twenty thousand iterations. Even though with only 534 iterations a result 16,7% better than the current state was already found, all this considering several stochastic variables in a supply chain planning with one year of simulation to run. Thus, the procedure attended to the gaps indicated in the research section, by providing a procedure capable of dealing with complex and stochastic scenarios, generating satisfying result within a short period of time. The performance of the procedure in terms of faster convergence can still be leveraged by the implementation of an evolutionary algorithm as a control algorithm to generate solutions based on the best solution already found.

5.6 CONCLUSION

Supply chain structures are becoming more complex and dynamic. Such transformation requires decision support tools, which can consider these characteristics. While Industry 4.0 concepts bring technologies that enable real-time data availability, decision support tools must be designed to better consider this transparent dynamic behaviour. As indicated in the introduction, approaches capable of dealing with highly complex and stochastic scenarios are needed to leverage the supply chain competitiveness, seeking a cross-company optimization, as stated by several authors.

The present work reported a simulation-based optimization approach, where the simulation tool enables the use of a complex and stochastic model as an objective function. The paper used the method capability to extend the planning scope of the supply chain, and simultaneously deal with material inventory, production, and transportation processes control, to show the capability of the method in dealing with high complexity scenarios. The presented approach obtained satisfying results significantly better than the result from the real supply chain, as a reference. Although the system does not optimize individually each area to its local optimum, the system was minimized to a lower global cost than the current state.

Therefore, it is suggested to extend the application of this approach to a deeper investigation for each area, as opportunities were spotted during the analysis of the results. First, evolutionary algorithms can be used as solution generation within the simulations, to obtain a faster convergence result and keep the best individual solutions, checking if the three areas (stock, setup and delivery) present interdependence. Also, different balances among the three costs significance can be tested. Furthermore, the evaluation of the local optimum can clarify the integrated behavior, for example, fixing an optimal individual solution for the delivery problem and testing a more refined optimization of the other two problems. Also, extending scenarios with different parameters such as capacity, processing times and so on can lead to a more limited capacity scenario to evaluate better the optimization under a scarce scenario.

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6 DISCUSSÃO E SÍNTESE DO TRABALHO

Este capítulo tem o objetivo de discorrer sobre as contribuições do trabalho desenvolvido e seu alinhamento com os objetivos citados nos elementos pré-textuais. Em sua primeira seção são apresentados os resultados e contribuições individuais de cada artigo que compõem o presente trabalho. Na última seção desse capítulo, é apresentada a contribuição da presente tese de doutorado ao estado da arte na área do conhecimento na qual se enquadra, apontado para as implicações gerenciais que essa pesquisa pode trazer para a prática.

6.1 RESUMO DAS CONTRIBUIÇÕES DOS ARTIGOS

O Quadro 7 apresenta resumidamente os principais resultados e contribuições de cada artigo que compôs a estrutura desse compêndio de artigos.

Quadro 7 – Resumo dos resultados e contribuições dos artigos

		Objetivos	Resultados	Contribuições
Fase 1	Capítulo 3 (artigo 1)	Através de revisão bibliométrica e de conteúdo sobre os tópicos envolvidos, identificar lacunas e oportunidades na área de planejamento integrado da cadeia de suprimentos além de elencar e discutir principais métodos / tecnologias de planejamento integrado da cadeia de suprimentos;	Cinco fluxos de pesquisa predominantes foram encontrados: (i) abordagens para lidar com a complexidade, (ii) consideração de incerteza, (iii) controle de estoque de matérias-primas e processos de compras, (iv) necessidade de considerar impactos ambientais, (v) e modelos específicos para lidar com produtos com vida útil limitada. Oportunidades comuns de pesquisa futura mencionadas: (i) incluindo comportamento estocástico e dinâmico nos modelos (ii) estendendo os modelos para incluir uma rede maior, mais variáveis ou estendendo os casos de teste para avaliar o modelo em maior escala, (iii) e desenvolver abordagens de solução mais eficientes.	Os resultados provenientes desse artigo servem como uma revisão do estado da arte sobre planejamento integrado em cadeias de suprimentos bem como as preocupações mais discutidas sobre o tema atualmente, direcionando o futuro das pesquisas.
Fase 2	Capítulo 4 (artigo 2)	Propor um modelo conceitual de planejamento integrado de estoque de matéria prima, produção e transporte utilizando otimização adaptativa baseada em simulação e comparar os resultados do modelo proposto com o de modelos já validados na literatura;	Os resultados obtidos mostram que a abordagem é capaz de lidar com a complexidade e cenários estocásticos dos sistemas de fabricação do mundo real, superando os métodos clássicos de controle.	Contribuição para o uso de novas tecnologias no planejamento de cadeias de suprimentos, bem como a integração de áreas da cadeia.
Fase 3	Capítulo 5 (artigo 3)	Avaliar o desempenho do modelo proposto utilizando dados provenientes de um potencial aplicação real, analisando potenciais ganhos em termos de desempenho operacional em cenários envolvendo comportamentos estocásticos.	O modelo se mostra aplicável e com um desempenho superior ao obtido no cenário real, ainda que o melhor resultado do sistema obtido pelo método não seja a soma dos melhores desempenhos observados por área (estoque, produção e entrega).	Contribuição para o debate científico sobre a utilização de modelos mais avançados no planejamento de cadeias de suprimentos reais.

