A Review of Cost and Profit Oriented Line Design and Balancing Problems and Solution Approaches

Öncü Hazır
TED University, Faculty of Economics, Administrative and Social Sciences, Ziya Gökalp Caddesi No.48, 06420, Kolej, Çankaya, Ankara, Turkey

Xavier Delorme
École Nationale Supérieure des Mines, CNRS UMR6158, LIMOS, F-42023 Saint-Etienne, France

Alexandre Dolgui
École Nationale Supérieure des Mines, CNRS UMR6597, IRCCYN, F-44307 Nantes cedex 3, France

Abstract
This review paper presents the state of the art on the problems, approaches and analytical models for assembly and transfer line design and balancing that addresses explicitly cost and profit oriented objectives. The discussions aim to facilitate identifying open problems and research areas that have wide practical applications and that necessitate further investigations. Moreover, they might serve as a foundation for developing decision support systems (DSS) that aid managers in planning and designing profitable or cost efficient assembly and transfer lines.

Keywords: Line Balancing, Cost Models, Optimization, Process Planning, Production Planning and Control, Decision Support Systems

Email addresses: oncu.hazir@tedu.edu.tr (Öncü Hazır), delorme@emse.fr (Xavier Delorme), dolgui@emse.fr, alexandre.dolgui@mines-nantes.fr (Alexandre Dolgui)
1. Introduction

Assembly and transfer lines contain serially located workstations in which operations are continuously carried out. They have been installed in various industries such as the automotive, home appliance or electronics; where the major goal is to efficiently produce and deliver large amounts of standardized products. As a consequence of efficiency pursuit of these industries, modeling and solving line balancing problems have gained importance. A rich assembly and transfer line balancing literature, which covers numerous optimization problems, emerged.

These problems require development of capacity or cost-based modeling and use of effective solution techniques. For more details on line balancing problems, modeling and solution methods, we refer to the survey papers [61, 52, 102, 12, 111, 27, 101]. We also cite Boysen et al. [26], Battaia & Dolgui [8] for classification of the problems.

Although these interesting surveys present a broad range of line balancing problems and methods, they do not provide an in-depth analysis of some important branches of line design and balancing literature. This lack is noticeable for cost and profit based models, despite their recognized importance [see, e.g., 55]. One possible explanation could be the scarcity (at the time these surveys were written) of publications on this topic, in comparison with other branches which had produced an abundant literature. Even though capacity oriented approach is more common in the literature, models where costs and profits are explicitly calculated and optimized in all phases of product life cycle are taking attention of researchers. Studies on this field have been rapidly increasing recently (almost half of the papers cited in this review were published during the last 8 years).

We concentrate on this particular branch and provide an in-depth analysis of cost and profit based line design and balancing models. Such a detailed study allow us to investigate the use of optimization tools in the design of production facilities, to explain their needs in planning and control of activities, from product and process design to recycling, and to clarify their characteristics and importance for product life cycle management (PLM).

It should also be noted that most of the models presented in this survey require various data on costs in order to produce cost-efficient line balance. It might not be always possible to have reliable cost figures at the point in time line balancing is performed. Thus, often researchers fall back on simple performance criteria of the capacitated models, which are available, e.g., the
number of stations or the cycle time. Moreover, under specific premises some simple line balancing problems also minimize costs, e.g., the capacity oriented Simply Assembly Line Balancing Problem of type 1 (SALBP-1) leads to a cost minimum, whenever any station costs the same. Also minimizing the cycle time for the capacity oriented Simply Assembly Line Balancing Problem of type 2 (SALBP-2) could maximize profit in specific circumstances.

However, nowadays many companies can reach to accurate data, they are more and more seeking to use this information and generate more effective designs. We also note that cost and profit based models are usually used at advanced stages of the design process. At the initial stages, a set of possible configurations is selected by using capacity oriented models. Cost- or profit-oriented approach is employed afterwards.

Considering the increase in the number of publications on cost- and profit-oriented models, we believe that it has become necessary to structure this field and develop a more detailed classification. Moreover, we make a concerted effort to present research gaps and explicitly list promising areas. We discuss the possible research perspectives. The discussion could help to identify open problems and research areas that have wide practical applications and need further investigation.

This article is an expanded and improved version of the paper presented at the 19th World Congress of the International Federation of Automatic Control in Cape Town, South Africa [69].

