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A report on "Industrial Assembly Lines with Multi-operated Workstations: Applications and Methods"

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RESUMO

Este relatório resume a tese de Adalberto Sato Michels, a qual trouxe avanços teóricos e práticos às linhas de montagem industriais do setor automotivo. Examinamos três problemas combinatoriais: o Projeto de Linha de Montagem Robótica e duas variantes do Problema de Balanceamento de Linha de Montagem Multi-operada. Manufaturas inteligentes surgem em estreita relação com suas soluções ótimas: projetar linhas eficientes é custoso pois fabricar veículos emprega diversos trabalhadores ou robôs com ferramentas, instalações e equipamentos diversificados. Desenvolvemos modelos de Programação Linear Inteira Mista e Algoritmos de Decomposição de Benders para minimizar custos na taxa de produção desejada ou tempos de ciclo dado recursos limitados. Este estudo incluiu características práticas, testes computacionais e estudos de caso em linhas robóticas de soldagem. Superamos abordagens do estado-da-arte e tais contribuições foram publicadas em periódicos renomados da área. Assim, candidatamos a referida tese ao Prêmio de Tese do LIII 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 summarises Adalberto Sato Michels' PhD thesis, which made theoretical and practical advances to industrial assembly lines in the automotive sector. Three combinatorial problems were examined: the Robotic Assembly Line Design and two Multi-manned Assembly Line Balancing Problem variants. The need for intelligent manufacturing emerges in close relation to optimally solving these problems: consciously designing an efficient line is costly because building vehicles employs several workers or robots with diversified tools, facilities, and equipment. We developed Mixed-Integer Linear Programming models and innovative Benders' Decomposition Algorithms to minimise total costs at the desired production rate or the cycle time under limited resources. This study included practical characteristics, computational tests, and real-world robotic welding line case studies. Our methods outperformed previous state-of-the-art approaches, and contributions were published in the field's renowned journals. Therefore, we present the referred thesis as a candidate to the LIII 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 concisely summarise Adalberto Sato Michels' PhD thesis, which is entitled "Industrial Assembly Lines with Multi-operated Workstations: Applications and Methods". The thesis addresses three combinatorial problems: (i) the Robotic Assembly Line Design (RALD) problem; (ii) the Multi-manned Assembly Line Balancing Problem (MALBP), with a focus on minimising the required workforce and facilities; and (iii) the MALBP with a focus on maximising productivity, i.e. minimising cycle time. As we made substantial theoretical and practical contributions to industrial assembly lines found in the automotive sector, we intend to participate in the LIII Brazilian Operational Research Symposium (SBPO 2021) Best Thesis Award, which will be held in João Pessoa, Paraíaba, from the 3rd of November to the 5th of November, 2021.

From a practical point of view, the need for an intelligent manufacturing industry is closely related to optimally solving these problems (RALD and MALBP). The efficient design and use of assembly lines are of strategic importance in an increasingly competitive and integrated environment. We must analytically evaluate costs associated with facilities, wages, equipment, and operations. Throughout the thesis, we developed mathematical formulations in Mixed-Integer Linear Programming (MILP) that considered several practical characteristics of the problems under analysis. In particular, the author spent two years in loco at a large manufacturing company in order to capture the fundamental characteristics of manual and robotic assembly lines.

We enriched these MILP models with sets of valid inequalities. Moreover, new Benders' Decomposition Algorithms (BDA) have been proposed and implemented in order to solve large-size instances optimally. From a theoretical perspective, in each of the studied problems, the proposed solution strategies outperformed the state-of-the-art approaches. We surpassed the previous best-known algorithms found in the literature in large benchmark datasets, reaching significantly better results in terms of obtaining improved primal bounds, new optimal solutions, and optimality proofs. Publications followed these contributions in renowned journals in the field of Operational Research (OR).

Therefore, we present the aforementioned thesis as a possible candidate for the SBPO 2021 Best Thesis Award. The remainder of this report provides an overview on the thesis' topic (Section 2), describes the author's trajectory throughout his PhD degree (Section 3), discusses the main contributions of his original work (Section 4), lists all the papers that were published as a result of this thesis (Section 5), and finally presents some concluding remarks (Section 6).

