

A report on “Cyclical Scheduling and Assembly Line Balancing”

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RESUMO

Este relatório resume a tese de Thiago Cantos Lopes, a qual trouxe avanços teóricos e práticos às linhas de montagem industriais do setor automotivo. Vários problemas combinatórios foram estudados, dentre eles balanceamento, sequenciamento e alocação de *buffers* em linhas de modelo misto. Variantes práticas como linhas com estações multi-operadas e sequências estocásticas de produtos foram também abordadas. Dentre os métodos de Pesquisa Operacional aplicados, encontram-se Programação Linear Inteira Mista, decomposições exatas e heurísticas, simulação, busca local e limitantes inferiores baseados em algoritmos em grafos. Dentre as contribuições da tese, destacam-se: a superação de *benchmarks* da literatura, ora em qualidade das soluções, ora em tempo de processamento, conclusões teóricas, mas de interesse prático sobre a relação entre variáveis físicas do problema e uma quebra de paradigma que permite reduzir o comprimento de linhas multi-operadas. Estas contribuições foram publicadas em revistas renomadas da área de Pesquisa Operacional, sendo a tese uma coletânea destas publicações. Desta forma, apresentamos a mesma como candidata ao prêmio de tese do LIV Simpósio Brasileiro de Pesquisa Operacional.

PALAVRAS CHAVE. Balanceamento de linhas de montagem, Programação linear inteira mista, Métodos de decomposição.

PT – Prêmio de Tese, POI – PO na Indústria

ABSTRACT

This report summarizes Thiago Cantos Lopes' PhD thesis, which made theoretical and practical advances to industrial assembly lines in the automotive sector. Various combinatorial problems were studied: task distribution balancing, product model sequencing, and buffer allocation in mixed-model assembly lines. Some contributions address practical variants such as multi-manned stations and stochastic product sequences. The thesis applied several Operations Research methods: Mixed-Integer Linear Programming, exact and heuristic decompositions, simulations, local search, and lower bounds based on graph algorithms. The thesis' contributions include surpassing literature benchmarks in terms of solution quality or computation time, theoretical conclusions of practical interest on the relationship between physical variables of the studied problems, and a paradigm shift that allows reducing the length of multi-manned lines. These contributions were published in renowned Operations Research journals, and the candidate's thesis is a collection of these publications. Therefore, we present it as a candidate for the LIV Brazilian Operational Research Symposium Best Thesis Award.

KEYWORDS. Assembly line balancing. Mixed-integer linear programming. Decomposition methods.

PT – Thesis Award, POI – OR in Industry

1. Introduction

This report aims to summarize Thiago Cantos Lopes' PhD thesis, which is entitled "Cyclical Scheduling and Assembly Line Balancing". The thesis addresses several combinatorial problems tied to assembly lines, such as assembly line balancing, mixed-model sequencing, and buffer allocation. Many problem variants of practical interest are considered, some combining optimization problems that were most often treated separately. The thesis is a collection of the candidate's nine main publications during his doctorate, each of which is the subject of a chapter in the thesis. Given the thesis substantial theoretical and practical contributions to industrial assembly lines found in the automotive sector, the candidate submit the thesis to participate in the LIV Brazilian Operational Research Symposium (SBPO 2022) Best Thesis Award, which will be held in Juiz de Fora, Minas Gerais, from the 8th of November to the 11th of November, 2022.

This report is structured as follows: Section 2 briefly introduces the thesis' context, Section 3 describes the candidate's trajectory during his PhD, Section 4 presents an overview of the thesis's chapters, Section 5 lists the author's publications related to the thesis, and Section 6 presents the report's concluding remarks.

2. Literature overview

The main focus of the thesis is the optimization of assembly lines found in the automotive sector. These are product-oriented manufacturing layouts commonly used for large-scale and mass production of either standardized or similar problems. Several optimization problems are tied to these manufacturing systems, the main ones being assembly line balancing [Scholl and Becker, 2006] and mixed-model sequencing [Boysen et al., 2009]. The former deals with the distribution of workloads (tasks) to stations, while the latter on ordering different product models in order to minimize the impact caused by differences between their tasks' processing times. Battaia and Dolgui [2013] present an in-depth survey and classification of balancing problems, which are typically NP-hard, because they subsume the bin-packing problem as a particular case [Álvarez-Miranda and Pereira, 2019].

