Assembly Optimization for High-Volume High-Flexibilty Robotic PCB Assembly

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Abstract: We describe the development of a novel vehicle-routing-based algorithm for the optimization of the chip/component placement sequences during an automated assembly of printed circuit boards using high-speed robotic equipment. We carry out sensitivity analyses and equipment re-design studies to determine maximal-impact improvement strategies for manufacturers of such equipment.

Keywords: printed circuit board, heuristics

1 Introduction

Many manufacturing organizations in the world today are under severe financial pressure to find ways to satisfy increasingly demanding customers who are seeking higher and higher levels of performance within the other two conflicting dimensions of cost and time to delivery. These pressures are mounting for organizations whose production processes require expensive, complex automation, and where the market forces them to offer a wide range of products. In such conditions, manufacturers must plan their production to enable themselves to meet both high resource utilization and quick market response.

The electronics industry continues to rank as a very key industry in this information age at the turn of the century and beyond. Most electronic products today contain printed circuit boards (PCBs) of different sizes and functionalities as crucial building blocks [12]. Global revenues for the PCB industry exceeded $50 billion in 2007 and are expected to reach more than $76 billion in 2012 [33]. Therefore, PCB manufacturing plays a very important role in today's economy.

Boards are manufactured on automated assembly lines where high-speed placement machines place components on the PCBs. A line can assemble components on multiple types of PCBs and has one or several high speed machines to perform the actual placement of operations [34, 19]. The assembly of PCBs is a complex task involving the placement of hundreds (even up to a thousand or more) of electronic components in different shapes and sizes.

Because electronics technology can quickly become obsolete, minimizing the time of PCB design and manufacture is crucial and an increasingly significant concern for electronics firms [17]. In order to remain competitive in the PCB market, manufacturers must concentrate their efforts on improving the efficiency of their assembly lines. Production planning and control, process planning, and quality control are important activities for achieving efficiency in the PCB industry. Of these activities, process planning is particularly important due to its direct impact on PCB assembly operations. With increasing market pressures, it has become imperative for companies to critically look at effective ways to reduce assembly time, which is one of the largest contributors in the makespan of PCBs, sometimes as much as 40-60%.

Not only are assembly machines frequent bottlenecks in production, but they are also expensive resources (a typical SMT equipment ranges in price from $250,000 to $1,000,000 [12]). Utilization of these expensive assembly machines is, therefore, an important issue in PCB assembly [46], especially for high-volume applications. Modern PCB production, therefore, utilizes computerized, highly automated equipment. Efficiency relies on the technical capabilities of the placement machines and the workflow to the machines [29]. Since sustained improvements in hardware are both limited and expensive, to improve performance, it is very important to know where to make improvements, i.e. where to get the invest in order to gain the maximum improvement.

The principal task of a placement machine is to pick a component from the feeder magazine/tray and place it on the right location on the board. Placement machines can be classified into two groups: (1) pick-and-place-type machines with single or multiple heads, or the relatively newer rotary collect-and-place-machines (CAPMs) and, (2) turret-styled placement machines. The difference between these two is due to which parts are moving parts. A pick-and-place-machine (PAPM) or a CAPM has a moving head while the circuit board is fixed, and the feeder may move linearly or is fixed. In contrast, a chip shooter machine operates with a rotating turret, which connects through its cruising radius the feeder with the table. Both, the feeder and the table, are moving, too.

An elementary machine is a PAPM with one head equipped with a single spindle. In each sequence a chip is picked up by the spindle from a feeder tray with multiple slots (each holding a specific type of chip/component), is transported to the board and placed on its intended location. Nowadays, the head typically has multiple spindles (called the multi-spindle pick-and-place machine) which are used to pick and place components. These spindles are loaded with vaccuum-suction operated nozzles each of which is capable of holding a single component at a time (see Figure 1).

Chip shooters have been around for decades and used to be renowned for their high speed. They had low flexibility in terms of handling varieties of components, but were very good at repetetive tasks. These machines are now almost phased out. On the other hand, the pick-and-place machines were typically slower and, being highly flexible, used more for placing odd and specialized components. They featured either a single spindle or multiple spindles.

Today, CAPMs are being increasingly used in the industry for meeting the high-volume, high-flexibility production requirements of today. CAPMs typically form the bottleneck in high-volume PCB production. Being an extremely versatile equipment often used for high- or very-high-volume production, they are a key resource on which even marginal savings in time can translate to substantial monetary savings.

1.1 Contributions and Outline

According to [34], problems about usage of these machines are interesting for (at least) two reasons. First, the competitiveness of individual companies in the field directly depends on the cost efficiency of the production, which in turn depends on the throughput of individual assembly lines. Second, the problems themselves are quite challenging due to their inherent difficulty and the fact that they offer not only an explosive number of combinatorial options for configuration of the machines as well as for planning production on them, but also the possibility of using several different approaches for formulation and solution. Thus, optimizing and planning assembly operations to minimize assembly cost and time with CAPMs offers a great challenge.

Further, there is a wide variation in the requirements of different applications. There are industries (e.g. avionics) that use large-sized boards (24 in. x 20 in. boards with several hundreds of components), but also most manufacturers of small, tiny boards (e.g. in the cellular phone industry) tend to produce their boards by batching or "bundling up" several (tens of) their boards together onto a platter that is later cut out into individual boards (this is to form a virtual large board for the sake of efficient processing). There is also a very large variation in the specific characteristics of boards used in different industries. For example, some applications use boards with hundreds of components, each of a different type, whereas some others use boards with hundreds of components, each being an exact replica of one standard type. Thus, it becomes important also to study which machine configurations and process parameter settings suit what types of board applications in terms of minimizing the total processing time.

Research literature is abundant for planning production on the chip shooter machines, and also to some degree for the pick-and-place machines, but happens to be quite limited for the CAPM configuration, inspite of their increasing popularity. Even more so, there have been even fewer papers focusing on such machines from the machine-design improvement perspective. The problem itself involves several factors, which play into the computation and optimization of the process plan, namely:

- robot motion control,
- assembly placement sequence,
- feeder magazine arrangement,
- nozzle set-up and inter-changability.

These different factors, in conjuction with the wide range of possible configurations of the parameters governing the operation of these machines (such as velocity profiles, capacities, etc. of the various moving and stationary components) provide a plethora of opportunities for optimization and cost reduction. In order to remain at the cutting edge, it is crucial that board assemblers use not only the best assembly pick-up and placement sequence, but also use the right machine configuration for the right products, and equipment manufacturers supply them with their desired configurations with minimum additional cost, thereby providing them with the capability to attain optimized performance for their applications.

Detailed sensitivity analysis also provides valuable insight into real world scenarios involving interplay of such interacting, moving components comprising more complex automation equipment. For instance, going from one to a dual-head or a quad-head configuration would introduce problems of load balancing, cycle sequence synchronization, and the geometrically challenging problem of collision avoidance.

In this paper, we summarize the methodology from [35] to solve these very interesting problems and uniquely exploit the opportunities for application of novel vehicle routing techniques and algorithms. This cross-domain application has not been explored before. We outline modeling, characterizing, and planning for the CAPM-type configuration using some of the state-of-the-art optimization tools.

The solution methodology outlined in this paper also provides a framework and an important link to the DFX (Design for Manufacturability/Assembly/Test) domain by providing cost estimates of downstream production of new designs on available equipment. Studies have shown that taking assembly costs early into account in the design cycle can have a significant effect on the cost to the consumer [32]. With short computational times, such a tool might be useful for providing quick feedback as early as the topology optimization stage.