Section 2 will introduce the classification and then review and discuss the main publications in each class. Section 3 will present a synthesis of this review and provide some discussions on future research directions.

2. Literature Review

Cost based models minimize long-term investment or short term operating costs, whereas in profit based models revenues hence price and production volumes are also incorporated. Main relevant cost categories that should be examined are wages, material and inventory expenses, equipment procurement and maintenance, set-up and idle time costs and the penalties of delays.

Some cost or profit based models optimize objective functions that include components concerning productivity or efficiency, which are the major concerns of the capacity approach. Indeed these models could be classified as “composite”, since they implicitly or explicitly optimize capacity as well
as the cost. For instance, maximizing the profits require optimizing production quantity/capacity and costs at the same time. Therefore, in our survey, these composite models are grouped into another subcategory, which covers cost of idleness and profit optimization. Figure 1 illustrates the classification that we use in this study. Note that the capacity oriented models are not detailed, since they are out of the scope of this review.

To develop the classification, we make use of the scheme of Boysen et al. [26]. However we detail the cost optimization category (see Figure 1). Instead of using a single notation to represent the cost minimization objective, i.e. $\gamma = Co$, we propose to use a more specific notation, $\gamma = Equ$, $\gamma = Lab$, $\gamma = Inv$, $\gamma = Set$, $\gamma = Inc$, $\gamma = Rec$, $\gamma = Idl$, for models optimizing the equipment, labor, inventory, setup, incompletion, reconfiguration and idle time costs respectively. As profit functions include cost components, we use only the notation $\gamma = Pr$ as suggested by Boysen et al. [26] for profit maximizing studies, and do not to write down the constituting cost components additionally. In our classification study, we require that cost figures are known or could be explicitly assigned, and the objective function includes a cost component related to the corresponding category.
2.1. Cost Based Models

2.1.1. Equipment Costs

This category includes cost of procuring, operating and maintaining machinery, tools and corresponding supplies.

In industry flexible manufacturing systems (FMS) have been developing rapidly, as a result, numerous processing and equipment alternatives become feasible to perform the tasks. This makes choosing the equipment/station and assigning tasks to stations interrelated. To take these decisions, investment and operating costs are evaluated; however usually there is a trade-off between those cost categories. Graves & Lamar [64] were among the first to examine line balancing problem with work station selection. Nicosia et al. [92] also studied this combined problem and proposed a dynamic programming algorithm. Addressing the assignment of heterogeneous resources, Corominas et al. [37] formulated a general model that minimizes the total cost, which includes cost of stations and the different resource types.

Bukchin & Tzur [30] optimized the equipment costs for simple model lines. Later, Bukchin & Rabinowitch [31] extended the study for mixed models; the assumption that a common task of different models is assigned to a single station was relaxed. Task duplications were penalized by integrating cost of duplications in the objective function. For solution, a branch and bound algorithm was developed. Models developed in these two studies have been further studied. Following a multi-criteria approach, Pekin & Azizoglu [95] generalized the work of Bukchin & Tzur [30]. They optimized the total equipment cost and the number of workstations simultaneously. Barutcuoglu & Azizoglu [6] fixed the number of stations and added the assumption that operation time and equipment cost are correlated so that the cheaper equipment never produces a shorter operation time.

Kazemi et al. [77] extended the model of Bukchin & Rabinowitch [31] for U-type lines. Compared to conventional straight lines, U-type lines offer more options to group the operations, hence they are more flexible, but more difficult to balance. The authors used genetic algorithms (GA) to solve the balancing problem. GA were also used to produce solutions for FMS planning [36]. Making use of Pareto dominance relationships, Chen & Ho [36] addressed four criteria: total flow time, machine workload unbalance, greatest machine workload and total tool cost.

An other relevant engineering optimization area that focuses on equipment selection is transfer line balancing. This problem has been studied by
Dolgui et al. [13, 46, 44, 47, 7, 9, 24, 39, 10, 11], see also the recent article by Osman and Baki [93]. In transfer lines, stations can be equipped with changeable units such as multi-spindle heads. These units that operate in parallel or sequentially at a station are called blocks. Each block executes several operations simultaneously. The major problem is to define the optimum number of stations and block assignments while minimizing the total line investment cost. In addition to precedence relations, operations and block compatibility constraints are important.

