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A Heuristic Algorithm for Two-Dimensional Rectangular Packing Problems

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Abstract

Two-dimensional rectangular packing problems occur frequently in various industries, such as paper, wood, glass, and steel. This paper focuses on the two-dimensional open dimension rectangular packing problem with the intention of placing a set of small rectangular items without overlapping into a large rectangle of minimal area. This problem is known as a NP-hard problem and conventional integer programming techniques may take exponential time to deterministically solve the problem to global optimality. This paper proposes an efficient heuristic algorithm to obtain a feasible solution to two-dimensional open dimension rectangular packing problems. Compared with the deterministic methods, the reduced solution time enhances the applicability of the proposed heuristic method.

Keywords: Two-dimensional rectangular packing, open dimension problems, heuristic algorithm

1. Introduction

The rectangular packing problem discussed in this study places a set of small rectangular items without overlapping into a large rectangle in such a way that the area of the enveloping rectangle is minimized. This problem arises frequently in different raw material manufacturing industries. In manufacturing industries, material utilization is an important issue. A high level of material utilization is of particular interest to mass-production manufacturing industries and small improvements in the layout can result in large savings in raw materials, significantly reducing production costs. In addition to manufacturing industries, this general problem has several practical applications, for instance, allocating the location of departments in the minimum area, and allocating all incoming ships to berths with the minimum completion time. Lodi et al. (2002a, 2002b) provided a complete survey of the applications, theoretical results and algorithmic advances in two-dimensional packing problems during 2000. Wäscher et al. (2007) categorized the literature on cutting and packing problems from the years between 1995 and 2004. According to the Wäscher et al. (2007) classification, the rectangular packing problem addressed in this study belongs to the category of two-dimensional open dimension problems.

Many approaches to two-dimensional rectangular packing problems have been proposed and can be classified into deterministic and heuristic. Although the deterministic method can guarantee to obtain a global optimum for the two-dimensional rectangular packing problem, the NP-hard characteristic of the problem implies that the solution time required by the deterministic optimization techniques may increase exponentially to gain the global optimal solution. Due to the complexity of the

problems, most research on these topics is based on heuristic methods. Jakobs (1996) applied genetic algorithms to the two-dimensional packing problem and employed the bottom-left strategy to locate the small rectangles. Hopper and Turton (2001) combined a meta-heuristic algorithm (genetic algorithm, simulated annealing, and naïve evolution) and a heuristic packing routine to place the small items on the large rectangle. Leung et al. (2003) applied a mixed, simulated annealing-genetic algorithm to two-dimensional orthogonal packing problems. Lin (2006) proposed a genetic algorithm using a novel random packing process and an encoding scheme for solving two-dimensional assortment problems. Gonçalves (2007) proposed an algorithm hybridizing a placement procedure with a genetic algorithm based on random keys. Wei et al. (2011) proposed a greedy heuristic method that places each rectangle according to an evaluation function involving several components of the nature of the two-dimensional packing problems. Leung et al. (2012) applied a constructive heuristic algorithm, based on the fitness strategy, to generate a solution for a rectangular knapsack packing problem. By combining the greedy strategy and a simulated annealing algorithm, a hybrid heuristic algorithm was proposed to find an improved solution. Zhou et al. (2012) adopted the approach of bottom left corner occupation as the placement strategy, and then developed a hybrid framework combining a genetic algorithm and a tabu search to solve a two-dimensional bin packing problem. Blum and Schmid (2013) proposed an algorithm to tackle a 2D bin packing problem using an evolutionary algorithm making heavy use of a randomized one-pass heuristic for construction solutions. Kierkosz and Luczak (2014) presented a hybrid evolutionary algorithm for a two-dimensional non-guillotine packing problem. A tree search improvement procedure was then used with an initial solution obtained from the best solution obtained by the evolutionary algorithm. Lu et al. (2013) proposed an integrated algorithm incorporating a genetic algorithm, a corner arrangement method, and a production plan model to solve the cutting stock problems in the TFT-LCD industry. The heuristic algorithms mentioned above have been developed based on different methodologies and presented to solve two-dimensional rectangular packing problems. Although the heuristic methods cannot guarantee to obtain a global optimum, they have the advantage of easy implementation and offer better potential for complex problems. Table 1 summarizes the characteristics of different heuristic approaches as reviewed previously.

Most of the heuristic methods investigated the two-dimensional rectangular packing problem whereby the extension of the enveloping rectangle is fixed in both dimensions. This study proposes a heuristic algorithm for two-dimensional packing problems where both the length and the width are variable. The concept uses the remaining space of the existing enveloping rectangle, and balances the length and the width of the enveloping rectangle, if expansion is necessary, to enable the insertion of a new small rectangle. Section 2 describes the proposed heuristic algorithm. Section 3 demonstrates the allocation process of the proposed heuristic algorithm using numerical examples. Finally, several concluding remarks are discussed in Section 4.