2. Topic overview

In the referred thesis, we studied industrial assembly lines found in the automotive sector. Assembly lines are production systems widely applied to manufacturing industries with a high-volume output of standardised products. Factories generally built their product-oriented layouts to fit flow-shops, which conveniently enables the mass production of homogeneous goods. These attributes have originated a complex combinatorial problem in the academic research environment. The literature broadly discusses this problem under the Assembly Line Balancing Problems (ALBP) classification. ALBPs are comprehensibly surveyed by Battaïa and Dolgui [2013] and, as they subsume the bin-packing problem as a particular case, most of them are NP-hard [Álvarez-Miranda and Pereira, 2019].

Baybars [1986] considers several simplification hypotheses to define the Simple Assembly Line Balancing Problem (SALBP). It consists of deciding the assignment of a task set to stations. Tasks cannot be arbitrarily assigned to any station; they must respect precedence constraints imposed by a precedence graph. As stations are organised in a serial layout, which enforces the line's pace to take the most loaded station's total processing time, known as the cycle time. Finally, the

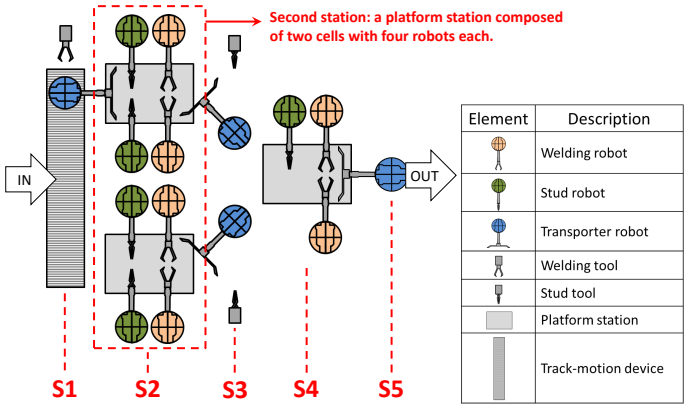
most common goals in a SALBP are separated into type-I and type-II, respectively minimising the number of stations (SALBP-1) and the cycle time (SALBP-2).

Since SALBPs do not describe all practical features found in the industry, some generalisations regard further industrial specifications, such as task incompatibility, space constraints, parallel station, multiple workers, equipment selection, and unproductive times. They imply in practical extensions of one or any combination of the SALBP's simplification hypotheses, giving rise to the General Assembly Line Balancing Problem (GALBP). Becker and Scholl [2006] conduct a particularly focused review on the GALBP.

For instance, by examining assembly lines applied to the automotive industry, we can notice that they commonly process large-size products, such as cars and buses. Therefore, it is possible to verify that the hypothesis of allowing only one worker or robot in each station is not a practical limitation. Compared to work-piece sizes and stations' physical space, an operator's working area is quite small. Thus, it becomes admissible to assign more than one worker or robot to each station and perform tasks simultaneously in different sectors of the same product. As a consequence, a task scheduling problem emerges in each multi-manned station. Moreover, analogous goal functions studied for SALBPs can also be considered to solve this problem [Becker and Scholl, 2006]. Such flexibility motivates the study of the MALBP, a subject of remarkable research interest [Michels et al., 2019, 2020].

Besides the multi-manned stations characteristic, further extensions can be observed in Figure 1. In this example, we must design a robotic line. The layout takes into account different types of robots and facilities. Equipment should be selected for each robot (welding, stud, transporter) depending on the task's nature. As the line design also considers the possibility of parallel stations, these robots work at platform stations or on track-motion devices. Lastly, we cannot neglect the work-piece transportation time between stations, i.e. dead times occur. We considered all these extensions in the thesis.

Figure 1: Extension examples: parallel stations, multiple robots holding different tools, and transportation systems. Source: Michels et al. [2018].