Fonte: Elaborado pelo autor (2023).

O Capítulo 3, onde é apresentada a primeira etapa da pesquisa, teve como objetivo identificar lacunas e oportunidades na área de planejamento integrado da cadeia de suprimentos além de elencar e discutir principais métodos e tecnologias de planejamento integrado da cadeia de suprimentos. A etapa então teve o objetivo de responder quatro perguntas elencadas como principais: (i) Estão os autores de planejamento da cadeia de suprimentos considerando as capabilidades provenientes da Indústria 4.0 nos seus modelos e *frameworks* propostos? (ii) Estão todas as etapas da cadeia de suprimentos (estoque de matéria prima, produção, entrega, vendas e assim por diante) sendo consideradas e quais métodos estão se utilizando para as mesmas? (iii) Quais são os problemas mais abordados pelos autores? (iv) Quais são as principais oportunidades de pesquisas futuras denotadas pelos autores? Para atingir tal objetivo foi aplicada revisão de literatura e revisão bibliométrica. Com o objetivo de garantir reprodutibilidade e clareza no processo de revisão, o procedimento PRISMA foi aplicado para revisão bibliográfica e bibliométrica. O modelo consiste em quatro macro etapas: coleta de trabalhos, seleção dos trabalhos coletados, coleta de dados dos trabalhos selecionados, e análise de conteúdo. Na etapa de coleta de trabalhos, três bases de dados foram consultadas: Scopus, Science Direct e Web of Science. Para padronização das consultas, *strings* e booleanos de busca foram padronizados *((TITLE("Supply Chain") AND TITLE(integrated) AND TITLE(planning OR control)) ANDDOCTYPE(ar OR re)* e *(TITLE(planning OR control) AND TITLE(integrated) AND TITLE("Supplier Selection" OR "Material Inventory" OR "Production" OR "Scheduling" OR "Transportation" OR "Distribution" OR "Routing" OR "Sales and Operations"))* retornando artigos de pesquisa e também de revisão de literatura relacionados ao planejamento da cadeia de suprimentos e suas etapas individuais. Ao todo, 2270 artigos foram retornados das pesquisas. Para as micro etapas de filtragem, foi elaborada uma lista de critérios de exclusão do trabalho, como: artigo não disponível em inglês, artigo publicado antes de 2011 (início da menção a Indústria 4.0), trabalho não relacionado ou pouco relacionado com a área alvo, artigo não considera planejamento operacional, entre outras. Após a remoção de duplicatas (consequência da consulta em mais de uma base), sobraram 1429 trabalhos. Aplicando-se o primeiro filtro, analisando apenas a *metadata* do trabalho, foram excluídos 768 trabalhos, todos referentes ao filtro de ano de publicação. Na segunda etapa, com 661 trabalhos, foi analisado o título, excluindo mais 278 trabalhos. A terceira etapa consiste na leitura de título e resumo, o que gerou a exclusão de mais 141 artigos. Restando-se ainda 243 trabalhos, foi decidido priorizar os com mais de 10 citações, com exceção dos publicados nos últimos dois anos da revisão de literatura, excluindo mais 153 documentos. 89 trabalhos sobraram então para a leitura na íntegra, onde mais 43 foram excluídos devido aos critérios pré-estabelecidos. Para avaliação de conteúdo, coleta de dados e análise bibliométrica então sobraram 46 trabalhos aptos. Na etapa de coleta de dados, alguns pontos principais foram coletados de cada artigo: contribuição do artigo (modelo, *framework,* revisão ou outros), quais eram os processos considerados da cadeia (estoque de matéria, produção, entrega e assim por diante) no documento, método de solução caso aplicável, e se há menção à Indústria 4.0. Para sumarizar os dados, uma tabela mostrando cada ponto coletado por artigo analisado foi desenvolvida. A tabela auxilia na interpretação dos dados, onde fica visualmente perceptível a baixa menção a