Table 1: Characteristics of Different Heuristic Approaches

Approach	Methodology	Characteristics
Jakobs (1996)	Genetic algorithm	Place a set of polygons on a rectangular board with minimal height.
Hopper and Turton (2001)	Genetic algorithm, simulated annealing, naïve evolution.	Pack a set of rectangles onto a rectangular object with minimal used object space.
Leung et al. (2003)	Genetic algorithm, mixed simulated annealing-genetic algorithm	Pack rectangular pieces of predetermined sizes onto a large rectangular plate with minimal unused area (trim loss).
Lin (2006)	Genetic algorithm using a problem-specific encoding scheme and a novel packing process	Place a set of rectangles within another rectangle with a minimal area.
Gonçalves (2007)	Genetic algorithm	Place a set of small rectangles onto a larger stock rectangle with minimal trim loss.
Wei et al. (2011)	Greedy heuristic method	Pack rectangles of predetermined sizes into a large rectangular plate with the maximal packed area.
Lu et al. (2013)	Genetic algorithm	Find all possible cutting patterns for the cutting of various TFT-LCD plates of predetermined sizes from a glass substrate with minimal trim-loss.

2. Proposed Heuristic Method

The concept of the proposed algorithm is to balance the length and the width of the enveloping rectangle if expansion is necessary to enable the insertion of a new small rectangular item. Table 2 lists several terminologies used in the proposed heuristic algorithm.

The following describes the detailed steps of the proposed algorithm for two-dimensional open dimension rectangular packing problems.

Step 1: Sort the small rectangles using the sum of their length and width to obtain an ordered set {*s_rectangle*$_1$, *s_rectangle*$_2$,…, *s_rectangle*$_n$ } where $(p_1+q_1)\geq(p_2+q_2)\geq\cdots\geq(p_n+q_n)$.

Table 2: Terminologies of the Proposed Algorithm

Terminology	Meaning
n	The number of small rectangles that are required to be packed
$[p_i, q_i]$	The length (long side) p_i and width (short side) q_i of a small rectangle i.
$R_i=[R_{ix}, R_{iy}, s_i]$	The bottom-left coordinate (R_{ix}, R_{iy}) of a small rectangle i. s_i=0 if the short side q_i is parallel to the *x*-axis; otherwise, s_i=1 if the short side q_i is parallel to the *y*-axis.
J	The number of the remaining rectangular spaces.
$C_j=[C_{jx}, C_{jy}, C_{jw}, C_{jh}]$	The bottom-left coordinate (C_{jx}, C_{jy}) of the remaining rectangular space j, the length C_{jw} of the side parallel to the *x*-axis, and the length C_{jh} of the side parallel to the *y*-axis.
$M=[m_x, m_y]$	The top-right coordinate (m_x, m_y) of the enveloping rectangle.

Step 2: Let $i=1$. Rectangle i is put with the bottom-left corner aligned with the origin and the short side parallel to the *x*-axis. $R_i=[R_{ix}, R_{iy}, s_i]=[0,0,0]$, $M=[m_x, m_y]=[q_i, p_i]$. Let $J=0$.

Step 3: Let $i=i+1$. If $i>n$, then go to Step 7. If $J=0$, then go to Step 4; otherwise, let $j=1$ and go to Step 5.

Step 4: If $m_x\leq m_y$, then rectangle i is inserted with the short side parallel to

the x-axis. $R_i = [R_{ix}, R_{iy}, s_i] = [m_x, 0, 0]$. Determine the required enveloping rectangle and the remaining rectangular spaces according to the following three conditions:

If $p_i < m_y$, then let $J = J + 1$, $C_J = [C_{Jx}, C_{Jy}, C_{Jw}, C_{Jh}] = [m_x, p_i, q_i, m_y - p_i]$, $M = [m_x, m_y] = [m_x + q_i, m_y]$;

If $p_i = m_y$, then $M = [m_x, m_y] = [m_x + q_i, m_y]$;

If $p_i > m_y$, then let $J = J + 1$, $C_J = [C_{Jx}, C_{Jy}, C_{Jw}, C_{Jh}] = [0, m_y, m_x, p_i - m_y]$, $M = [m_x, m_y] = [m_x + q_i, p_i]$.

If $m_x > m_y$, then rectangle i is inserted with the short side parallel to the y-axis. $R_i = [R_{ix}, R_{iy}, s_i] = [0, m_y, 1]$. Determine the required enveloping rectangle and the remaining rectangular spaces according to the following three conditions:

If $p_i < m_x$, then let $J = J + 1$, $C_J = [C_{Jx}, C_{Jy}, C_{Jw}, C_{Jh}] = [p_i, m_y, m_x - p_i, q_i]$, $M = [m_x, m_y] = [m_x, m_y + q_i]$;

If $p_i = m_x$, then $M = [m_x, m_y] = [m_x, m_y + q_i]$;

If $p_i > m_x$, then let $J = J + 1$, $C_J = [C_{Jx}, C_{Jy}, C_{Jw}, C_{Jh}] = [m_x, 0, p_i - m_x, m_y]$, $M = [m_x, m_y] = [p_i, m_y + q_i]$.

Go to Step 6.