In our sensitivity analysis we use a novel algorithm to solve the placement sequence planning problem for the CAPM type automated placement equipment the features and benefits of which are described in [35]. In this paper, we use this developed algorithm to answer interesting process effectiveness and machine-design questions faced by assemblers and equipment manufacturers, respectively.

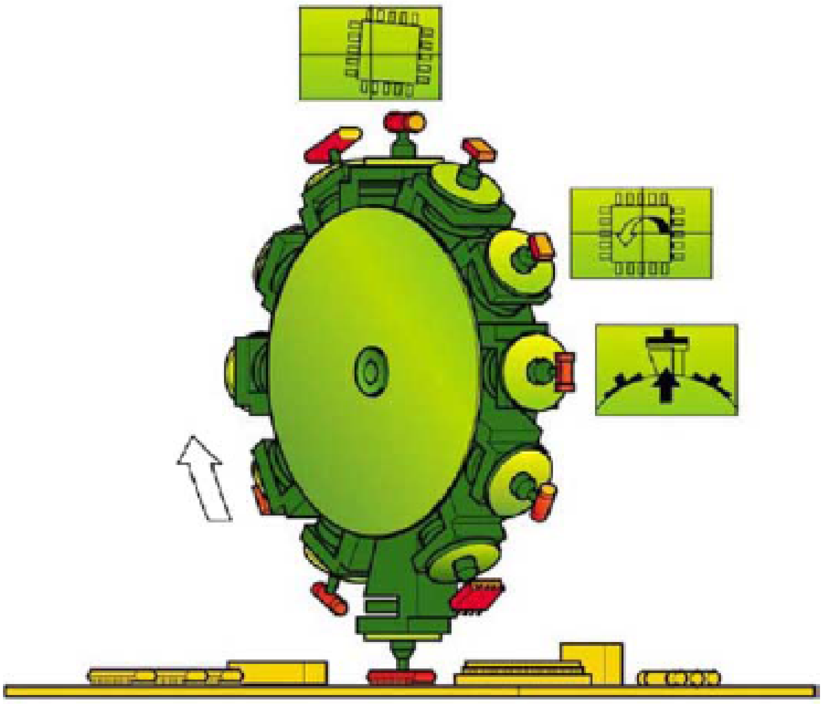

Figure 1: Detailed view of a rotary collect-and-place head [36]

We limit the problem scope to studying a single-head single board scenario while there now exist machines that can synchronize up to four placement heads (see Figure 1) simultaneously operating on two boards (for example, the Siemens' SIPLACE HS or Universal Instruments' Quadris S). If several boards or heads are present, the problem can be decomposed into several single head single board cases. The single-board single-machine scenario provides an insight into a subproblem that is part of the very core of the planning hierarchy (classified into seven sub-problems by Crama et. al. [10]).

We study the problem of optimizing the placement sequence of components in a CAPM (see Figure 1). We allow and exploit more automation flexibility than has been ever explored earlier. We allow interleaving of pick-ups and placements and multi-stepped bidirectional head rotation (this means that we do not have to follow the sequential ordering of spindles to use in successive placements, but can use spindle sequences such as {1, 3, 5, 2, 8, ...} consecutively in a given route in order to optimize the linear distance to be traveled by the rotary head, see Figure 1). This way we can exploit the flexibility already provided in the hardware design. We can also incorporate the effects of allowing the entire feeder magazine to move along the horizontal direction. This allows greater efficiencies to be achieved, but also causes the problem to become much more complicated and is the first time this aspect is ever included in the analysis of a CAPM machine.

Given these assumptions and specific constraints posed by the configuration of the machine, the placement sequencing problem becomes very similar to a complex version of the vehicle routing problem with a single capacitated vehicle (in our case, the rotational robotic head with multiple spindles loaded onto a dual XY gantry) performing multiple trips from the depot (in our case, the feeder magazine) to satisfy customer demand (in our case, the design requirements being met, stipulating the specific component type to be inserted at each placement location).

In [35] this challenging problem is tackled by a two phase optimization approach. In the first phase a feasible solution is constructed by using greedy principles combined with mathematical programming. In the second phase this solution is iteratively improved.

The solution of this problem not only allows board assemblers and end-product manufacturers of electronic equipment in reducing cycle assembly time but also is of great value to assembly machine and equipment manufacturers in answering design questions such as:

- Should feeder movement capability be added or should the head index time be reduced?
- Should head capacity be increased or should XY traverse speed be increased?

This paper attempts to help establish a framework to study, analyze, and answer some of such questions. The primary contributions include:

- a methodology for customizing PCB assembly solutions to user requirements,
- a study of the effects of incorporating, for the very first time, the effect of feeder motion and spindle jumping in a CAPM,
- a detailed characterization of the effects of the various board characteristics on the assembly time on the CAPM,
- charaterization and sensitivity analysis of the influence of CAPM operating conditions allowing configurability of PCB equipment to specific customer needs, and
- providing a missing link to a DFX system in order to provide accurate feedback on estimates of assemblability.

We contribute findings on specific effects of various factors such as board and machine parameters, upon the assembly time and cost. We demonstrate that the effects of allowing feeder motion and spindle jumping are significant. For denser relative component diversity, we observe a greater increase in the assembly time on larger capacity machines while the trend is somewhat reversed on smaller capacity machines. Adding head capacity is shown to be greatly beneficial for all scenarios, but most beneficial when boards have a large number of components to be inserted. We note that the linear gantry velocities play the most significant role on assembly time. Increasing rotational head velocity was found to be more helpful for larger capacity machines, but the gains are significant regardless of the number of components on the board and even on smaller capacity machines, especially when processing high relative component diversity boards. Feeder motion velocity reduces assembly time as well, especially in the case of high relative diversity boards.

In Section 2, we describe details of CAPM operating principles, along with specific examples of such machines marketed by industrial manufacturers. In Section 3, we provide a formal statement of the problem and describe the underlying network model used in our approach and outline the two-phase solution methodology developed to tackle this problem. In Section 4 we present our compational study results, analyze trends, and develop a regression equation to fit the data. Finally, in Section 5, we conclude with possible future extensions.

1.2 Literature Review

We first examine literature in the PCB manufacturing planning domain. Excellent surveys on production planning problems in PCB assembly and on the overall area of assembly optimization for PCBs are given in Crama et. al. [10], Smed et. al. [37] and Ji and Wan [23]. These reviews establish a framework for the general classification and categorization of production planning problems arising in electronics assembly. They also classify research according to the problems addressed for different machine configurations. A very recent survey can be found in Ayob and Kendall [5], wherein the various machine configurations and important optimization algorithms to solve production problems on them are exhaustively reviewed.

While there is an abundance of literature on the turret-type placement machine (see for example, some excellent work carried out Wilhelm et. al. in [45], Kumar et. al. in [26], and Ellis et. al. in [13]) and both the single-headed (Ho and Ji [20], Ayob and Kendall [4], and Ball and Magazine [6]) and multi-headed pick-and-place machine configurations (Burke et. al. [8], Ahmadi et. al. [1], Wilhelm et. al. [43], and [44]), there seems to be a much less research on the CAPM concept. Part of this might be due to the fact that this machine configuration is fairly recent, being introduced to the commercial market by machine manufacturers only a few years ago as opposed to the longer history of usage of the other machine types. The increasing popularity of this machine type led by its unique high-volume, high-flexibility production capabilities demands in-depth studies on the specific problems arising in production planning on machines of this configuration.