3. On the thesis development

Adalberto Sato Michels started his PhD in July 2017. The PhD studies were developed at the Federal University of Technology – Paraná (UTFPR) under the supervision of Prof. Leandro Magatão[1]. The Graduate Program in Electrical and Computer Engineering (CPGEI) hosted this

[1] http://lattes.cnpq.br/4652695720103701

optimisation 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 incentivise academic institutions' articulation with industries and favour 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. Collaborating in the former led to optimised assembly lines in industry, whilst the latter group effort yielded scientific publications. Academically, the candidate participated in the SBPO 2017 (Blumenau), the SBPO 2018 (Rio de Janeiro), and the 29th European Conference on Operational Research (EURO 2018, Valencia – Spain). He also presented the group's research output to engineers at Bentley (Crewe – UK) and colleagues at the Institute for Operations Research (Hamburg – Germany).

In the last year, the thesis defence took place on the 17th of December 2020. The examining committee was formed by Prof. Ricardo Lüders[2] as an internal member from CPGEI, Prof. Arinei Carlos Lindbeck Da Silva[3] (PPGMNE/UFPR), Prof. Leandro Callegari Coelho[4] (FSA/Laval University), and Prof. Maristela Oliveira Dos Santos[5] (ICMC/USP) as external members. The thesis defence was recorded and its presentation video is available on YouTube (in Portuguese). Finally, the final revised version of the thesis manuscript is available on UTFPR's repository. Section 4 describes its contributions by chapter in practical and theoretical terms.

4. Contributions

This thesis proposed solution methods that combine mathematical programming and decomposition algorithms to solve assembly line balancing problem's extensions. We considered several real-world operational aspects of industrial assembly lines, e.g. robotic assembly lines and multi-manned stations. Among theoretical contributions, we can mention introducing new concepts, definitions, and property demonstrations for both the RALD problem and the types-I and II of the Multi-manned Assembly Line Balancing Problem (MALBP-1 and 2, respectively). We demonstrated practical applications of MILP models with valid inequalities for both the RALD problem and the MALBP. Furthermore, novel exact solution approaches based on BDA and Combinatorial Benders' cuts (CBC) were developed to solve MALBPs. The obtained solutions were analysed and compared to real-world as-built robotic lines or previous state-of-the-art results from benchmark datasets. In the remainder of this section, we describe the major contributions of each chapter.

Chapters 1 and 2 (Introduction and ALBP) introduce usual assembly lines found in manufacturing industries, focusing on decision aid models' primary importance for ALBPs. We are concerned about design and operational costs, i.e. facilities, equipment, robots, workforce, and productivity levels. The details and main terminologies of these particular assembly line balancing problems are described, such as its elements, physical characteristics, operational constraints, and typical simplification hypotheses. Moreover, an extensive literature review based on publications and surveys regarding the ALBP is conducted to define the proposed problems further. Variations that are applicable in the automotive industry are presented, describing their distinctive characteristics. Finally, we assess gaps in the literature. In conjunction with introductory sections of the

[2] http://lattes.cnpq.br/5158617067991861
[3] http://lattes.cnpq.br/3094470512414488
[4] http://lattes.cnpq.br/5085659938072564
[5] http://lattes.cnpq.br/0756373063566786

following chapters, robotic assembly lines and multi-manned stations are thoroughly examined to place the proposed research into the gap and evidence its contribution.

Chapter 3 (RALD) defines the RALD and proposes a MILP formulation for it, taking into account several real-world practical extensions of a RALD scenario. The proposed model incorporates the linearisation of a cubic constraint and explicitly evaluates costs and benefits associated with parallel stations in an exact manner. Providing the best solution to real-world problems has been the most significant interest of practical optimisation applications. Nonetheless, a gap between the academy research and industrial applications still exists in the literature. We observe one of them on robotic welding assembly lines found in automotive industries, as defining their production layout design is an important global and strategic decision. Some practical contributions of this chapter are (i) the development of a validation dataset for the parameters' influence analysis, (ii) the model's computational results analyses themselves, (iii) the presentation of an industrial case study from a real-world automotive assembly line to apply the RALD model, and (iv) the possibility to design robotic assembly lines at lower costs in the future.