Indústria 4.0, estoque de matéria prima e compras, simulação e otimização baseada em simulação, respondendo as duas primeiras questões levantadas para essa etapa. Análises bibliométricas expressas em gráficos apontam principais autores, artigos, periódicos, e uma grande tendência de aumento do tema em 2018. Após a leitura na íntegra dos 46 artigos selecionados, lacunas de pesquisa e tendências de pesquisa relacionadas ao planejamento integrado de cadeias de suprimentos foram elencadas, respondendo as duas últimas questões objetivadas na presente etapa. Das principais problemáticas abordadas pelos autores, é possível elencar as principais: (i) desenvolvimento de modelos capazes de lidar com cenários cada vez mais complexos, (ii) consideração de incerteza nos modelos de planejamentos, (iii) consideração da etapa de compra e controle de estoque de matéria prima, (iv) consideração de impactos ambientais, e (v) desenvolvimento de modelos que lidem com produtos com alta perecibilidade. Já entre as lacunas identificadas pelos autores e oportunidades de pesquisas futuras, é possível destacar e sumarizar algumas delas, como a necessidade de se desenvolver alterativas de otimização que lidem com sistemas complexos, com comportamentos estocásticos, que levem em consideração também o estoque de matéria prima, e que possa ter tempo de execução factível para a aplicação. Tais linhas entraram em evidência por conta da quarta revolução industrial e suas tecnologias capacitadoras, que tornam o sistema de estudo/otimização maiores, mais complexos, e em tempo real, devido a facilidade na aquisição de dados de diversas áreas em tempo real. Além disso, muitos problemas de planejamento integrado não exploram com profundidade a implementação dos mesmos em casos reais, e sua comparação com o desempenho real do sistema.