In relation to the CAPM, various algorithms have been presented. Altinkemer et. al. [2], [24] have solved the integrated feeder location and placement sequencing problem for a single rotary head machine both in the case of a moving and a non-moving feeder using Lagrangian relaxation. Günther et. al. [15] solve the integrated problem of feeder location and placement sequencing using a 3-stage heuristic. They extended their work in [25] by using genetic algorithms (GAs) to solve the same problem. Ho et. al. [21] have also developed two hybrid GAs to solve the feeder assignment and placement sequencing problems on the CAPM. Tirpak et. al. [41] describe the development of an optimization software for the Fuji NP-132, a dual-station, dual revolver head, high-speed placement machine. Gyorfi et. al. [16] generalize the GA by Leu et al. [30] for planning component placement sequences and feeder assignments for pick-and-place PCB assembly tasks to support multiple-placement nozzles and independent feeder and board links (chromosome) evaluation methods.

None of the publications mentioned have looked at the problem from the perspective of design-change and improvement of assembly equipment, and merely have dealt with efficient production planning for this machine configuration. Further, several of them make severely limiting assumptions on automation flexibility and capabilities of the CAPM in order to simplify the planning problem down to a more tractable one.

From a machine-design studies perspective, Lambert et. al. [28] focus on using simulation to develop an integrated model to evaluate the effect of several independent variables on the performance of SMT production line. They use real data and an existing SMT line from a high product mix/low volume electronics manufacturer to conduct analysis. The independent variables are set-up policies, feeder types, similarity factor in set-ups, parts reduction at product design step, and inter- and intra-family scheduling rules; and the performance measures are average lead time, average work-in-process inventory and average set-up time. They propose a new method of grouping products and show that their proposed method reduces set-up time and lead time while slightly increasing the work-in-process inventory. The model thus helps assess the effects of some of the independent variables on line performance. Recommendations are made in order to help choose the best alternatives in order to improve production line flexibility and productivity.

The authors in [7] study the inadequacy of concurrent engineering and design for manufacture and assembly strategies, focusing on product and process design issues related to capability concerns, which had been historically justified using cost savings calculations focusing on easily quantifiable costs such as raw material savings or manufacturing or assembly operations. Product and process design strategies should include both capability and capacity concerns and justification procedures should include the financial effects that the product and process changes would have on the entire company. The authors propose an innovative new design strategy using a comprehensive enterprise simulation tool and show that both the design strategy and the simulator show promise for industrial use.

In Stuart, et. al. [39], electronic assembly product-and-process design alternatives were investigated using a quantitative methodology with life cycle considerations for environmental impacts; energy usage, material consumption, waste generation, process yield, and product reliability.

The work by Kusiak and He [27] studies the concept of agile manufacturing and manufacturing system reconfigurability and methodologies of design for agile manufacturing by considering operational issues in assembly systems at the early product design stage. Three rules intended to support the design of products to meet the requirements applicable to the design of products for agile assembly from an operational perspective are proposed, and examples provided in order to demonstrate the potential of the design rules, along with procedures and algorithms for implementing them.

We note that none of these studies focus on determining the most suitable configuration of automation equipment at the level of detail carried out by us, and are restricted to more general studies on design improvement at the plant or assembly-line levels.

2 Detailed Operating Principles and Machine Specifications

Kulak et. al. [25] describe the general working principle of a CAPM. In the assembly stage, the PCB resides on a stationary work table while electronic chips are gathered from a magazine accommodating a limited number of component feeders. The CAPM concept has the advantage of achieving high placement speeds inspite of a stationary work table. This is beneficial for lower error rates in placement due to avoidance of the possibility of components shifting from their desired position as is the case in chip-shooter type machines [42] (due to high accelerations and decelerations of the work table). Each component feeder holds components of one type. Feeder magazines can be of different types - array-type, tray-type, matrix-type, etc. The amount of space (i.e. number of slots) occupied by a feeder depends on the width dimensions of the components. Typically, small components occupy 1-2 feeder slots, whereas larger components can occupy 4-5 feeder slots.

The principal characteristic of the CAPM is the use of a revolver-type unit as the placement head. The placement head is equipped with a number of nozzles, most commonly 6 or 12, and is mounted on a dual-axis XY gantry system. The assembly cycle begins with the placement head traveling to the component magazine and collecting components from the various feeders performing stepwise rotary movements in order to pick up the types of components needed to be populated onto the board. Then, the placement head travels to the board area and places components one at a time at pre-defined positions on the PCB. Reverse rotation of the placement head is possible, but often disallowed in production planning due to resulting additional complexity. Thus, most approaches assume that the placement sequence on the PCB is always the same as the pick-up sequence from the magazine, which can often be sub-optimal. Furthermore, existing planning approaches also sometimes simplify the problem by requiring the head to be fully loaded upon its visit to the feeders, and fully unloaded before it can return. Again, this is clearly sub-optimal, and is merely a restriction imposed by the planning approaches rather than of the automation equipment itself. After the placement tour is completed, the placement head needs to travel back to the feeder magazine, collect the next set of components and start a new placement tour. The feeders themselves are capable of moving along the X-direction in order to enhance speed during the pick-up operations. In order to further increase the assembly speed, dual-gantry types of CAPMs, having upto four parallelly operating rotary placement heads, have now been introduced. With this type of a machine, the collect-and-place cycles can be performed concurrently. While the first placement head collects components from the magazine, the other head carries out the placement operations, and vice versa. In such a scenario, additional constraints have to be imposed to avoid geometric interference of the operations of the two gantries for obvious reasons. In the ideal case, the placement speed is doubled compared with single-gantry machines. However, such an effect is barely achieved in practice due to workload balancing and potential interference issues.

In this section, we introduce three CAPMs together with their specifications in order to provide an idea of the most commonly-used configurations.

2.1 SONY SI-G200

The SONY SI-G200 machine is a CAPM SMT that uses a placement mechanism mounted on a rotating turret with multiple heads that can pick-and-place several components every time. An earlier version of the machine was described in [31]. The SONY machine boasts one of the best performances with the smallest footprint and the minimum power consumption [38]. On SONY SI-G200, feeders are fixed and lie on both sides of the machine, each side having 40 slots. Each feeder that carries components can be assigned to one or more slots depending upon its width. The rotating turret has 8 or 12 heads, which can move in X, Y and Z axes simultaneously. The heads and nozzles are mounted on the turret. Each head is equipped with a nozzle that holds and grips a component until it has been placed on the circuit board. Nozzles are of different diameters according to the component size to be held. On the SONY SI-G200 machine, nozzles cannot be automatically changed once the assembly cycle has begun - they can only be carefully chosen at the beginning of the particular assembly set-up so as to maximize utilization.

2.2 Siemens SIPLACE X-Series

The Siemens X-Series offers high-speed placement solutions that claim to give the world's fastest placement speeds with an IPC (Association Connecting Electronics Industries) benchmark performance exceeding 100,000 components per hour [36]. The platform allows custom configuration options with 2, 3, or 4 gantries with a dual-conveyor based PCB transport mechanism. Heads may have 6, 12 and 20-nozzle capacities. The machine is capable of "hot-swapping" feeders in order to change set-ups for a fresh batch of PCBs without having to 'down' the line. The machines typically have 148, 160, or 180 feeder slots, each slot capable of holding an 8-mm tape.