Chapter 4 (MALBP-1) addresses the MALBP-1 to minimise the number of workers and stations. A new decomposable MILP model is developed along with several valid inequalities that work as symmetry break constraints to solve the optimisation problem. This proposed formulation outperforms previous formulations [Kellegöz, 2017] in solution quality and computational processing time. By analysing the problem's structure, we can infer that the problem is hierarchically divisible. Hence, we forge a BDA strategy and compare its results to previous state-of-the-art methods [Kellegöz, 2017]. Our method produces improved solutions while maintaining reasonable CPU times. Since past exact approaches were only able to solve some instances with up to 45 tasks, this work's main contribution is the ability to solve benchmark instances up to 148 tasks optimally.

Chapter 5 (MALBP-2) correspondingly approaches the MALBP-2 to minimise the line's cycle time and the number of stations. We extend the MILP model to the MALBP-2 version along with appropriate valid inequalities for the problem at hand. Crucial modelling decisions to clarify the definition of what constitutes the MALBP-2 in the literature are explored. Our model outperforms previous formulations [Roshani and Giglio, 2017; Chen, 2017] in terms of solution quality and computational processing time. We also present an exact method for the MALBP-2, integrating an initial solution procedure [Lopes et al., 2019], model-based heuristic ideas [Lopes et al., 2020], and an enhanced BDA adapted from the previous chapter. Compared to previous state-of-the-art methods [Roshani and Giglio, 2017; Chen, 2017], our approach produces improved primal bounds for virtually all instances. Once again, past formulations could only solve few instances with up to 30 tasks optimally. This work's main contribution is to develop a method capable of optimally solving instances up to 83 tasks, including real-world cases from the benchmark. Finally, we develop innovative CBCs and verify synergies between the initial procedure and the enhanced BDA.

Chapter 6 (Concluding remarks) provides final considerations along with future research directions. Although Chapter 3 exposed how effective the proposed MILP formulation is in designing a robotic assembly line, future research can widen the proposed model to incorporate task scheduling for each robot in the station. Chapters 4 and 5 allowed multiple workers to simultaneously perform different tasks, which is a notable realistic feature widely employed in the industry. Nonetheless, incorporating more practical extensions into the developed BDAs is a desirable modification. That could undoubtedly facilitate applications, improve solution quality, and enhance the proposed methods' performance.

5. Publications

This section presents publications related to the thesis research. Sections 5.1 and 5.2 list peer-reviewed journal publications that were published as a result of the research carried out for the development of the thesis. For each paper, the number of citations according to the author's Google Scholar and a brief synthesis on its content are provided. Section 5.3 lists the author's prominent conference publications. Besides the publications listed herein, the candidate also co-authored five papers in OR-related journals[6] and four conference papers[7].

5.1. Journal publications

- Michels, A. S. et al. The Robotic Assembly Line Design (RALD) problem: Model and case studies with practical extensions. **Computers & Industrial Engineering**, 2018. 14 citations.

  This paper studies spot welding assembly lines found in the automotive manufacturing industry based on practical characteristics. We develop a MILP model allowing station paralleling, equipment selection, and multiples robots per workstation. The aim is to minimise the total cost at the desired production rate, which involves robots, tools and facilities. The proposed model considers dead time during a cycle, space constraints, task assignment restrictions, and parallelism possibilities. We perform computational experiments and conduct practical case studies with real-world data. By finding the optimal solution and comparing it with the as-built design, a cost reduction of 5.9% can be achieved. In absolute values, it translates into potential 6-digit savings on the company's production layout cost.

- Michels, A. S. et al. A Benders' decomposition algorithm with combinatorial cuts for the multi-manned assembly line balancing problem. **European Journal of Operational Research**, 2019. 17 citations.

  Previous exact methods could only solve few MALBP-1 small-size instances, while large cases were solved by (meta)heuristics that do not guarantee optimality. This paper presents a new MILP model with strong symmetry break constraints and decomposes the original problem into a BDA to solve large instances optimally. Tests on a literature dataset show that our model outperforms previous formulations [Kellegöz, 2017] in both solution quality and computational processing time. The proposed BDA yielded 117 optimal solutions out of a 131-instance benchmark. Compared to previous methods [Kellegöz, 2017], this translates into 44 new best primal bounds, out of which 42 are optimal solutions.