When assembly line balancing and equipment selection problems are simultaneously treated, the resulting more complex problem is called assembly system design problem (ASDP). Fixed cost of installing the equipment in the stations and the station dependent variable cost of operations are optimized [99, 96, 120, 97, 57, 98, 121]. A relevant interesting problem is multi-criteria ASDP. To solve this problem, Ozdemir & Ayag [94] first generated line design candidates using a branch and bound algorithm, then compared them using analytic hierarchy process (AHP).

One of the main challenges of industry is to respond to the rapid changing demands of the customers. To satisfy this need, reconfigurable manufacturing systems (RMSs), which give emphasis to modularity and customization of machines and processes, have been widely employed recently. RMSs facilitate configuration changes such as altering the layout or adding machines cost-effectively [50]. For balancing RMS planning problems, integer programming models minimizing equipment and installation were formulated and approximate solution methods were developed [124, 54, 51, 53, 22, 23].

An other flexible assembly system and the corresponding line balancing problem was studied by Hamta et al. [67, 68]. They assumed flexible operation times in the sense that processing times can be reduced up to a limit with additional costs. Like the crashing practice in project management, they considered linear time/cost relationships.

We summarize the findings related to equipment costs in Figure 2. This histogram presents the distribution by year of publication and clearly illustrates that there is an increasing trend in this category in recent years. We notice that even if several papers consider equipment costs in combination with other costs, most of the studies only focus on equipment costs.

2.1.2. Labor Costs

Labor costs represent a significant part of the total production costs in many industries. Wages generally depend on the work content and the re-
quired qualifications to perform the tasks. Many companies ask their workers to work overtime, because it is usually cheaper than hiring new employees.

Focusing on cost of labor, Amen formulated models that minimize the total of labor and capital costs, which considers the life cycle cost of installing and operating stations [1, 2, 3, 4]. The cost of a station was calculated using the maximum of the wage rates, since the most demanding operation defines the necessary qualification level [103]. In our classification, we take the capital costs as a part of equipment costs.

To solve the problem, Amen developed a branch and bound algorithm [1]. He also presented heuristics, basically the ones based on priority rules [2], and compared their effectiveness on experimental tests [3]. In addition, a review of relevant models, solution approaches, lower and upper bound techniques, were presented [4]. A note on one of the dominance rules was written by Scholl [110]. Recently, Roshani et al. [106] extended Amen’s approach to two-sided assembly lines and solved the problem by using simulated annealing. Kazemi & Sedighi [76] addressed multi-manned assembly lines and used genetic algorithms for solution.

An interesting application of a mixed-model assembly line balancing was described by Bock [17]. His model is used for detailed personnel scheduling using predefined wages and skill levels of the labor. It basically addressed the trade-off between wage reductions and additional expenses caused by the reduction in worker qualifications. A tabu search algorithm was used for solution. In another study on mixed-model lines, Zhang & Gen [125] followed a multi-criteria approach, optimized time based objectives and the total worker cost. They used genetic algorithms for solution.
As a part of labor costs, over-time expenses could be significant in many industries. In that sense, optimization tools might support to use regular time units more efficiently and limit overtime work. Doerr et al. [40] examined unpaced lines and addressed assigning tasks to workers in a way that sum of expected regular and over time cost becomes minimal. To reduce the labor cost, Li & Gao [82] emphasized overtime planning and focused on the time periods of high demand or high task processing time variations. Sabar et al. [107] addressed the personnel scheduling/rescheduling problem in multi-product assembly lines. Sungur & Yavuz [115] addressed the hierarchical workforce structure and the resulting unit cost differences.

Considering U-shape lines, Kara et al. [75] developed a model that minimizes the sum of fixed station cost, equipment and labor cost. Cakir et al. [33] addressed parallel stations using multi-objective optimization. Tuncel & Topaloglu [117] examined a specific case in electronics industry and tested the efficiency of approaches with computational experiments.

Besides modeling operation times as deterministic or random variables, various processing alternatives (modes) could be considered by modeling the trade-off between time and cost. Some of the alternatives might be capital intensive and faster, others labor intensive and slower. Pinto et al. [100] formulated a discrete model that minimizes the total cost including both the fixed equipment costs and the labor cost. They developed a branch and bound algorithm for solution.

Figure 3 below presents the distribution by year of the publications related to labor costs. This histogram shows that labor costs have generated fewer papers than equipment costs but have received a constant interest during the last 40 years. It is also interesting to note that, even if labor costs have only been considered in combination with others costs until 2000, some studies dealing specifically with labor costs have appeared in the last years.