Mais adiante, no Capítulo 4, onde a segunda etapa da pesquisa é apresentada, tem-se como objetivo a proposição de uma alternativa para lidar com as principais lacunas identificadas na etapa anterior: uma abordagem onde é possível modelar um sistema complexo, com comportamento estocástico e tempo factível de execução. Uma análise na literatura retornou que modelo de otimização baseados em simulação são alternativas capazes de lidar com tais problemas, onde a simulação como função objetivo traz a possibilidade de se modelar um sistema complexo com comportamento estocástico, utilizando-se de heurísticas e meta-heurísticas para a variação de um vetor de solução para rápida convergência e identificação de soluções satisfatórias. Logo, é proposto um modelo conceitual de otimização baseada em simulação para uma cadeia de suprimentos, visando propor um modelo integrado de planejamento para lidar com sistemas mais complexos, envolvendo estoque de materiais, produção e controle dos processos de transporte, com comportamentos estocásticos e capaz de ser executado em tempos viáveis de processamento em relação ao período planejado, conforme lacuna apontada na etapa anterior da pesquisa. Após a apresentação do modelo conceitual um cenário hipotético foi apresentado para servir de base comparativa em relação a aplicação de modelos clássicos de planejamento. O cenário hipotético apresenta uma cadeia onde uma matéria prima é fornecida através de apenas um fornecedor com tempo de entrega variável, onde a variável de decisão para a compra de matéria prima se resume em decidir os valores de estoque de segurança e tamanho de lote econômico. No cenário comparativo, as decisões sobre compra de matéria prima obedecem aos modelos analíticos de cálculo de tamanho econômico de lote e estoque de segurança. Logo após, a matéria prima sofre industrialização em dois processos sequenciais, cada um tendo duas máquinas paralelas com diferentes tempos estocásticos de processamento, assim como diferentes custos de utilização. A decisão então consiste no despacho dos produtos entre as máquinas, sendo feito no modelo SBO como duas variáveis que indicam a porcentagem de probabilidade de alocar na primeira máquina, e no modelo de comparação utilizando-se o algoritmo de otimização de Jaya. Como última etapa, a entrega dos produtos acabados deve ser feita aos cinco clientes diários, tendo eles diferentes distâncias entre si e demandas estocásticas. Logo, o tempo de transporte em cada trecho também é variável, bem como a prioridade de atendimento no dia. Sendo assim, no modelo implementado são apresentadas cinco variáveis que ditam a ordem de atendimento aos clientes, enquanto no modelo de referência é aplicado o algoritmo das economias de Clark e Wright. Como algoritmo de geração de soluções para a implementação do SBO, um algoritmo de *simulated annealing* foi implantado. O cenário teste consiste na execução de uma simulação de dez dias de ambos os cenários, calculando a rentabilidade de cada um, dada pela diferença entre a receita de produtos entregados e os custos de operação da cadeia (custo de pedido, fixo e variável, custo de estoque considerando a rentabilidade do valor agregado em um rendimento financeiro padrão, custo de produção dado por cada máquina, e custo final da rota de entrega). Ambos os cenários foram replicados 10 vezes. A implementação do SBO apresentada obteve resultados satisfatórios significativamente melhores do que a abordagens clássicas da literatura utilizadas como modelo comparativo, apresentando uma rentabilidade da cadeia 35% maior. Em testes posteriores, o método também apresentou um desempenho computacional satisfatório, executando 100 000 iterações em menos de uma hora, sendo que com apenas 200 iterações (em menos de um minuto) o resultado obtido já apresentava uma rentabilidade apenas 3,3% menor do que a melhor solução encontrada nas 100 000 iterações. Ao final dessa etapa, foi identificado que o modelo conceitual na implementação proposta conseguiu lidar com um cenário mediano, composto por diversas variáveis estocásticas, retornando soluções satisfatórias em baixo tempo computacional. No entanto, ainda seria desejável estender a aplicação do modelo a cenários ainda mais complexos para avaliar seu comportamento. Ainda, a implementação de um caso teste baseada em um cenário real é necessária para avaliar a performance frente a complexidade (tamanho) e aplicabilidade.