2.3 Fuji NP-132

Tirpak et. al. [41] described the functionality of the Fuji NP-132 machine, which is a small-footprint, high-speed, flexible chip placer. The design of the machine includes dual turret-type placement heads mounted on two overhead ball-screw XY gantries driven by independent servo motors. Each turret head contains 16 spindles capable of holding a variety of nozzle sizes (0.7 to 7.0 mm). Automatic nozzle changeovers are enabled by an optional nest on each side of the machine. Each turret head carries a camera for efficiently reading fiducial marks. Each head is also equipped with an internal parts camera for visual inspection of parts on-the-fly.

3 Problem Statement, Modeling, and Methodology

This section outlines the formal statement of the exact problem we are solving, and also provides details of the formulation of our network model developed to represent and solve the original problem. This is a shortened version of the material presented in [35].

In this work, we focus on optimizing the placement sequence of components for a CAPM, and (Figure 1) assuming that the arrangement of the feeder is prescribed in a separate pre-optimization step. This is not an unreasonable assumption even though the optimal sequence is heavily dependent on the feeder arrangement as an input since one could arrive at an arrangement by iteratively solving the placement sequencing and feeder arrangement problems within a feedback loop. This has often been done in the literature for these kind of problems.

Our problem is robust enough to allow the feeder rack to hold each component type in multiple slot locations to account for varying width components. We assume for the sake of simplicity that the acceleration and velocity profiles of the robotic head and feeder magazine remain independent of the size of the components that they carry. However, these assumptions can be easily relaxed.

The problem is to find the least cost sequence of picking components from the feeder magazine and the placing them on the board, subject to the following conditions:

(1) all components required by the design must be placed,

(2) every component that is placed must have been picked up previously (and not yet placed),

(3) every spindle may contain only one component during a "route" (to be defined shortly), and

(4) at no time in a route must the capacity of the head be violated.

(5) the cost implications of the loading and unloading sequence for the vehicle are accounted for.

We want to fully exploit opportunities offered by simultaneous motion, spindle jumping (a phenomenon caused by allowing bidirectional and multi-stepped indexing motion of the placement head), and feeder magazine movement.

3.1 Network Model

We formulate a network model $G(\mathcal{N}, \mathcal{A})$, where $\mathcal{N}$ is the set of nodes and $\mathcal{A}$ the set of arcs in order to aid in defining a solution methodology.

We define a board node (BN_i) corresponding to each physical board onsertion location and a feeder node (FN_i) corresponding to each feeder slot location. From each BN_i and FN_i, we construct a series of nodes called the greater board nodes (GBN_i) and greater feeder nodes (GFN_i), respectively. The board nodes contain only the physical location and component-type information, whereas, the greater board nodes has a pointer to the board node and the active spindle position on the head at this node. Similarly, each feeder nodes contain the slot location and component-type information, whereas each greater feeder nodes have a pointer to a feeder node, the active spindle position on the head, and the feeder magazine's current position at the time of the head's visit to this node. To put it formally,

$$\begin{aligned}
BN_i &= \text{Board Location } i \text{ with some associated Component Type}\\
FN_i &= \text{Slot Location } i \text{ with some (possibly, other) associated Component Type}\\
GBN_i &= \text{Set of } k \text{ nodes for } 0 \leq k \leq \text{maximum number of spindles}\\
&\qquad \text{with each node of the form } (BN_i, \text{Spindle } k)\\
GFN_i &= \text{Set of } kl \text{ nodes for } 0 \leq k \leq \text{maximum number of spindles,}\\
&\qquad\qquad\qquad\qquad 0 \leq l \leq \text{maximum number of feeder magazine positions}\\
&\qquad \text{with each node of the form } (FN_i, \text{Spindle } k, \text{Feeder Magazine Position } l)\\
GBN &= \{GBN\}_i\\
GFN &= \{GFN\}_i\\
\mathcal{N} &= GBN \cup GFN\\
\mathcal{A} &= \mathcal{N} \times \mathcal{N}.
\end{aligned}$$

These principles are illustrated in detail along with an example in [35]. We focus next on arc costs. In PCB manufacturing, cost is driven by time, and thus all arc costs are measured in time units, i.e., the time to move between two nodes. To this end, we define:

$$\begin{aligned}
IndexTime &= \text{Turret/Head spindle-to-spindle rotational index time}\\
SlotWidth &= \text{Width of one slot on the feeder}\\
Velocity_{hx} &= \text{Head traverse velocity in the X direction}\\
Velocity_{hy} &= \text{Head traverse velocity in the Y direction}\\
Velocity_{f} &= \text{Feeder magazine movement velocity in the X direction}\\
h(a) &= \text{Head node of arc } a\\
t(a) &= \text{Tail node of arc } a\\
\Delta SpindlePos_a &= \text{Smallest relative displacement regardless of orientation}\\
&\quad\ \text{between active spindle positions at nodes } h(a) \text{ and } t(a)\\
&= \min(|\text{Spindle } h(a) - \text{Spindle } t(a)|,\\
&\qquad\quad \text{Max No. Of Spindles} - |\text{Spindle } h(a) - \text{Spindle } t(a)|)
\end{aligned}$$

In $\Delta SpindlePos_a$, we capture the number of unit spindle motions between two spindle indices. The reason there are two terms is because to get from one position to the other one the head can turn either clockwise or in the other direction.

We can now define the costs on the arcs in the network, where X_i, Y_i are the x-co-ordinate and y-co-ordinate of node i respectively.

$$\text{Type (I) arc: } (t(a) \in GBN, h(a) \in GBN): \tag{1}$$

$$c_b(a) = \max(|X_{h(a)} - X_{t(a)}|/Velocity_{hx}, |Y_{h(a)} - Y_{t(a)}|/Velocity_{hy}, \Delta SpindlePos_a \cdot IndexTime) \tag{2}$$

$$\text{Type (II) arc: } (t(a) \in GFN, h(a) \in GBN): \tag{3}$$

$$c_{fb}(a) = \max(|X_{h(a)} - X_{t(a)}|/Velocity_{hx}, |Y_{h(a)} - Y_{t(a)}|/Velocity_{hy}, \Delta SpindlePos_a \cdot IndexTime) \tag{4}$$

$$\text{Type (III) arc: } (t(a) \in GBN, h(a) \in GFN): \tag{5}$$

$$c_{bf}(a) = \max(|X_{h(a)} - X_{t(a)}|/Velocity_{hx}, |Y_{h(a)} - Y_{t(a)}|/Velocity_{hy}, , \Delta SpindlePos_a \cdot IndexTime) \tag{6}$$

$$\text{Type (IV) arc: } (t(a) \in GFN, h(a) \in GFN): \tag{7}$$

$$\begin{aligned} c_f(a) = \max(&|X_{h(a)} - X_{t(a)}|/Velocity_{hx}, \qquad (8)\\ &|\text{Feeder position } h(a) - \text{Feeder position } t(a)| \cdot SlotWidth/Velocity_f, \qquad (9)\\ &\Delta SpindlePos_a \cdot IndexTime) \qquad (10) \end{aligned}$$

For type (I), (II), (II) arcs, the first two terms capture the fact that the head can move simultaneously in both horizontal and vertical coordinates and the third term captures the time to move the head from one spindle to the next one. If this time is longer, the head waits at $h(a)$ until it rotates to the desired spindle. For type (IV) arcs, the feeder moves concurrently with the head. The first and last terms capture the head operations, while the middle term captures the time for the feeder movement. It is noteworthy that the trianlge inequality does not hold on all the arcs in this network.