2.1.3. Inventory Costs

In production systems, raw materials, finished goods and semi-finished goods, work-in process (WIP), are stockpiled to protect against variations in demand and supply. However, holding inventory is costly; especially if opportunity cost is significant. Even though, inventory holding costs are imperative in designing the supply chains and just in time (JIT) production systems, the majority of line balancing studies do not consider them.

WIP inventory costs might be crucial especially in the cases with low volume production and with expensive components like in aircraft manufac-
turing. To study this, Lee & Johnson [81] focused on WIP costs in flexible assembly systems design. They developed an integer programming model to calculate the number of stations and machines at each station and to optimize the total cost, which contains WIP inventory cost, maintenance and amortization costs of machines and equipment. Considering the variability in operation times, they used queuing network analysis to determine the capacity of the material-handling system.

Buffer storages serve as a hedge against breakdowns and other variations in production systems. In line with the wide acceptance of JIT philosophy in the industry, optimization of storage amounts and locations have become important to minimize holding costs. Malakooti [85, 86] worked on line balancing both without and with buffers, they considered multiple objectives: total cost of production, production rate, number of stations and buffer sizes. Total cost function includes the cost of operation (product cost and cost of operating each station) and buffers (maintenance and operating cost). In the first study, a goal programming model was formulated, whereas in the second, heuristics were used to generate the set of efficient candidates.

To minimize inventory costs in mixed model lines, apart from task assignment, sequencing become critical [28]. We refer the readers to the survey paper of Boysen et al. [29] for a detailed discussion of related studies.

Figure 4 presents the distribution by year of the publications. This histogram illustrates the scarcity of papers on inventory costs, notably in recent years. This reduced interest could be explained by the fact that the authors actually mainly view inventory costs as a complementary objective.
<table>
<thead>
<tr>
<th>Years</th>
<th>Inventory cost with other costs</th>
<th>Inventory cost alone</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970-74</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>1975-79</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>1980-84</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>1985-89</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>1990-94</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>1995-99</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>2000-04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2005-09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010-2014</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4: Histogram of publications related to inventory costs

2.1.4. Setup Costs

Industrial assembly systems usually require that various product types assembled on the same line. Processes of product types might differ significantly, hence activities are required to reconfigure and prepare a station between product and/or process changes. These setup activities include loading, unloading, adjusting and cleaning. Although setup activities, their time and cost requirements are widely studied in production scheduling, they have usually been ignored in line balancing. Nevertheless, in many cases, setups are inevitable, they affect cycle time and production rates significantly.

In the work of Dolgui et al. [45], transfer lines are modeled taking into account several of their life cycle costs, including the setup, labor and equipment costs. A discrete non-linear model is presented and solved by using decomposition techniques and a branch and bound algorithm. Assuming U-type assembly configuration and applying multi-criteria approach, Kara et al. [74] addressed mixed-model lines. More recently, Giard & Jeunet [62] minimized the costs of additional utility workers and setups, simultaneously. Yoosefelahi et al. [123] worked on an extension of the work of Bukchin & Tzur [30], studied cycle time, total equipment cost and setup cost objectives. Since it becomes too difficult to generate the exact set of non-dominated solutions, they used an evolutionary algorithm.

Even though sequencing products in mixed model lines has been largely studied, setup costs are rarely taken addressed. Sequence dependent setup costs have been analyzed in some studies [35, 32, 71, 62]. Chakravarty & Shtub [35] accommodated labor, inventory and setup costs and used two approximate solution techniques. Burns & Daganzo [32] demonstrated the
trade-off between capacity and setup costs, whereas Hyun et al. [71] concentrated on multi-objective analysis and developed a genetic algorithm for solution. Bolat et al. [19] used a branch and bound algorithm and heuristics to minimize the cost of setups and utility work.

Kovalev et al. [79] examined a specific setup case in manufacturing and assembly lines. Their model sets the number of stations and assigns operations to workstations minimizing the total number of stations and costs induced by the preparation of stations for each part. These costs depend on part types and are paid for each part processed in a station. Dolgui et al. [49] studied the computational complexity of some special cases of this problem with sequential operations processing.

Scheduling to optimize setup costs, have been studied in automobile [18] and electronic cards [5, 56] assembly lines. For details of studies on these specialized assembly systems, we refer to the surveys of Boysen et al. [27] and Gelogullari & Logendran [60].