Finalmente, durante o artigo 3, onde a terceira e última etapa da pesquisa é apresentada, o modelo conceitual é novamente apresentado, e então implementado em um cenário baseado em uma indústria real para comparativo. O cenário para aplicação teste se baseia em uma indústria de motores elétricos brasileira. O cenário teste é composto pela compra e estoque de três tipos de aço em bobinas, onde é possível obter as duas primeiras variáveis de decisão da aplicação: tamanho de lote econômico e frequência de pedido. O tempo de processamento e de entrega de cada um dos aços são triangularmente variados. Os custos relacionados a compra ocorrem dos custos de pedido (fixo e variável) e os custos de estoque de matéria prima, calculado como o custo de oportunidade do montante financeiro em questão aplicado na taxa de juros brasileira. Uma vez que chegam na empresa, as bobinas são cortadas em diferentes espessuras e uma máquina só. Estando em tiras, cada tira é encaminhada para qualquer uma das três máquinas similares de estampagem. Porém, são demandados durante o ano mais de 700 produtos acabados diferentes, sendo que cada par (lâmina de estator e lâmina de rotor) possui sua ferramenta específica para estampagem, necessitando tempo de setup para cada troca de material demandado. Dentro os três tipos de aço, um deles necessita, posteriormente a estampagem, passar 24 horas em um forno para tratamento técnico, sendo esse forno único. Após a estampagem e tratamento térmico ou não, as lâminas de rotor são consideradas produto acabado, enquanto as de rotor ainda são encaminhadas para o processo de grampeamento, feito em máquina única. Logo, em se tratando da produção, a decisão consiste em escolher a melhor regra de despacho a ser utilizada durante o ano na priorização das ordens de produção que ocorrem diariamente de forma estocástica. Na simulação, elas aparecem um dia antes de serem executadas, assim como acontecem no estado atual da cadeia. As regras de prioridades levadas em consideração foram: FIFO (*First In, Firt Out*), LIFO (*Last In, First Out*), EDD (*Earliest Due Date*), MDD (*Modified Due Date*), ODD (*Operation Due Date*), FASFS (*First Arrival in System, First Served*), e SPT (*Short Processing Time*). O processo de produção gera custo de duas principais formas: custo de *setup*, que ocorre toda vez que muda o produto em processamento, e custo de atraso da ordem, calculado também como custo de oportunidade. Posteriormente, as lâminas (tanto de rotor quanto estator), são encaminhadas para a entrega, que acontece uma vez por dia com rota fixa, para seis clientes em diferentes localizações. O custo da rota é calculado como a distância total percorrida (a ser otimizada) vezes o custo de operação por quilometro de um caminhão no Brasil, considerando mão de obra e combustível. Em suma, o objetivo do modelo proposto é otimizar o tamanho de lote de compra e a frequência de compra, ambos para cada tipo de aço, definir a melhor regra de despacho dos pedidos, e definir a rota ótima de entrega. Sendo assim, a implementação do SBO otimizar as 13 variáveis de decisão, medindo o desempenho através de uma função objetivo representada pela simulação de um ano de aplicação das variáveis resultando em um custo final total. No estado atual da cadeia, as decisões são tomadas em uma série de procedimentos locais manuais de acordo com a experiência dos envolvidos. Como heurística de variação de parâmetros, foi implementado o recurso de *parameter variation* do *software* AnyLogic, onde as variáveis de tamanho de lote, frequência de reposição e regras de despacho eram variadas linearmente entre máximos e mínimos, buscando todas as combinações, enquanto as rotas eram geradas aleatoriamente em cada combinação dos parâmetros anteriores, gerando um total de 23625 iterações com vetores de soluções diferentes. O desempenho do modelo foi comparado então através dos seus custos totais com os custos totais obtidos no cenário real. Os resultados indicaram então um desempenho satisfatórios obtidos com a aplicação do SBO em um planejamento integrado da cadeia de suprimentos. Conforme indicado na revisão da literatura, o método deve ser capaz de lidar com sistemas altamente complexos e estocásticos. O procedimento proposto levou menos de vinte horas em um computador comum para executar mais de vinte mil iterações. Mesmo assim com apenas 534 iterações já foi encontrado um resultado 16,7% melhor que o estado atual, tudo isso considerando diversas variáveis estocásticas em um planejamento da cadeia de suprimentos com um ano de simulação para rodar. No melhor cenário encontrado pela aplicação da otimização baseada em simulação, as variáveis geraram um custo 22,1% abaixo do resultado obtido no cenário atual da cadeia. Analisando os mínimos custos encontrados em cada área, é possível ver que os mínimos locais das iterações chegam a ser ainda menores que o melhor resultado geral da implementação do modelo, chegando a uma redução de 31,2% no custo, sendo necessário estudos futuros para analisar se os mínimos individuais podem ser encontrados simultaneamente. Foi possível ver na composição do problema que no caso do SBO implementado mais de 92% do custo anual é referente a custos de entrega, sendo interessante para estudos futuros fixar tal solução ou usar algoritmos evolutivos para acelerar a convergência do problema. Enquanto no estado atual da cadeia os custos de setup foram relativamente menores, enquanto o maior ganho da otimização proposta foi no custo de estoque e compras, sendo quase 82% menor que o do estado atual da cadeia. Entretanto, em soluções com desempenho global menores, custos de estoque ainda mais baixos foram encontrados, havendo possibilidade investigação da factibilidade de tais soluções com outras variáveis. Em termos de custos de entrega, foi identificada uma grande sensibilidade dos custos em relação as rotas. Enquanto a melhor solução entregava um desempenho satisfatório, a décima melhor solução, de 720 possíveis, entrega um custo 162% maior, inviabilizando várias soluções globais. Em suma, em convergência com alguns autores, essa etapa relatou uma abordagem de otimização baseada em simulação, onde a ferramenta de simulação possibilita o uso de um modelo complexo e estocástico como função objetivo. O trabalho utilizou a capacidade do método para estender o escopo do planejamento da cadeia de suprimentos e, simultaneamente, lidar com estoque de materiais, produção e controle dos processos de transporte, para mostrar a capacidade do método em lidar com cenários de alta complexidade. A abordagem apresentada obteve resultados satisfatórios significativamente melhores do que o resultado da cadeia de suprimentos real, como referência, em tempo computacional factível com o horizonte de planejamento. Entretanto, é desejável estender a aplicação dessa abordagem para uma investigação mais profunda de cada área, pois oportunidades foram identificadas durante a análise dos resultados. Primeiramente, algoritmos evolutivos podem ser usados como geração de soluções dentro das simulações, para obter um resultado de convergência mais rápido e manter as melhores soluções individuais, verificando se as três áreas (estoque, setup e entrega) apresentam interdependência. Além disso, diferentes equilíbrios entre a significância dos três custos podem ser testados. Além disso, a avaliação do ótimo local pode esclarecer o comportamento integrado, por exemplo, fixando uma solução ótima individual para o problema de entrega e testando uma otimização mais refinada dos outros dois problemas. Além disso, estender cenários com diferentes parâmetros, como capacidade, tempos de processamento e assim por diante, pode levar a um cenário de capacidade mais limitada para avaliar melhor a otimização em um cenário escasso.

