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Celso Gustavo Stall Sikora

Assembly-Line Balancing under Demand Uncertainty

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Abstract

The automotive industry is highly dependable on assembly lines for the production of today's demand volumes. Assembly lines were once introduced as an efficient production configuration for a single product, in which the production tasks are divided among multiple workstations organized along a conveyor belt. Nowadays, the automotive manufacturers cannot rely on production systems for a single model: the choice of vehicle comes with innumerous configurations, options, and add-ins. In the production site, these different vehicles must share the same resources and may flow on the same assembly line. As a result, assembly lines must be at the same time specialized to provide high efficiency, but also flexible to allow the mass customization of the vehicles.

In this thesis, a compendium of problems and solution algorithms for the assembly line balancing problem considering demand uncertainty is presented. As planning and building an assembly line is a commitment of several months or even years, it is understandable that the demand will fluctuate during the lifetime of an assembly line. New products are developed, others are removed from the market, and the decision of the final customer plays a role on the immediate demand. In this work, the demand or production sequence is modeled using three different view points of a system configuration.

A first approach proposed in this thesis considers total control of the production sequence. In this first problem, the assembly line planner can optimize the assembly line and the production sequence simultaneosly. The uncertainty is due to the different time frames of both problems. The planning of an assembly line is a long term decision, while the sequencing problem is solved in short-time based on the customer orders. An exact solution procedure is proposed in this thesis for the optimal design of a paced assembly line, which must operate with uncertain demand to be sequenced in the future. The expected amount of utility work for the production is minimized using a combinatorial version of the Benders' decomposition.

A second problem dealt with in the thesis is the design of an assembly line when the planner plays no role in the production sequence. In this approach, the production sequence is considered to be random. A Branch-and-Bound Algorithm using Markov chains to evaluate partial solutions is proposed and used to solve instances exactly.

A third contribution considers a restriction on the sequence control. The planner has at disposal a buffer to alter the production sequence locally. For this problem setting, the buffer operation is optimized, in which selection policies are proposed and tested. The uncertainty is modeled through a random buffer entry, that must be resequenced respecting production and due date restrictions in an online setting.

Contents

Acronyms

ACEA	European Automotive Manufacturers Association
AGV	Automated Guided Vehicle
ALB(P)	Assembly Line Balancing (Problem)
AS/RS	Automated Storage and Retrieval System
BA(P)	Buffer Allocation (Problem)
BAS	Blocking After Station
BBS	Blocking Before Station
CMS	Cellular Manufacturing Systems
CT	Cycle Time
EU-15	The first 15 countries of the European Union
FiFo	First-in-First-out
FMS	Flexible Manufacturing Systems
GALB(P)	General Assembly Line Balancing (Problem)
MP	Master Problem
MPS	Minimal Part Set
NP	Non-deterministic Polynomial
OICA	International Organization of Motor Vehicle Manufacturers
SALB(P)	Simple Assembly Line Balancing (Problem)
SP	Sub Problem
WIP	Work-In-Process

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1 Introduction

1.1 Motivation and Overview

There are few products nowadays that can be compared to an automotive vehicle. Usually weighing from 800 kg to several tons and costing several thousand or even extremes such as a couple of million Euros, it is astonishing to see such a large product playing a major role in our society. According to the European Automotive Manufacturers Association [ACEA, 2020], there were 610 vehicles for every 1000 inhabitants in the European Union in 2018. Such numbers require an annual production of 92.8 million vehicles worldwide or 18.5 million vehicles in the European Union [ACEA, 2020], which is equivalent to almost 3 vehicles per second worldwide. Such production levels require large facilities and a significant part of the labor workforce. In the European Union, direct and indirect jobs in this industry account for 6.7% of the total job market.

Although automotive vehicles and large-scale production existed before, the mass production shift of durable automotive vehicles is credited to Henry Ford with his Ford Model T in 1908 [Binder and Rae, 2020]. The innovation was to consider the transport of the products or workpieces in conveyor belts, on which the vehicles flow through a series of workstations [Binder and Rae, 2020]. The hundreds or thousands of individual tasks are divided among the workers in an assembly line. This way, each worker performs simple tasks in which he or she can specialize. Each worker can then perform the operations within a small cycle time, after which the workpiece is transported to the next station.