We define a route as an ordered list of arcs beginning with a type III arc, comprising several type IV arcs which are followed by a type II arc, multiple type I arcs, and ending with again a type III arc.

Let $\mathcal{R}$ be the set of arcs in route r. Let a_1 be an arc in $\mathcal{R}$ such that $h(a_1) \in GBN$ and $t(a_1) \in GFN$ and a_2 be an arc in $\mathcal{R}$ such that $h(a_2) \in GFN$ and $t(a_2) \in GBN$. Let also a_3 be an arc such that $h(a_3)$ is the 'last' GFN node to be visited by r and $t(a_3)$ is the first GFN node to be visited by the 'next' route. The total time for executing route r reads:

$$C(r) = \sum_{a \in \mathcal{R}: h(a) \in GFN,\ t(a) \in GFN} c_f(a) + \max\left\{\left\{c_{bf}(a_1) + \sum_{a \in \mathcal{R}: h(a) \in GBN,\ t(a) \in GBN} c_b(a) + c_{fb}(a_2)\right\}, c_f(a_3)\right\}.$$

3.2 Solution Methodology

The general problem is a very hard one to solve to optimality because of the nature of the problem itself as a combination of several NP-hard problems including the Travelling Salesman problem, the Bin Packing problem, and the Quadratic Assignment problems combined together. A pure mathematical programming approach is therefore not going to work. Hence, we resort to a novel heuristic, and instead of employing a traditional local search strategy or a pure meta-heuristic, we combine very large-scale neighborhood search ideas with mathematical programming [35] using a two-phase solution methodology. First, we employ a complex heuristic that generates a good initial solution. This solution is then iteratively improved at each subsequent iteration by an interchange algorithm in order to find no worse a solution than the one we begin with. Our companion technical report [35] provides a detailed account of the methodology, but we present an overview herein for the sake of completeness.

The initial solution is generated by applying a heuristic designed along the lines of the iterated tour partitioning heuristic [18], but for our much more complicated vehicle routing problem (VRP) scenario. We first neglect the computations on the feeder side and solve the problem on the board side. Taking this solution, the computations on the feeder side are then carried out in order to get a feasible and good initial solution. The iterative improvement phase heuristic is based upon the algorithm proposed by Franceschi et. al. [14] for the standard VRP.

In the first step, nodes from the initial solution are selected to be marked for extraction. The selection can be based on multiple schemes, which can be used individually or in conjunction with each other, to maximally gain benefits from individual characteristics at each stage of the execution of the algorithm. In the next step, we extract the nodes marked in the selection step. Typically, nodes can again be pulled with several different strategies. Pulling out nodes destroys the routes, which are reconstructed by short-cutting the solution, i.e. creating a new arc between the two nodes neighboring the extracted nodes. We then use all the extracted nodes to create a pool of subsequences formed by all possible combinations of the extracted nodes, spindles, and feeder magazine positions, to be potentially reinserted into the solution, albeit at a cheaper location than earlier. This means that we would have an enormously large number of possible candidates for reinsertion. Therefore, we use the idea of pricing out these candidates based on the solution of the LP relaxation of an ILP. The insertion ILP reinserts the extracted nodes. Essentially, the ILP is an assignment problem with many additional constraints and has a large number of columns. We solve this model by resorting to column generation. Finally, we incorporate the optimal results obtained from the reallocation ILP into the solution using specially designed insertion operations. This re-insertion step marks the end of an iteration, and the entire series of steps is repeated in the next major iteration.

4 Computational Results

4.1 Experimental Design

Extensive computational experiments were designed and carried out in order to examine the sensitivity of the assembly time (and hence, assembly cost) to various machine configurations, and input and design parameters such as board size (i.e., the total number of components), the number of component types or component diversity, the number of spindles present on the head, the head linear and rotational velocities, the feeder movement velocity, and feeder arrangement. Results presented and discussed in the following sections are representative of results obtained on multiple runs over test cases of varied problem complexity and dimensions.

The experiments were carried out on a cluster of 52 computing nodes, each having two 64-bit 3.2GHz Pentium 4 Xeon processors sharing 6GB RAM with InfiniBand, running Red Hat Enterprise Linux 4 and compiled under GCC version 4.1.2. The implementation however does not currently exploit multiple processors; it is sequential. We used the Concorde Lin-Kernigan TSP Solver [3] to solve TSPs, an in-house implementation of a version of Dijkstra's algorithm [11] to solve shortest path problems, and CPLEX 11.0 MIP solver [22] as the generic ILP solver. All times are reported in minutes.

The test instances were generated using a randomized model for the board with key parameters such as the number of components, component diversity, and number of spindles as inputs. Statistical analysis of the board designs released at a major electronics manufacturer over the last year (2008-2009) were used to determine the ranges of these parameters. Machine parameters such as velocities, on the other hand, were fixed based on ranges found most commonly in such configurations. The algorithm tuning parameters were chosen so that consistently the best solution quality is obtained across different test cases within a reasonable amount of computing time.

Solution quality and scalability of our heuristic procedure is discussed in [35].

4.1.1 Examined Factors, Their Levels, and Interaction Effects

The following factors were analyzed for sensitivity of design and configuration changes and enhacements to improving the assembly time for boards wih different parameters and sizes:

- No. of spindles (head capacity) = $N_S = \{5, 10, 15\}$
- No. of components = $N_C = \{50, 100, 200, 400\}$
- Relative component diversity = $p_{CD} = \{10\%, 40\%, 80\%\}$
- Head x, y velocities = $V_{xy} = \{300, 800, 2400\}$ mm/sec.
- Head rotation velocity = $V_r = \{20{,}000, 60{,}000, 180{,}000\}$ rpm
- Feeder movement velocity = $V_f = \{160, 640, 960\}$ mm/sec
- Component width = Randomly chosen between 8 to 32 mm
- Component distribution = Uniform over area of board

- Maximum board dimensions = 25 in. by 50 in.

- No. of feeder slots = 150,

where p_{CD} is defined as the percentage of the number of component types on a board relative to the total number of components.

A 3^3 full-factorial experimental design was carried out to examine the variation in assembly time based on the number of components, number of component types (i.e. component diversity), and the number of spindles (i.e. head capacity on the machine) at the aforementioned levels. Default settings for all other parameters were taken in order to study the effect of these three input parameters. Statistical tests (ANOVA) using the SAS software system [9] were performed in order to determine the main and interaction effects of these three parameters with respect to the assembly time.

The default setting consists of the following choices of values for the velocity parameters.

- Head x, y velocities = V_{xy} = 800 mm/sec

- Head rotation velocity = V_r = 60,000 rpm

- Feeder movement velocity = V_f = 160 mm/sec.

A second study was carried out to examine the sensitivity of assembly time to variation in three different key velocities, namely, the linear or translational velocity of the head over the gantry system, the rotational speed of the head itself, and the linear or translational velocity of feeder movement. Statistical tests (ANOVA) were carried out to determine the significance of the effect of changing the velocity parameters on assembly time over all of the 27 test cases generated as a result of the full-factorial design mentioned above.