- Michels, A. S. et al. An exact method with decomposition techniques and combinatorial Benders' cuts for the type-2 multi-manned assembly line balancing problem. **Operations Research Perspectives**, 2020. 2 citations.

  Once again, only few MALBP-2 small-size instances could be solved by preceding approaches, whereas large and real-life cases lacked optimality proofs. This paper presents a new MILP model and an exact solution procedure. We employed a combination of decomposition techniques and CBC to solve large instances optimally. Tests on an extended literature dataset and a real-life assembly plant case study demonstrate that our algorithm outperforms previous methods [Roshani and Giglio, 2017] in terms of solution quality by an ample margin in efficiency gains. Synergies between the algorithm's components are also revealed. Finally, our exact method yielded 60 optimal solutions out of a 108-instance benchmark, with the remaining 48 solutions presenting a small integer gap (less than 2%).

[6] Including these papers on Annals of Operations Research, International Journal of Production Economics, Journal of Manufacturing Systems, International Journal of Production Research, and Computers & Operations Research

[7] In SBPO 2017, 2018, and CLAIO 2018

5.2. Co-authored journal publications

We highlight these two co-authored publications as they focused on multi-manned stations (i.e. the problem studied in this thesis) and were developed as part of the PhD research.

- Lopes, T. C. et al. A note to: A hybrid algorithm for allocating tasks, operators, and workstations in multi-manned assembly lines. **Journal of Manufacturing Systems**, 2019. 3 citations.

  We point out previous inconsistencies in this note that involves a MALBP problem. Some results and properties in Chen [2017] appear to be questionable. This note also presents an alternative method to obtain solutions that dominate those reported by the recent paper and support the critiques hereby presented. We integrate this decomposition method into our paper [Michels et al., 2020].

- Lopes, T. C. et al. Flexible Multi-Manned Assembly Line Balancing Problem: Model, Heuristic Procedure, and Lower Bounds for Line Length Minimization. **Omega**, 2020. 17 citations.

  Previous MALBP papers defined stations with fixed, discrete, and restrictive frontiers. This paper proposes a flexible version that allows shorter line lengths. A MILP model and a heuristic procedure are presented to describe and optimise the problem. Lower bounds are introduced and our formulation is compared to a literature benchmark of regular MALBP solutions [Kellegöz, 2017]. Experiments show that our model may lead to line length reductions of up to 42%. We obtained reductions for 81 out of 88 instances, with an average reduction of 18%. We also demonstrate that efficient solution sets can be continuous or discrete by analysing the relationship between cycle time and minimal line length.

5.3. Conference publications

- Michels, A. S. et al. A new mathematical formulation with search-space reduction techniques for the multi-manned assembly line balancing problem. *In*: **29th European Conference on Operational Research**, 2018.

- Michels, A. S. et al. An MILP Formulation for Local Search k-Opt Improvement Procedures. *In*: **L Simpósio Brasileiro de Pesquisa Operacional**, 2018.

6. Conclusion

This report presented a summary on the PhD thesis entitled “Industrial Assembly Lines with Multi-operated Workstations: Applications and Methods”. It proposed solution methods that combine mathematical programming, model-based heuristics, and decomposition algorithms to solve extensions of the ALBP. We took several real-world operational aspects into account for the studied industrial assembly lines, namely robotic assembly lines and multi-manned stations. We analysed the obtained solutions and compared them to real-world as-built robotic lines or previous results from benchmark datasets.

Outstanding results were achieved in each research branch. Compared to the as-built robotic line designed by the engineering team, we obtained a significantly less costly system for the production of the car’s body. We also outperformed recent models and methods that were considered the state-of-the-art at the beginning of the author’s PhD [Kellegöz, 2017; Roshani and Giglio, 2017; Chen, 2017]. Therefore, our research contributions could be endorsed by the scientific community, with several relevant peer-reviewed publications and citations.

Lastly, future research avenues were opened with the literature gap assessment. We are already working on some of them. As mentioned, both the thesis manuscript and the defence presentation are available online, so we openly invite the OR scientific community to take on these propositions collaboratively with us whenever possible.

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