In its most basic form, the Simple Assembly Line Balancing Problem (SALBP) includes only precedence constraints and relates to deterministic, single model lines [Baybars, 1986]. In this version of the problem, the instance data can be fully described by an acyclical graph with directional edges, in which each node is a task with a given processing time, and the edges represent precedence constraints. In this case, scheduling variables may be unnecessary to fully define the optimization models tied to the line. This is the case because the cycle time constraint can be added to the problem as a limitation on the sum of task processing times within each station.

However, several practical features common in assembly lines require scheduling variables in order to be adequately described. These features are tied to deviations from the typical assumptions of SALBP, and typically are associated with important economic considerations. For instance, the increased product diversity leads to variable processing times, which lead to scheduling variables becoming more relevant [Boysen et al., 2008]. The space-saving possibility of multi-manned lines similarly require tasks to be scheduled within each station [Kellegöz, 2017]. Meanwhile, parallel stations can further complicate mixed-model scheduling, by allowing different product sequences per station [Öztürk et al., 2015]. Physical characteristics of the line, such as pace line control, also affect the required scheduling model [Karabati and Sayin, 2003], and the problem can be particularly challenging when cyclical scheduling - *i.e.* the description of a stable steady-state - is considered. The candidate's thesis is positioned in this context, considering several combinations of these (practical) features and presenting contributions to assembly line balancing problems related to cyclical scheduling.

3. On the thesis development

Thiago Cantos Lopes started his PhD in May 2017. The PhD studies were developed at the Federal University of Technology – Paraná (UTFPR) under the supervision of Prof. [Leandro Magatão](#) and Prof. [Nadia Brauner](#) from Université Grenoble Alpes, France. The Graduate Program in Electrical and Computer Engineering (CPGEI) hosted this optimization research under the concentration area of automation and systems engineering.

During the PhD, the candidate worked at [Renault](#) under the agreement 041/2020, in partnership with [Fundação Araucária](#). The project entitled “Production Line Balancing and Mix Analysis” was announced in a [public call for proposals](#) to foster academic institutions’ articulation with industries and favor practical knowledge related to the automotive universe. This project focused on developing mathematical programming models for balancing and sequencing passenger vehicle manufacturing lines at Renault’s factory. This period resulted in several contributions, both in terms of practice applications and academic research. The former led to optimized assembly lines in industry and an international [patent](#), whilst the latter group effort yielded scientific publications.

Academically, the candidate also participated in the [SBPO 2016](#) (Vitoria), the [SBPO 2017](#) (Blumenau), the [SBPO 2018](#) (Rio de Janeiro), the [CLAIO 2018](#) – XIX Latin-Iberoamerican Conference on Operations Research (Lima, Perú), and the [ROADEF 2020](#) – *Congrès Annuel de la Société Française de Recherche Opérationnelle et d'Aide à la Décision* (Montpellier, France).

The candidate made a doctoral stay at Grenoble University, France, in the laboratory G-SCOP (*Sciences pour la conception, l'Optimisation et la Production*). Professor Nadia Brauner supervised his work during this *sandwich* period, during which the candidate was the co-winner of the Best Student Paper of [ROADEF 2020](#), with the work entitled *Optimally solving multi-objective MILP problems with part-wise continuous Pareto fronts*. This international cooperation was particularly fruitful as it also led to three scientific papers published in respected journals, one of which was published in the International Journal of Production Research during the doctorate years [[Lopes et al., 2022a](#)], while the second and third were accepted for publication [[Lopes et al., 2021, 2022b](#)] only after the thesis defense.

During the doctorate period, the candidate and coworkers were granted an international patent in a subject related to the thesis. The initial procedures were started during the candidate’s master’s degree, with concomitant developments during the doctorate. The [patent](#) is entitled *Method For Reducing Cycle Time Of An Automated Welding Line And Corresponding Welding Plant*. The thesis contributes to intelligent production systems, providing tools to improve the competitiveness of companies. According to [Scopus](#), the candidate has an *h-index* of 8.