The division of the task elements among the multiple workstations is a classical problem in Operations Research named *Assembly Line Balancing Problem* (ALBP) and was firstly discussed in a thesis by Bryton [1954] and in a research paper by Salveson [1955]. A related optimization problem is the *Bin Packing Problem*, in

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which objects have to be assigned and fitted into bins in a way that the number of required bins is minimized. In assembly lines, the objects can be seen as the operational tasks, while the bins are the workstations. Instead of having a physical dimension, each task requires a given amount of time in the station. The limitation is not the bin size, but the cycle time of the assembly line. A difference between the Assembly Line Balancing Problem and the Bin Packing Problem is due to precedence relations [Wee and Magazine, 1982]. In the basic version of the Bin Packing Problem, each object can be assigned freely among the bins. A production sequence, on the other hand, usually requires some partial order between the tasks. As products and pieces are assembled, interior parts are not reachable anymore. Hence, there exist precedence relations between the tasks.

The Assembly Line Balancing Problem in its base form as described in the last paragraph is called *Simple Assembly Line Balancing Problem* (SALBP) [Scholl and Becker, 2006] and has very strict assumptions such as deterministic and known production times, a serial line, and the production of a single product. Although these assumptions may be true for Ford's Model T, the automotive market requires a high level of customization nowadays [Boysen et al., 2008]. It is not possible to establish an assembly line for a single- vehicle anymore. Instead, the production system has to be flexible enough to assemble several vehicle variations. Boysen et al. [2008] describe the new paradigm as mass customization, in which the customer can select almost every element of the product from a given range of options. The number of theoretically possible combinations resulting in unique products is huge. Boysen et al. [2009a] report the number of variations of popular vehicle models in 2004, which vary from 40,000 to $3.35 \cdot 10^{24}$ for a selection of European cars.

The presence of multiple product models results in a more complex optimization problem, since not only the assignments of tasks to stations are important, but also how the product models are sequenced. Different production layouts, the presence of buffers, and the production sequence greatly affect the productivity of an assembly system. Furthermore, the customer's taste changes and evolves. So the demand itself may vary during the operational time of an assembly line. Such complexity factors are explored in this manuscript, mainly dealing with the uncertainty of demand in the balancing of multiple-product assembly lines.

1.2 Objectives and Document Outline

The outline of the document is described along with the objective of each chapter. In general, the thesis brings new contributions to the research of assembly line balancing under demand uncertainty.

The first objective of the document is to describe the production stages at automotive manufacturers. The production of vehicles is different than considering a general product because of the large dimensions. Cars, trucks, or buses are large and heavy products, so their handling is rather limited. The deviations of production times cannot be easily compensated by buffers, since the size of the products poses a strong restriction. In Chapter 2 the different stages of production are described, among related optimization problems, such as production planning, assembly line balancing, sequencing, resequencing, etc.

Chapter 3 contains a literature review on different sources of uncertainty in the balancing of assembly lines. A classification of the literature is extended to model the stochastic components of the problem. The uncertainty is mostly modeled in the processing times, while much fewer references deal with uncertain demand or production sequences. Chapter 3 is also used to identify gaps in the literature, which are partially filled by contributions described in Chapters 4–6.

The research core of the manuscript consists of three chapters containing each a problem definition and a solution procedure. All of the contributions deal with assembly lines under uncertain demand, although in each chapter a different assumption or view of the problem is proposed. One key aspect to distinguish the three problems is the control over the production sequence.

The first contribution is detailed in Chapter 4. For this problem setting, production sequencing is totally defined by the planner of the assembly line. This assumption allows selecting a production sequence that matches well with the assignment of tasks in the assembly system. For this problem, the assembly line problem and production sequencing problem are solved in an integrated form. As both decisions are taken in different time frames in practical applications, a hierarchical approach is defined. The assignment of tasks to stations is a medium to long-term decision, while the production sequencing is solved on a daily or weekly basis. The uncertainty in the problem is represented by an uncertain demand at the planning stage of the assembly line. This way, the balancing of the assembly line has to be defined before the realization of the demand, while the sequencing can be solved after the customers define their orders. The problem is defined in a two-stage stochastic programming model, for which an exact solution procedure is proposed to minimize the expected utility work (amount of work from auxiliary versatile workers). A Benders' Decomposition Algorithm based on combinatorial cuts is developed among valid inequalities and improvements. The contents of Chapter 4 has some overlap to the published article version of the chapter (see Sikora [2021]). The results of both publications, however, are complementary.

At the other end of the control spectrum, the second approach models the balancing problem under no control over the sequence. In Chapter 5, the production