Figure 5 presents the distribution by year of the publications related to setup costs. This histogram shows that line balancing problems with setup costs seem to have regained some interest of researchers in recent years. Setup costs have generated few publications but, contrary to the previous categories, the studies are nearly equally split between papers focusing on setup costs and papers considering several other costs.

2.1.5. Incompletion and Failure Costs

In assembly lines it is widely encountered that some operations require more time than expected. In these cases, in order not to decrease produc-
tion rates, incomplete tasks are usually completed off-line, which implies additional rework and costs. Kottas & Lau [78] modeled operation times using random variables and considered that some operations might not be finished within the cycle time. Their model minimizes the expected total cost, which contains the task incompletion cost and the labor cost. For solution, a heuristic procedure was developed. The model, problem extensions and solution approach were further investigated by various authors [118, 113, 80, 83, 108, 63]. Vrat & Virani [118] integrated the modular assembly concept; Silverman & Carter [113] and Lau & Shihub [80] considered that it might be more economical to stop the line to finish uncompleted tasks. To improve the solution quality, Lyu [83] combined stochastic optimization tools and simulation; whereas, Sarin et al. [108] made use of a truncated dynamic programming and branch and bound algorithm. Gokcen & Baykoc [63] inserted buffers between the stations and integrated the storage cost; effectiveness of the proposal was tested using simulation. They found that buffer insertion smoothens product flow and decreases the total cost.

Similarly, considering the stochastic character of operation times, precedence relations and cycle time restrictions, McMullen & Frazier [90] and McMullen & Tarasewich [91] assigned workers and tasks to stations. Having calculated the cost parameters for workers and equipment, the former used simulated annealing and the latter employed ant colony optimization to address four performance criteria: Total design cost (equipment and labor), smoothness, the probability of completing all tasks within cycle time. For this aim, a composite objective function is formulated and optimized.

Today, environmental concerns in society grows and consequently, PLM involves in disassembly of products for reusing the components. Unlike the assembly systems, a major concern in disassembly systems is the quality of returned products and the effect of these products on the lines. Due to defective or polluting items, down time, breakdowns, task delays, or failures might be encountered. Disassembly line balancing has been increasingly studied by researchers, we refer to the book of McGovern & Gupta [89] and the survey of Battaia & Dolgui [8] for characteristics of the disassembly lines and details of the studies in this related research area. The most recent results were presented in the articles by Bentaha et al. [14, 16, 15].

Figure 6 presents the distribution by year of the publications related to incompletion or failure costs. Similarly to labor costs the interest of researchers seems to have been rather constant in the last 40 years and all studies consider it as a complementary objective.
2.1.6. Reconfiguration Costs

Rebalancing assembly lines might decrease costs, when demand structure of products or processing methods change, for example due to seasonal variations in demand or new technology investments. Tasks reassignments usually increase the efficiency but cause instability. Re-balancing usually necessitates hiring/firing workers, retraining them, reconfiguring machines and equipment and redesigning WIP buffers. Therefore, in the analysis, additional costs caused by these adjustments and layout changes should be taken into account. Gamberini et al. [59, 58] and Yang et al. [122] integrated the re-balancing cost to their model as a penalty function to discourage reassigning tasks to different stations. All these three studies followed a multiple criteria approach. The first one used TOPSIS method that defines the weights of different criteria by using an aggregation operator; whereas the others created the Pareto frontier of the problem.

Several reconfiguration scenarios were investigated by Borgia & Tolio [21] and Tolio & Urgo [116]. Borgia & Tolio [21] combined equipment costs and reconfiguration costs by giving weights according to the probability of each considered scenario; whereas Tolio & Urgo [116] developed two separate models: configuration and reconfiguration models. Recently the reconfiguration of machining transfer lines with multi-spindle workstations has been considered by Makssoud et al. [84].

Figure 7 presents the distribution by year of the publications related to reconfiguration costs. This histogram clearly shows that the interest for reconfiguration costs is recent and begins to generate some studies.
2.2. Composite Cost and Capacity Optimization Models

2.2.1. Idle-Time Costs

Idle times signals unused production capacities, and limiting them is crucial to minimize profit losses. For this aim, in their mixed assembly line balancing model, Chakravarty & Shtub [34] considered cost of idle time in addition to inventory and setup costs. They developed two solution methods: a dynamic programming algorithm and a single pass heuristic. Sarker & Pan [109] analyzed movements of operators and the inherent inefficiencies. Based on the analysis, they presented two models to minimize utility and idle time costs. Utility time defines the additional time needed to complete operations whereas idle time is observed if an operator waits for a work piece to process. In addition to these models, we also note that mixed model assembly line sequencing models could reduce total utility work [29, 20].