4.2 Sensitivity and Machine Design-Change Analysis

For the default settings, the ANOVA table (shown in Table 1) indicates that all of the main and interaction effects are significant. The model summary and significant effects are shown in Tables 2 and 3. The number of components plays the most dominant role in determining assembly time, followed by the head capacity on the machine. The interaction effect of these two factors turns out to be very important as well. Component diversity does not play as major of a role as these two factors, even though it is significant in statistical terms.

Table 1: ANOVA table

Source	DF	Sum of Squares	Mean Square	F Value	Approx. Pr > F
Model	26	346,221.94	13,316.24	506.90	<.0001
Error	27	709.29	26.27		
Corrected Total	53	346,931.24			

Table 2: Model summary

R-Square	Coeff Var	Root MSE	Yield Mean
0.99	3.68	5.12	139.15

As the effects are all significant, we examine carefully the plots for the trends observed, and provide necessary interpretations. Figures 2, 3, and 4 demonstate the overall effect that the three factors, N_C, p_{CD}, and N_S have on the assembly time for various combinations of the three levels of each of the three factors. It is obvious from these figures that while it is clear that the number of components and the number of spindles play a very significant role in determining the assembly time of a board, the influence of the relative component diversity is not clear and needs more careful investigation. The observed trends correspond to common sense expectations of the assembly time being inversely proportional to the number of spindles on the machine and directly proportional to the number of components to be assembled on a given board.

Table 3: Significance of effects

Source	DF	Type I SS	Mean Square	F Value	Pr > F
N_C	2	237,180.22	118,590.11	4,514.27	<.0001
p_{CD}	2	2,349.79	1,174.90	44.72	<.0001
$N_C * p_{CD}$	4	493.25	123.31	4.69	0.0053
N_S	2	87,899.25	43,949.62	1,672.99	<.0001
$N_S * N_C$	4	15,376.14	3,844.04	146.33	<.0001
$N_S * p_{CD}$	4	1,573.32	393.33	14.97	<.0001
$N_S * N_C * p_{CD}$	8	1,349.95	168.74	6.42	<.0001

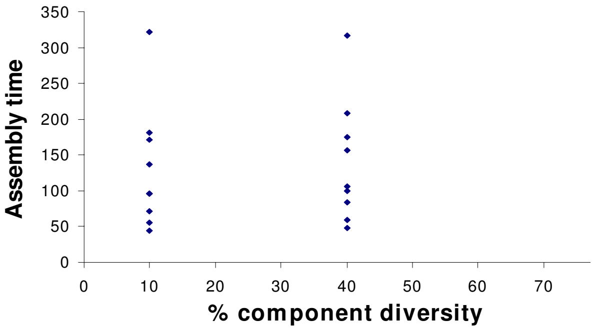

Figure 2: Overall effect of p_{CD}

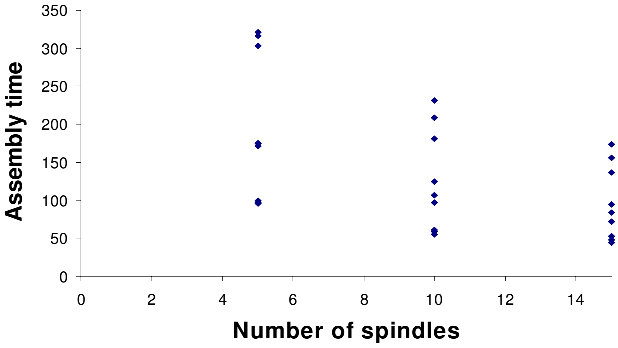

Figure 3: Overall effect of N_S

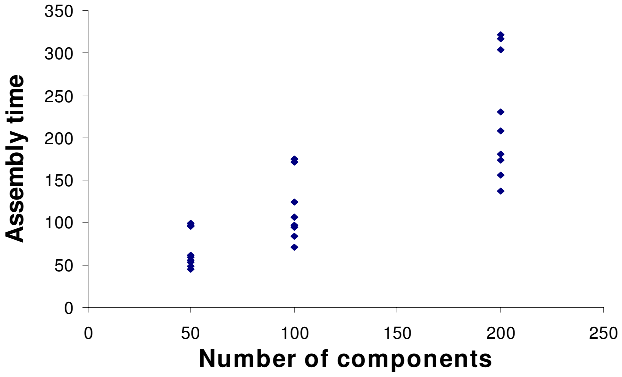

Figure 4: Overall effect of N_C

4.2.1 Effects of various board and machine size parameters

In this section we discuss the effects of the number of components, component diversity, and machine head capacity.

Effect of Number of Components We analyze the effect of increasing the number of components on a board of a given area on the assembly time. Observing Figures 5, 6, and 7, we realize that this effect is much more dominant for smaller head capacity machines regardless of the relative component diversity. This can be explained by the fact that smaller head capacity machines need to do many more back and forth movements between the board and the feeder magazine for the same amount of increase in the number of components on the board as compared to a larger capacity machine.

We also notice from Figures 11, 12, and 13 that the effect on assembly time of an increasing number of components on the board is more significant when the boards have a higher relative component diversity. This is especially true for larger head capacity machines. This is because for higher relative component diversity, the feeder locations are constrained to be more geographically spread out, leading to higher costs. Smaller head capacity machines benefit from opportunities for optimizing pick-ups from multiple feeder slots at several spatially diverse locations carrying the same component type, whereas larger head-capacity machines are unable to take advantage of such opportunities to the same extent due to expensive route maneuvers.

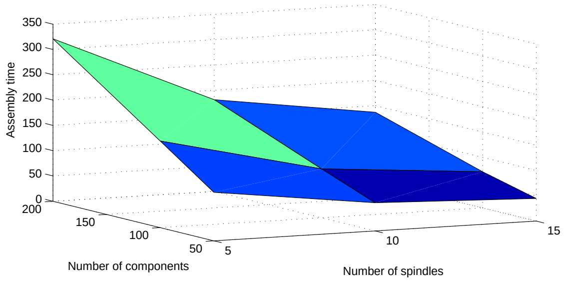

Figure 5: Effect of N_C and N_S for low p_{CD} boards

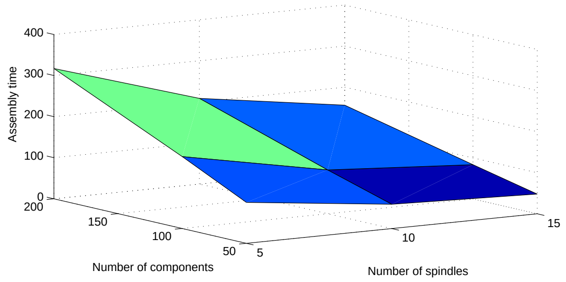

Figure 6: Effect of N_C and N_S for medium p_{CD} boards

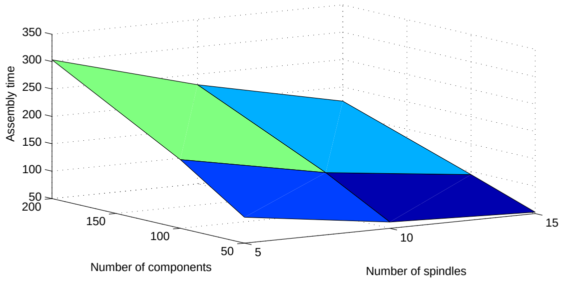

Figure 7: Effect of N_C and N_S for high p_{CD} boards

Effect of Number of Component Types From Figures 8 to 10 and 11 to 13, we observe that increasing relative component diversity increases assembly time in general with some exceptions. This is more pronounced in the case of large head capacity machines and exceptions typically occur in the case of small head capacity machines. This is explainable by the same arguments as above.