6.2 CONTRIBUIÇÕES TEÓRICAS E PRÁTICAS

A três etapas de pesquisa, apresentadas nos Capítulos 3 a 5, possuem objetivos individuais específicos, sincronizados em uma única linha para a formação de uma contribuição geral, atingindo o objetivo geral proposto. Dessa forma, fazendo diferentes contribuições em questões teóricas e práticas.

A grande revolução em sistemas ciber-físicos juntos com a tecnologia de computação na nuvem e outros capacitadores como conexões de rede mais disponíveis têm alavancado a desginada quarta revolução industrial, ou Indústria 4.0. Tal revolução tem aumentado a disponibilidade de dados de sistemas que compõem a cadeia de suprimentos em tempo quase ou real, possibilitando a alimentação de gêmeos digitais e execução de algoritmos de tomada de decisão dinâmico, considerando o estado atual do sistema. Sistemas esses compostos de diversos agentes individuais e com comportamentos não determinísticos. Porém, como indicado na primeira fase da pesquisa, onde uma revisão literária foi executada sobre o planejamento integrado da cadeia de suprimentos, há pouca menção sobre a Indústria 4.0 nos artigos sobre planejamento da cadeia de suprimentos. Corroborando com o novo cenário da Indústria 4.0, os autores, sem mencioná-la, indicam necessidade de desenvolvimento de modelos de planejamento da cadeia de suprimentos com viável implementação de sistemas complexos e com comportamento estocástico e dinâmicos. Sendo assim, a primeira fase, através da seleção de mais de dois mil documentos e aplicação de metodologia replicável, auxiliou na identificação de uma lacuna de pesquisa na área de planejamento da cadeia de suprimentos que vai ao encontro das oportunidades de uma das grandes correntes de desenvolvimento tanto no campo teórico quanto na indústria em si: a quarta revolução industrial. Tal lacuna direcionou então o desenvolvimento do presente trabalho.

A segunda etapa da pesquisa, por sua vez, propõe uma metodologia presente na literatura para lidar com as exigências dos cenários provenientes da Indústria 4.0. A otimização baseada em simulação permite a utilização de um modelo de simulação, base do gêmeo digital, como função objetivo de uma ferramenta de otimização. Modelos de simulação possuem uma melhor factibilidade de emulação de sistemas mais complexos, podendo-se fazer uso de diferentes paradigmas de simulação (eventos discretos, baseada em agentes, ou sistemas dinâmicos) permitindo a implementação de diversos comportamentos, estocásticos ou não, de forma intuitiva e visual. A implementação do SBO na segunda etapa do presente trabalho demonstra a factibilidade dos seus resultados ainda que em tempos computacionais satisfatórios perante o horizonte de planejamento do caso teste, especialmente com o poder computacionais disponível comercialmente na atualidade. Sendo assim, a abordagem de otimização baseada em simulação se mostra uma alternativa factível para os desenvolvimentos teóricos que buscam aproximar os cenários testes aos cenários reais e seus comportamentos, e atrativa para as indústrias que estão fazendo parte da revolução industrial, principalmente alavancando a utilização de gêmeos digitais. A indústria, muitas vezes cética aos modelos matemáticos lineares, tende a absorver melhor modelos de simulação que desempenham comportamentos mais próximos aos reais, facilitando a implementação e aceitação desses modelos de simulação.