Figure 8 presents the distribution by year of the publications related to idle-time costs. Publications on this matter are actually very scarce with nearly one paper in 20-25 years.

2.2.2. Profit Based Models

Profit based models include various cost components and in addition, incorporates production volume or price decisions. Even though companies seek to maximize the profits, in the line balancing literature, they are less commonly studied than the cost based ones.

Rosenblatt & Carlson [104] showed that maximizing the efficiency of a line does not necessarily lead to maximum profits. Because minimizing the idle time decreases the number of workstations but increases cycle times (see also...
Deckro [38]). As a result, the quantity of production and revenue might decrease. Martin [87] reconsidered this profit maximizing model, examined the stochastic lines and integrated inventory cost to the model. Rosenblatt & Lee [105] demonstrated that task assignment is determinant in inventory holding costs and hence in profit. They developed a branch-and-bound procedure that maximizes the profit, which is defined as net revenue minus inventory holding cost and fixed cost of the stations.

Wei et al. [119], Kalir & Arzi [72, 73] formulated profit maximizing models for flexible production lines. Wei et al. [119] did not consider the inventory costs, but incorporated the setup and idle-time cost. Kalir & Arzi [72, 73] concentrated on buffers. Assuming infinite buffer capacities, they presented an exact solution method [72]. On the other hand, for finite buffer capacities, they developed an approximation procedure that involves three components: a solution algorithm to define the number and type of machines given the buffer size is infinite, a procedure to estimate the production rate and finally, an algorithm to approximate buffer capacities [73].

Dolgui et al. [41, 43] optimized the size of buffer storages between stations and presented Markov models. Their models include revenues, buffer equipment acquisition cost and inventory costs. To solve the problems, they respectively used genetic algorithms and branch and bound method. The optimization problem has recently been shown to be NP-hard [42]. More recently, Shi & Gershwin [112] and Massim et al. [88] have also worked on sizing buffers. The former study presented a nonlinear profit maximization model and used an iterative solution algorithm. Whereas the latter optimized buffers in transfer lines and used an approximate solution method, which is
based on an artificial immune system.

Boysen & Fliedner [25] suggested an adaptable profit maximization model for general assembly line balancing. In their objective function formulation, the revenue depends on the cycle time and the number of stations. As cycle time decreases, revenues increase. A fixed cost per station is charged for each station. They also considered various extensions of the model: parallel stations and tasks, resource and wage synergies, various processing alternatives, zoning restrictions and stochastic processing times. They decomposed the general problem to sequencing and assigning subproblems and solved them interactively using an ant colony algorithm.

Figure 9 presents the distribution by year of the publications related to profit. This histogram shows that profit maximization has generated a moderate but rather constant interest from researchers in the last 30 years. A specificity of this category is that authors exclusively consider profit as the sole objective, which seems logical since it is already a composite objective.

3. Conclusions and Future Research Directions

We summarized the existing cost and profit based research studies in Tables 1 & 2. The first table presents studies which addressed a single category, however the second table focuses on the ones that examined multiple cost categories. In both of the tables, the first column refers to the cost or profit, whereas the second to the relevant studies addressed.

Examining the tables we conclude that equipment costs took attention of many researchers. Studies that examine other cost categories or profit
Table 1: Summary of Studies that Focuses on a Single Cost/Profit Category