The thesis defense took place on the 21th of May, 2021. The examining committee was formed by Prof. Ricardo Lüders¹, chair of examiners and internal member from CPGEI, Prof. Flávio Neves Jr.² as internal member from CPGEI, Prof. Cassius Tadeu Scarpin³ (PPGMNE/UFPR), Prof. Nadia Brauner⁴ (Université Grenoble Alpes, France), and Prof. Reinaldo Morabito Neto⁵ (UFSCar) as external members. The final revised version of the thesis manuscript is available on UTFPR’s [repository](#).

¹<http://lattes.cnpq.br/5158617067991861>

²<http://lattes.cnpq.br/0494282486171725>

³<http://lattes.cnpq.br/9339655232048898>

⁴<https://pagesperso.g-scop.grenoble-inp.fr/braunern/>

⁵<http://lattes.cnpq.br/4194801952934254>

4. Contributions

The thesis is composed of 11 chapters. The first one is an introduction, Chapters 2-9 are the main contributions, each based on a publication, and the final one is a summary of the thesis. In this section, the main contributions of each article that based the main thesis' chapters are listed and briefly discussed.

Chapter 2 presents a new mixed-integer programming model that describes and optimizes the steady-state of a mixed-model assembly line under known product sequences and buffer distributions. This formulation was validated with simulations and shown to outperform literature alternatives consistently. A case study with practical industrial data presents a detailed analysis of different sequencing strategies and buffer layouts.

Chapter 3 extends the previous chapter's formulation to incorporate mixed-model sequencing and line-pace. The proposed approach allows performance comparisons between synchronous, asynchronous, and hybrid lines, which can help decision-makers choose between the different types of line control. The formulation was also shown to outperform a literature benchmark that was explicitly designed for synchronous lines [Karabati and Sayin, 2003].

Chapter 4 extends Chapter 2's model differently, by adding parallel stations. This formulation includes a boundary-wise scheduling definition that allows different product sequences to operate cyclically and consistently in each station. This different strategy allowed the formulation to outperform a literature benchmark that studied the same problem [Öztürk et al., 2015].

Chapter 5 further extends Chapter 3's formulation by incorporating buffer allocation as decision variables. Given the resulting problem's complexity, an iterative decomposition is proposed and shown to outperform the monolithic MILP model. While the decomposition is a heuristic solution method, it can solve some instances to optimality and prove it under the right circumstances.

Chapter 6 departs from the previous Chapters by considering a problem variant with stochastic product sequences. A new algorithmic simulator and a simheuristic procedure are presented. The simulator is shown to be around ten times faster than a literature benchmark for the type of lines studied [Tiacchi, 2012], and the simheuristic outperformed a relevant literature benchmark formulation that studied the same problem [Venkatesh and Dabade, 2008].

Chapters 7 and 8 present contributions to assembly lines with multi-manned stations. Only single product lines were considered in them. Hence, cyclical scheduling plays a role within stations rather than between them, as in Chapters 2-5. Chapter 7 presents a shorter contribution that questions some results of a recent article. Chapter 8 presents a more flexible multi-manned line concept that allows shorter line lengths. It presents a heuristic decomposition and graph-based lower bounds for line length.

Chapter 9 addresses a line balancing problem with fractional task allocations. The chapter describes the relationship between internal storage costs and cycle time. By doing so, it corroborates to Chapter 8's observation that multi-objective disputes can happen between line length and cycle time in paced lines and reinforces the interpretation that the former can act as continuously distributable buffers.

Chapter 10 returns to the mixed-model context of Chapters 2-5 by addressing this multi-objective relationship with a case study with Chapter 2's data. The chapter presents an algorithm that can find the Pareto front of a mixed-integer linear bi-objective problem. By doing so, it allows paced line control to be compared to unpaced line control.

Finally, Chapter 11 presents a summary of the thesis, tying the contributions of each chapter to one another and discusses what are some of the possible research directions that further works can address.

5. Publications

Each main chapter in the candidate's thesis is based on a scientific paper published in a journal (Except for Chapters 10, which is based on a conference paper). This section lists the candidate's publications as well as other works authored and co-authored by the candidate. First, the thesis articles for Chapters 2-9 are listed in the same order as in the thesis. For each paper, the number of citations (in September 2022) according to the author's [Google Scholar](#) is provided. The last two articles in this first list were only accepted for publication after the thesis defense. While they are not part of the thesis document, they were also developed during the thesis international partnership period.