A última fase da pesquisa também contribui em aspectos tanto teóricos quanto práticos. Em termos teóricos, a implementação do método de otimização baseada em simulação nas três etapas de uma indústria (*procurement*, produção e entrega) demonstra que a abordagem é capaz de emular um sistema com várias variáveis, agentes e diversificações de produtos e roteiros, ainda alcançando desempenhos computacionais satisfatórios. Em termos práticos, a etapa mostra a viabilidade da criação de um modelo de simulação que emule os comportamentos da cadeia, usando o mesmo para alavancar resultados na cadeia e testar hipóteses.

Por fim, ambas as áreas impactadas possuem a possibilidade de utilização da abordagem proposta para ganhos de desempenho, ainda auxiliando na geração de conhecimento sobre as etapas de compra de matéria-prima, produção, e entrega de produtos acabados, podendo gerar avaliações de desempenho, custos, ociosidade, atrasos, em assim por diante. Essa plataforma pode ser utilizada como auxílio na tomada de decisão pelos responsáveis da indústria, auxiliando no entendimento e planejamento de cenários, engrandecendo a competitividade da cadeia, reiterando a importância e utilidade de gêmeos digitais.

7 CONSIDERAÇÕES FINAIS

O presente trabalho teve como objetivo a proposição de uma abordagem de otimização baseada em simulação capaz de abranger estoque de matéria prima, produção e entrega, lidando com sistemas complexos, estocásticos e capaz de ser solucionado em tempo viável em comparação com o horizonte otimizado, com aplicação em caso real factível e capaz de prover resultados superiores aos desempenhos clássicos da literatura e de casos reais como objetivo geral.

O primeiro objetivo desse trabalho consiste em identificar lacunas e oportunidades na área de planejamento integrado da cadeia de suprimentos, seguido do objetivo de delimitação das principais técnicas e métodos utilizados nos problemas da área. Para isso, na primeira etapa do trabalho, uma revisão de literatura sobre planejamento integrado em cadeias de suprimentos foi realizada para identificar tais lacunas de pesquisa bem como tendências de pesquisa no meio científico, avaliar o estado da arte, e analisar se os conceitos da Indústria 4.0 estão sendo considerados nessa área. Como resultado, foram obtidas as principais tendências e necessidades, dentre elas, a necessidade de considerar estoque de matéria-prima, a necessidade de modelos que lidem com sistemas estocásticos e complexos, bem como modelos que tenham tempo de execução e resultados satisfatórios, e ainda considerando as capabilidades da Indústria 4.0, assim direcionando as etapas seguintes do presente trabalho.

Na segunda etapa, com o intuito de atingir as necessidades e oportunidades elencadas na primeira etapa, e o objetivo de proposição de um modelo conceitual, foi proposto então um modelo conceitual de otimização baseada em simulação para a gestão de estoque, produção e entrega. Esse modelo foi aplicado em um caso teste hipotético e comparado com modelos clássicos de planejamento não integrado, obtendo resultados superiores em termos de desempenho, validando sua eficácia, e em tempo computacional factível para o horizonte de planejamento.

Na última fase, para cumprir o objetivo de avaliar o desempenho do modelo proposto em um cenário baseado em um problema real envolvendo alta complexidade e comportamento estocástico, o modelo proposto foi implementado em um caso teste baseado em uma fábrica real de lâminas de estatores e rotores, considerando o fluxo de aquisição de matéria prima, as regras de despacho de ordens de produção, bem como a roteirização da entrega. Como função objetivo, os custos que compõem cada área foram somados a cada simulação, compondo a função objetivo a ser minimizada. Os custos otimizados obtidos após um número fixo de iterações foram significantemente menores que os custos registrados no cenário real.

7.1 OPORTUNIDADES PARA TRABALHOS FUTUROS

É importante ressaltar que o presente trabalho teve seu escopo delimitado, trazendo limitações e oportunidades de extensão dos estudos. Primeiramente, a revisão de literatura, etapa inicial do trabalho, foi limitada a um conjunto de apenas três bases de artigos científicos principais, bem como limitada a escrita inglesa somente. Uma revisão mais complete do tema, explorando mais bases, mais idiomas e mais palavras-chaves relacionadas ao tema pode levar a novas conclusões.