<table>
<thead>
<tr>
<th>Cost/Profit Category</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment (Equ)</td>
<td>Barutcuoglu &amp; Azizoglu [6], Battaia &amp; Dolgui [7], Battaia et al. [9, 10, 11], Belmokhtar et al. [13], Borisovsky et al. [24, 22, 23], Bukchin &amp; Tzur [30], Bukchin &amp; Rabinowitch [31], Chen &amp; Ho [36], Corominas et al. [37], Delorme et al. [39], Dolgui et al. [44, 46, 47], Osman &amp; Baki [93], Dou et al. [51], Essafi et al. [53, 54], Gadidov &amp; Wilhelm [57], Graves &amp; Lamar [64], Hamta et al. [67, 68], Kazemi et al. [77], Nicosia et al. [92], Ozdemir &amp; Ayag [94], Pekin &amp; Azizoglu [95], Pinnoi &amp; Wilhelm [96, 97, 98, 99], Wilhelm [120], Wilhelm &amp; Gadidov [121], Youssef &amp; ElMaraghy [124]</td>
</tr>
<tr>
<td>Labor (Lab)</td>
<td>Bock [17], Doerr et al. [40], Li &amp; Gao [82], Sabar et al. [107], Sungur &amp; Yavuz [115], Zhang &amp; Gen [125]</td>
</tr>
<tr>
<td>Inventory (Inv)</td>
<td>Boysen et al. [28]</td>
</tr>
<tr>
<td>Setup (Set)</td>
<td>Balakrishnan &amp; Vanderbeck [5], Bolat [18], Bolat et al. [19], Burns &amp; Daganzo [32], Dolgui et al. [49], Hyun et al. [71], Kara et al. [74], Kovaliev et al. [79]</td>
</tr>
<tr>
<td>Idle Time (Idl)</td>
<td>Sarker &amp; Pan [109]</td>
</tr>
<tr>
<td>Profit (Pr)</td>
<td>Boysen &amp; Fliedner [25], Dolgui et al. [41, 42, 43], Kalir &amp; Arzi [72, 73], Martin [87], Massim et al. [88], Rosenblatt &amp; Carlson [104], Rosenblatt &amp; Lee [105], Shi &amp; Gershwin [112], Wei et al. [119], Bentaha et al. [14, 16, 15]</td>
</tr>
</tbody>
</table>

optimization are relatively scarce. More than half of the papers examined deal with a single criterion, the ones that consider more than three criteria simultaneously are very rare. To the best of our knowledge, many combinations of cost categories have not been investigated yet, i.e. inventory and reconfiguration costs. Future studies could investigate these combinations. Even though idle time minimization studies are abundant in line balancing, there are only few studies that consider idle-time costs and combine them with other cost categories.

To summarize we present the distribution by year of the whole set of publications analyzed in this review in Figure 10. This histogram confirms that, overall, there is an increasing trend in publications on cost or profit oriented assembly line design. For example, the number of papers published on this matter in the sole year of 2014 is actually equal to the number of
Table 2: Summary of Studies that Focuses on Multiple Cost Categories

<table>
<thead>
<tr>
<th>Cost Categories</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equ &amp; Lab</td>
<td>Amen [1, 2, 3, 4], Cakir et al. [33], Kara et al. [75], Kazemi &amp; Sedighi [76], Pinto et al. [100], Rosenberg &amp; Ziegler [103], Roshani et al. [106], Scholl &amp; Becker [110], Tuncel &amp; Topaloglu [117]</td>
</tr>
<tr>
<td>Equ &amp; Inv</td>
<td>Lee &amp; Johnson [81]</td>
</tr>
<tr>
<td>Equ &amp; Set</td>
<td>Yoosefelahi et al. [123]</td>
</tr>
<tr>
<td>Equ &amp; Rec</td>
<td>Borgia &amp; Tolio [21], Tolio &amp; Urgo [116]</td>
</tr>
<tr>
<td>Lab &amp; Set</td>
<td>Giard &amp; Jeunet [62]</td>
</tr>
<tr>
<td>Lab &amp; Inc</td>
<td>Kottas &amp; Lau [78], Lau &amp; Shtub [80], Lyu [83], Sarin et al. [108], Silverman &amp; Carter [113], Vrat &amp; Virani [118]</td>
</tr>
<tr>
<td>Equ &amp; Lab &amp; Inv</td>
<td>Malakooti [85, 86]</td>
</tr>
<tr>
<td>Equ &amp; Lab &amp; Set</td>
<td>Dolgui et al. [45]</td>
</tr>
<tr>
<td>Equ &amp; Lab &amp; Inc</td>
<td>McMullen &amp; Frazier [90], McMullen &amp; Tarasewich [91]</td>
</tr>
<tr>
<td>Lab &amp; Inv &amp; Set</td>
<td>Chakravarty &amp; Shtub [35], van Zante-de Fokkert &amp; de Kok [56]</td>
</tr>
<tr>
<td>Lab &amp; Inc &amp; Rec</td>
<td>Gokcen &amp; Baykoc [63]</td>
</tr>
<tr>
<td>Inv &amp; Set &amp; Idl</td>
<td>Chakravarty &amp; Shtub [34]</td>
</tr>
</tbody>
</table>

papers published from 1970 to 1990. This trend can be observed both for papers dealing with a specific cost and for papers dealing with several costs.