Effect of Number of Spindles (Head Capacity) We observe from Figures 8 to 10 and 5 to 7 that the assembly time decreases sharply with an increasing number of spindles on the head. The decrease is sharpest for larger boards as can be expected due to the number of additional tours saved. We also observe that low component diversity enhaces the effect.

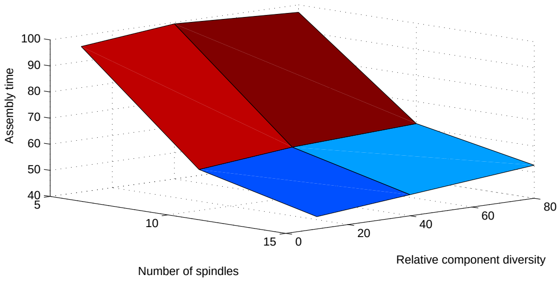

Figure 8: Effect of N_S and p_{CD} for small boards

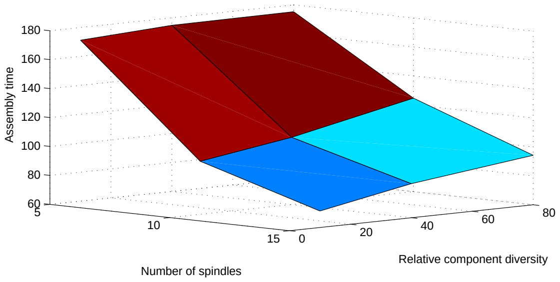

Figure 9: Effect of N_S and p_{CD} for medium boards

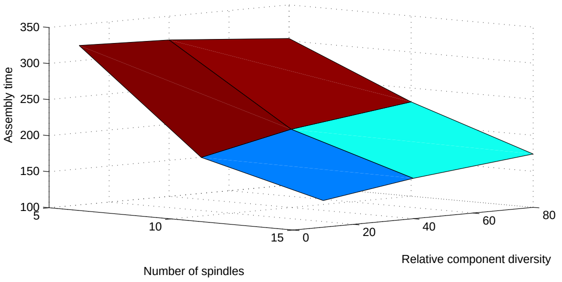

Figure 10: Effect of N_S and p_{CD} for large boards

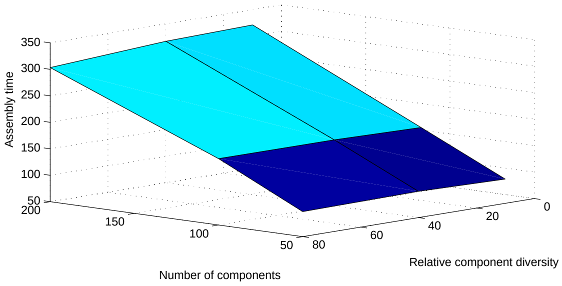

Figure 11: Effect of N_C and p_{CD} for small N_S machines

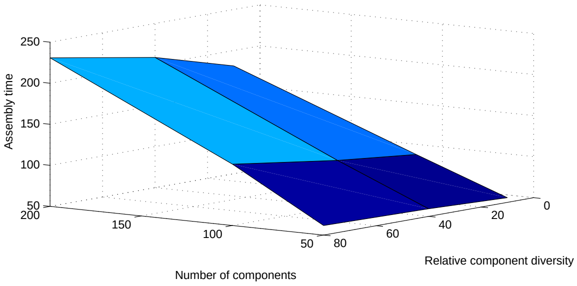

Figure 12: Effect of N_C and p_{CD} for medium N_S machines

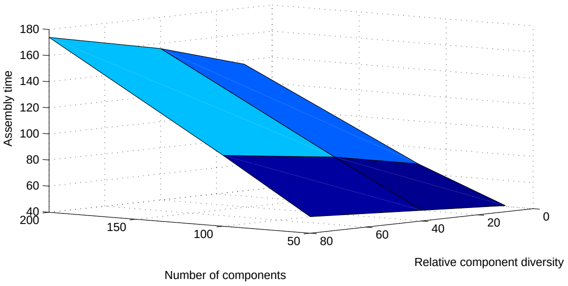

Figure 13: Effect of N_C and p_{CD} for large N_S machines

For the velocity change study, we observe again from the ANOVA table that the differences in assembly time caused due to changes in all of the three velocity settings are significant. A representative ANOVA table has been shown in Table 4 and a sample multiple means comparison table is Table 5. We observe now the trends caused by the changes in velocity settings for the 27 different scenarios.

Table 4: ANOVA table

Source	DF	Sum of Squares	Mean Square	F Value	Approx. Pr > F
Model	2	295.48	147.74	596.30	<.0001
Error	12	2.97	0.25		
Corrected Total	14	298.45			

Table 5: Multiple means comparison

Tukey Grouping	Mean	N	V_r
A	105.85	5	1,800
B	99.34	5	600
C	95.06	5	200

4.2.2 Effects of Velocities

In this section, we discuss the effects of the translational and rotational velocities of the machine components on assembly times.

Effect of Translational (Linear) Head Velocities Based on the results from our statistical tests, we found that increasing the translational (linear) head velocities has a strong dominant effect regardless of scenario or case type, i.e. no matter whether we are dealing with small or large boards of low or high diversity and on small or high head capacity machines. The linear X- and Y-gantry velocities play a major role in determining the assembly time. Typically, a 200% increase in velocity was seen to lead to a reduction of almost 50-60% in assembly time. This was also observed to be independent of the range of operating speed at which the machines could be run, i.e. no matter whether odd-form, tiny or specialized components (at low operating speeds), or regular components (at high operating speeds) were being placed, it is critical that the process be operated at the maximum possible linear velocity that technological constraints (such as accuracy, forces applied and subjected to, etc.) allow in order to gain maximum achievable efficiency in assembly time.

Effect of Rotational Head Velocity The effect of increasing the rotational head velocity was found to be most significant for machines that feature larger heads in line with the expectations of the performance of these systems, see Figure 14. However, it is interesting to note significantly high gains even for small head-capacity machines when high diversity boards are being processed. This was anticipated due to the increased head rotational motions as a result of optimization through bi-directional head rotations in order to more efficiently load and unload the head. Interestingly also, the relative gain is more or less indifferent to the number of components on the board, which means that no matter whether we are processing large or small boards, benefits from an increased rotational velocity are assured.

It was also observed that the effect of increasing head rotational velocity was not significant at lower operating ranges, but very important once a certain threshold velocity limit was crossed. This can be explained by the fact that the head undergoes a stepped index motion, creating thereby “free zones”, i.e. pockets of time when the head is still rotating even though the linear displacement required of the head has already been completed by the gantry. These are exploited in our optimization algorithm in order to achieve maximum throughput through the elimination of such sub-system idle time.