1. [Lopes et al. \[2020e\]](#) - **Annals of Operations Research** (Ch. 2) - 20 citations;
2. [Lopes et al. \[2018a\]](#) - **Int. Journal of Production Economics** (Ch. 3) - 16 citations;
3. [Lopes et al. \[2019b\]](#) - **Journal of Manufacturing Systems** (Ch. 4) - 22 citations;
4. [Lopes et al. \[2020d\]](#) - **Int. Journal of Production Research** (Ch. 5) - 23 citations;
5. [Lopes et al. \[2020b\]](#) - **Computers and Operations Research** (Ch. 6) - 15 citations;
6. [Lopes et al. \[2019a\]](#) - **Journal of Manufacturing Systems** (Ch. 7) - 4 citations;
7. [Lopes et al. \[2020c\]](#) - **Omega** (Ch. 8) - 26 citations;
8. [Lopes et al. \[2022a\]](#) - **Int. Journal of Production Research** (Ch. 9) - 4 citations.
9. [Lopes et al. \[2021\]](#) - **Computers and Industrial Engineering** (published after thesis defense).
10. [Lopes et al. \[2022b\]](#) - **Int. Journal of Production Research** (published after thesis defense)⁶.

Second, during the years the research compiled in this thesis was developed, the author participated in several publications. Some of those are more related to his work during his Master's degree⁷, but others are more directly related to chapters in this thesis:

1. [Sikora et al. \[2017a\]](#) - **European Journal of Operational Research** - 55 citations;
2. [Sikora et al. \[2017b\]](#) - **Computers and Industrial Engineering** - 15 citations;
3. [Michels et al. \[2018\]](#) - **Computers and Industrial Engineering** - 27 citations;
4. [Michels et al. \[2019\]](#) - **European Journal of Operational Research** - 34 citations;
5. [Michels et al. \[2020\]](#) - **Operations Research Perspectives** - 10 citations.

Finally, papers presented by the candidate in scientific conferences also played a role in this thesis, both laying building blocks for some of the journal publications and as a base for one of the chapters:

1. [Lopes et al. \[2016\]](#) - **XLVIII SBPO**⁸ Vitória-ES, Brazil, 2016 - Related to Chapter 2;
2. [Lopes et al. \[2017\]](#) - **XLIX SBPO**⁹ Blumenau-SC, 2017 - Related to Chapter 4;
3. [Lopes et al. \[2018b\]](#) - **L SBPO**. Rio de Janeiro-RJ - Related to Chapter 6;
4. [Lopes et al. \[2019c\]](#) - **XIX CLAIO**. Lima-Peru, 2019 - Related to Chapter 6.
5. [Lopes et al. \[2020a\]](#) - **XXI ROADEF**¹⁰ Montpellier-France, 2020 - Base for Chapter 10.

⁶This article is an extension of the thesis' Chapter 10

⁷This work also lead to the development of an international patent (Number: [FR3062492A1](#))

⁸This paper was selected amongst the five best articles presented in the XLVIII SBPO conference (2016).

⁹This paper was selected amongst the five best articles presented in the XLIX SBPO conference (2017).

¹⁰This paper shared the first prize of best student article presented in the XXI ROADEF conference (2020).

6. Conclusion

This report presents a summary on the PhD thesis entitled “Cyclical Scheduling and Assembly Line Balancing”. The thesis addressed various assembly line problems of practical relevance and presents contributions in a wide range of Operations Research methods. These include mathematical models, decompositions, simulation, local-searches, graph-based lower bounds, complexity proofs, and mathematical descriptions of the relationship between practical features of optimization problems.

During his doctorate, the candidate produced contributions ranging from innovative mathematical descriptions, and surpassing literature benchmarks to a demonstrably fruitful international collaboration - which led to a prize in an international conference as well as three scientific articles published in renowned Operations Research journals. The candidate’s research and partnerships achieved over 200 citations in peer-reviewed papers, conferring him an *h*-index of 9, according to [Scopus](#).

Finally, the doctoral thesis (available on UTFPR’s [repository](#)) describes several directions for further research. The candidate and coworkers open an invitation for the OR community to new research partnerships on the studied subject.

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