![Figure 10: Histogram of the whole set of publications analyzed](image)
3.1. Implications for Future Research Directions

Possible directions for future work are summarized as follows:

a. Line balancing studies usually consider cost categories separately and impose restrictive assumptions. For example, some of them model only equipment costs. Since many of them come from real life applications, a large number of context dependent assumptions are made in the models. More general, comprehensive and less restrictive models are required. To deal with the complexity of the general models, effective approximate solution approaches need to be developed.

b. Even though profit maximization is the major goal in majority of organizations, profit based approaches and models are rare in the literature. Cost based ones are studied relatively more. However, time based models are the most investigated. Which is somewhat surprising because optimizing for the least time is not always the path to the maximal profit. We conclude that it is necessary to identify and further investigate factors that affect profitability of line designs and the new findings should be reflected in the future models.

c. Most of the academic studies on line balancing tackle single objective problems. However, in reality, managers are confronted with optimizing multiple criteria. Therefore, multi criteria models that consider time and cost based criteria or various cost categories simultaneously are promising research areas. They are more suitable for the needs of industry (see Zhang & Gen [125] as an example).

d. Regarding the multi-criteria analysis, operation processing alternatives and inherent time/cost trade-offs, both continuous and discrete, could be investigated. In continuous models, cost is assumed to be linear or non-linear continuous functions of processing time; whereas discrete versions would consider discrete sets for processing modes. Indeed, these relationships have been widely studied in the area of resource constrained project scheduling, which contains problems that are closely related to line balancing problems [114].

e. Another relevant and interesting study topic is the robustness regarding cost and profitability. Majority of the existing studies ignore disruptions like the machine breakdowns. Robust optimization studies for time based oriented objectives have been started [70, 48, 66]. Furthermore, to the best of our knowledge and excluding the preliminary stability analysis presented in Gurevsky et al. [65], robust cost based models do not yet exist. Regarding
this topic, two research directions are interesting: formulating mathematical
models to construct robust designs and developing measures to assess ro-
bustness of a given line design so that alternative designs might be compared
with respect to robustness.

f. Finally, we emphasize that it is imperative to incorporate these models
into a computerized decision support system and guide managers in their
investment decisions [55]. Integrating these DSS tools into a commercial
software package will be indispensable for the industry. Although line bal-
ancing problems have been widely studied in academia, development and
use of commercial software applications is not so frequent [102]. They are
mostly used by automotive industry. Some of them are OptiLine, Proplaner
and Delmia. We believe that investigating further to define specific require-
ments of various industries and integrating model based DSS tools to offer
profit maximizing solutions would increase software usage.

3.2. Conclusions

In this review paper, we focused on cost and profit based assembly and
transfer line balancing. We comprehensively discussed the cost components,
analytical models and the solution algorithms. We examined both the progress
in academic knowledge and the current needs of the practitioners. Reviewing
the previous and current studies meticulously and studying the needs of the
industry lead us to identify and highlight the research areas that are worth
further investigation.

Acknowledgments: This work was partially supported by the European
Commission 7th Framework Project ‘Advanced Platform for Manufacturing
Engineering and Product Lifecycle Management’ (AmePLM).

References

95.

68, 1–14.


design problem with equipment decisions. *International Journal of
Production Research, 46*, 6323–43.

the design of deterministic assembly systems. *International Journal of


assembly system problems. *European Journal of Operational Research,
126*, 31 – 50.

workload smoothing on assembly lines. *INFORMS Journal on Com-
puting, 9*, 335–50.

balancing with processing alternatives: An application. *Management

[101] Rashid, M., Hutabarat, W., & Tiwari, A. (2012). A review on assem-
bly sequence planning and assembly line balancing optimisation using
soft computing approaches. *The International Journal of Advanced
Manufacturing Technology, 59*, 335–49.

art of optimization methods for assembly line design. *Annual Reviews
in Control, 26*, 163–74.

rithms for cost-oriented assembly line balancing. *Mathematical Methods


inventory costs on the design and scheduling of assembly lines with low


31