Effect of Feeder Movement Velocity We note that increasing the feeder movement velocity also helps reduce the assembly time significantly regardless of the operating range of the velocity. It is also noteworthy that this effect is more dominant for higher relative component diversity boards, see Figure 15. This can be

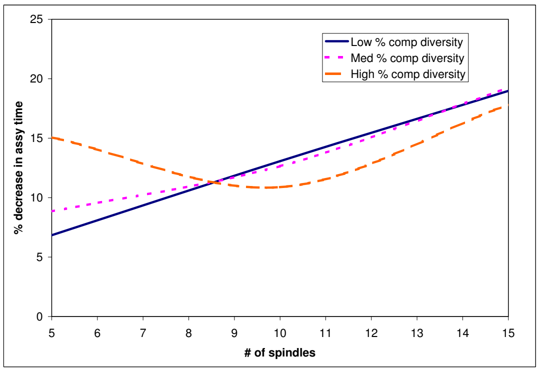

Figure 14: Effect of increasing V_r

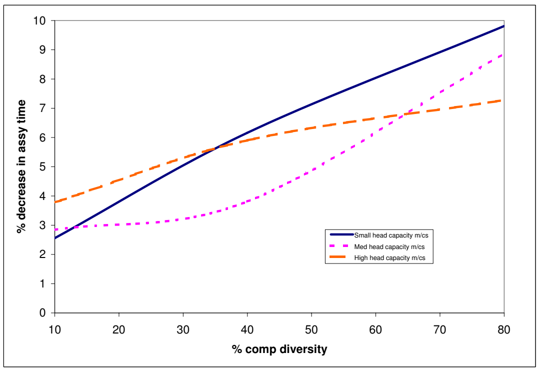

Figure 15: Effect of increasing V_f

explained by the fact that the faster feeder motion helps compensate for the spatially diverse slot locations by translating the magazine to a more desirable location before the start of a new route.

4.2.3 Effect of Incorporating Feeder Motion and Bi-directional, Multi-stepped Rotation Capability

Figure 16 shows that there is a considerable amount of the feeder magazine motion that is being utilized by our algorithm in generating a solution to the problem. This is indicative of the amount of flexibility that is being currently exploited, which was unutilized before and would have led to a higher cost solution. Figure 17 shows that there is also a considerable amount of spindle jumping (due to allowing multi-step and bidirectional rotations on the head) that is being utilized by the algorithm in generating the initial solution to the problem. This is again indicative of the amount of flexibility that is being currently exploited to generate a lower cost (assembly time) solution.

Interestingly, feeder magazine motion seems to play an important part only when the head capacity is low. For larger heads, spindle jumping dominates. This is quite reasonable because for larger heads, the maximum flexibility is obtained through spindle jumping whereas for smaller heads, it is obtained by the feeder magazine motion.

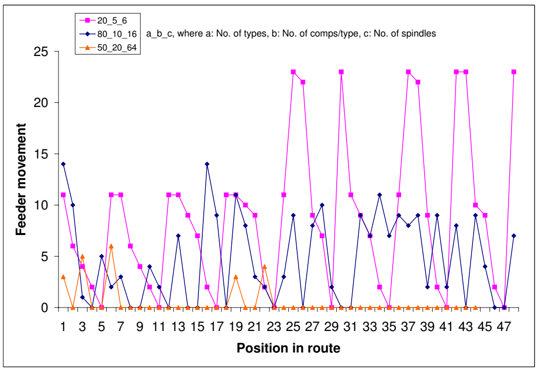

Figure 16: Effect of incorporating feeder motion capability

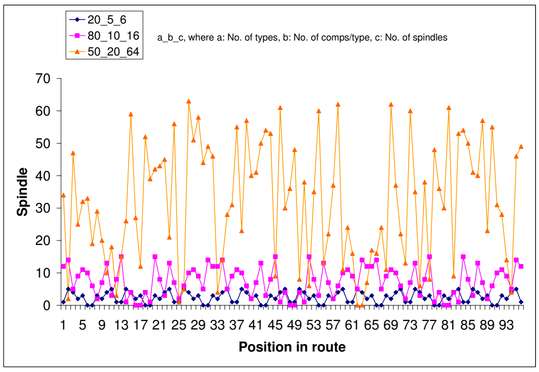

Figure 17: Effect of incorporating bi-directional and multi-stepped rotation capability

4.3 Development of a Regression Equation

Based on the experimentation carried out over typical parameter and problem size ranges found in the industry, we developed a regression equation incorporating the influence of the number of components, number of spindles, the feeder motion velocity, and the linear and rotational velocities of the head in order to be able to provide a mechanism for estimating the assembly time given a machine and board configuration. The regression reads

$$Y = p_0 + p_1 * X_1 + p_2 * X_2 + \frac{p_3}{X_3} + \frac{p_4}{X_4} + \frac{p_5}{X_5} + p_6 * X_6. \tag{11}$$

In (11), Y is the predicted variable, namely, the expected assembly time as a function of the predictor variables $X_1, ..., X_6$, which refer to the number of components, the number of spindles, the component diversity, the translational velocity, the feeder motion velocity, and the rotational velocity. The corresponding parameters $p_0, ..., p_6$ are used to fit the curve to the experimental data and for validating the regression model. Table 7 lists the regression coefficients.

This equation was validated over collected data and yields a good fit with an R^2 value of 0.82. Table 6 shows a summary of the fitted model. The model provides a good explanation of the observed data and contains terms that logically make sense in light of the physical understanding of the system being modeled, e.g., the time dereases inversely with respect to the number of spindles used on the machine and the translational velocity, and is proportional to the number of components on the board.

Table 6: Regression model summary

Source	Degrees of freedom	Sum of Squares	Mean Square	F Value	Approx. Pr > F
Model	6	2,328,282	388,047	131.63	<.0001
Error	182	536,554	2,948.1		
Corrected Total	188	2,864,836			

Table 7: Regression model parameter estimates

Parameter	Estimate	Approx Std Error	Approx 95% lower confidence interval	Approx 95% upper confidence interval
p_0	-238.7	17.8694	-274.0	-203.5
p_1	0.2566	0.1377	-0.0152	0.5284
p_2	1.1219	0.0633	0.9970	1.2469
p_3	829.1	69.7101	691.6	966.7
p_4	85,358.7	4,821.5	75,845.3	94,872.1
p_5	2,879.3	1,891.6	-853.1	6,611.7
p_6	0.0119	0.00864	-0.00516	0.0289

5 Conclusions

This work makes a valuable contribution to the field of PCB manufacturing through the use of sophisticated large-scale optimization techniques. It is a unique study on utilizing advanced modeling techniques and intelligent algorithms as a tool to aid in design-change analysis for manufacturers of such assembly equipment. It also provides board assemblers and machine manufacturers insight into customizing their solutions to their specific industry requirements. It is also valuable in providing a missing link to a DFX system and can be used to provide accurate feedback on estimates of assemblability.

In summary, our study shows that for boards with larger numbers of components, we need more time to assemble them. The effect is especially strongly dominant on smaller capacity machines regardless of relative component diversity. However, for denser relative component diversity, we observe a stronger increase on larger capacity machines. On smaller capacity machines, the trend is somewhat reversed. Adding head capacity is shown to be a benevolent change for all scenarios, but especially useful for boards with a high number of components to be inserted.

In case of the machine velocities, we observe that the linear or translational velocities of the gantry play a very significant role on the assembly time obtainable by the machine. However, the potentially high costs for such increases must be weighed against the benefits for a given industrial application setting. Increasing the rotational head velocity was found to be more beneficial for larger capacity machines, but again can be expected to be more difficult due to higher inertia and bulkiness. However, the gains are significant even on smaller capacity machines, especially in the case of high relative component diversity boards. It is also noteworthy that the gains are consistent regardless of the number of components. The feeder motion velocity is also observed to reduce the assembly time. This is true even more so for higher relative diversity boards.

The effects of uniquely incorporating feeder motion and allowing spindle jumping are demonstrated to be significant and apparent in the optimization of the assembly system operation.

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