Na segunda etapa, a comparação entre o modelo proposto e as abordagens clássicas da literatura foi realizada em um cenário hipotético e simplificado. Variações no sistema, aumento do grau de complexidade podem engrandecer a linha de pesquisa. Ainda é possível citar a comparação da abordagem proposta com abordagens clássicas em um cenário real.

Em se tratando da terceira e última etapa, é desejável estender a aplicação dessa abordagem para uma investigação mais profunda de cada área de planejamento, pois oportunidades foram identificadas durante a análise dos resultados. Primeiramente, algoritmos evolutivos podem ser usados como geração de soluções dentro das simulações, para obter um resultado de convergência mais rápido e manter as melhores soluções individuais, verificando se as três áreas (estoque, setup e entrega) apresentam interdependência. Além disso, diferentes equilíbrios entre a significância dos três custos podem ser testados. Além disso, a avaliação do ótimo local pode esclarecer o comportamento integrado, por exemplo, fixando uma solução ótima individual para o problema de entrega e testando uma otimização mais refinada dos outros dois problemas. Além disso, estender cenários com diferentes parâmetros, como capacidade, tempos de processamento e assim por diante, pode levar a um cenário de capacidade mais limitada para avaliar melhor a otimização em um cenário escasso.

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APÊNDICE A – Títulos e autores dos artigos que compõem esta coletânea

Títulos	Autores	Publicado em	Fator de Impacto
Integrated Operational Supply Chain Planning in Industry 4.0	Matheus Cardoso Pires, Renato Parreira e Enzo Morosini Frazzon	International Journal of Integrated Supply Chain Management	CiteScore: 2.2
Simulation-Based Optimization for the Integrated Control of Production and Logistics: A Performance Comparison	Matheus Cardoso Pires, Enzo Morosini Frazzon, Djonathan Quadras, Eike Broda e Michael Freitag	IFAC-PapersOnLine (IFAC World Congress 2020)	CiteScore: 2.1
Simulation-Based Optimization for Material Inventory, Production And Delivery Control: A Test Case In The Electrical Equipment Industry	Matheus Cardoso Pires, Djonathan Quadras, Lúcio Galvão e Enzo Morosini Frazzon	Artigo submetido ao *Journal of Msnufacturing Systems*	

Fonte: Elaborado pelo autor (2023).

APÊNDICE B – Primeira página dos artigos publicados da tese

Artigo 1 – Publicado no International Journal of Integrated Supply Chain Management, 2021.

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Integrated operational supply chain planning in Industry 4.0

Matheus Cardoso Pires, Renato Parreira and Enzo Morosini Frazzon

Published Online: February 5, 2021 · pp 28-49

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Abstract

The scenario of isolated companies competing with each other has evolved to a holistic vision, where companies collaborate and work together to maintain supply chain competitiveness. Integrated supply chain planning, although challenging, is necessary to foster competitive advantage and to ensure companies' survival in difficult times. Concepts and technologies introduced by the Fourth Industrial Revolution support such integrated planning models. This paper presents a systematic literature review on integrated supply chain planning aiming to identify research streams, opportunities and the impact of Industry 4.0. The study identified the lack of research on supply chain planning which considers Industry 4.0 concepts and opportunities. Five prevailing research streams stand out: 1) approaches to deal with complexity; 2) the consideration of uncertainty; 3) raw material inventory control and procurement processes; 4) the necessity of considering environmental impacts; 5) particular models for dealing with limited lifetime products. Finally, the following future research opportunities were identified: 1) improving decision-making models to consider stochastic and dynamic behaviours; 2) extending the models to include larger networks with more variables; 3) developing more efficient solving approaches.

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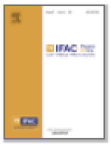

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Matheus C. Pires *, Enzo M. Frazzon *, Djonathan Quadras **, Eike Broda ***, Michael Freitag ****

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Abstract

Manufacturing systems' efficiency depends on the proper assignment of orders to resources. Due to existing interdependencies, the integrated consideration of production, inventory and delivery processes can improve the overall manufacturing performance. However, the integration can result in high

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APÊNDICE D – Permissões de direitos autorais do artigo 2 (capítulo 4)

Preprints, Proceedings, Copyright Conditions and Article Sharing Policy

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