Step 5: If $q_i \le C_{jw}$, then $M = [m_x, m_y]$, $R_i = [R_{ix}, R_{iy}, s_i] = [C_{jx}, C_{jy}, 0]$. Determine the remaining rectangular spaces according to the following four conditions:

If $q_i < C_{jw}$ and $p_i < C_{jh}$, then $C_j = [C_{jx}, C_{jy}, C_{jw}, C_{jh}] = [C_{jx}, C_{jy} + p_i, C_{jw}, C_{jh} - p_i]$, let $J = J + 1$, $C_J = [C_{Jx}, C_{Jy}, C_{Jw}, C_{Jh}] = [C_{jx} + q_i, C_{jy}, C_{jw} - q_i, p_i]$;

If $q_i < C_{jw}$ and $p_i = C_{jh}$, then $C_j = [C_{jx}, C_{jy}, C_{jw}, C_{jh}] = [C_{jx} + q_i, C_{jy}, C_{jw} - q_i, C_{jh}]$;

If $q_i = C_{jw}$ and $p_i < C_{jh}$, then $C_j = [C_{jx}, C_{jy}, C_{jw}, C_{jh}] = [C_{jx}, C_{jy} + p_i, C_{jw}, C_{jh} - p_i]$;

If $q_i = C_{jw}$ and $p_i = C_{jh}$, then $C_j = [C_{jx}, C_{jy}, C_{jw}, C_{jh}] = [0,0,0,0]$.

Go to Step 6.

If $q_i \le C_{jh}$, then $M = [m_x, m_y]$ and $R_i = [R_{ix}, R_{iy}, s_i] = [C_{jx}, C_{jy}, 1]$. Determine the remaining rectangular spaces according to the following four conditions:

If $q_i < C_{jh}$ and $p_i < C_{jw}$, then $C_j = [C_{jx}, C_{jy}, C_{jw}, C_{jh}] = [C_{jx}, C_{jy} + q_i, C_{jw}, C_{jh} - q_i]$, let $J = J + 1$, $C_J = [C_{Jx}, C_{Jy}, C_{Jw}, C_{Jh}] = [C_{jx} + p_i, C_{jy}, C_{jw} - p_i, q_i]$;

If $q_i < C_{jh}$ and $p_i = C_{jw}$, then $C_j = [C_{jx}, C_{jy}, C_{jw}, C_{jh}] = [C_{jx}, C_{jy} + q_i, C_{jw}, C_{jh} - q_i]$;

If $q_i = C_{jh}$ and $p_i < C_{jw}$, then $C_j = [C_{jx}, C_{jy}, C_{jw}, C_{jh}] = [C_{jx} + p_i, C_{jy}, C_{jw} - p_i, C_{jh}]$;

If $q_i = C_{jh}$ and $p_i = C_{jw}$, then $C_j = [C_{jx}, C_{jy}, C_{jw}, C_{jh}] = [0,0,0,0]$.

Go to Step 6.

Let $j = j + 1$. If $j \le J$, then reiterate Step 5; otherwise, go to Step 4.

Step 6: Remove the remaining rectangular space that is fully filled with the small rectangles. Re-sort the remaining rectangular spaces by the area of each remaining rectangular space. Go to Step 3.

Step 7: Output $M = [m_x, m_y]$, $R_i = [R_{ix}, R_{iy}, s_i]$, $i = 1, 2, \ldots, n$.

3. Numerical Examples

Herein is an example with eight small rectangles required to be allocated without overlapping into a large rectangle to demonstrate the placement process of the proposed heuristic algorithm. The size of the eight small rectangles are (50,15), (38,15), (35,17), (30,11), (26,20), (25,15), (24,12), (18,4), respectively. Figures 1 to 8 illustrate the allocation of the eight small rectangles sequentially according to the proposed algorithm.

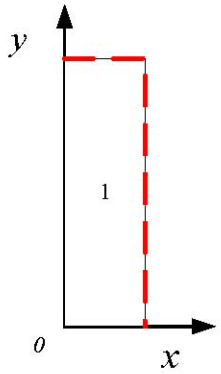

Figure 1: The Placement of Rectangle 1

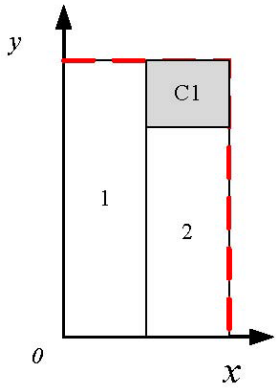

Figure 2: The Placement of Rectangle 2 and the Remaining Spaces

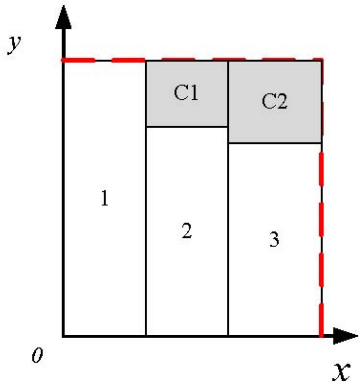

Figure 3: The Placement of Rectangle 3 and the Remaining Spaces

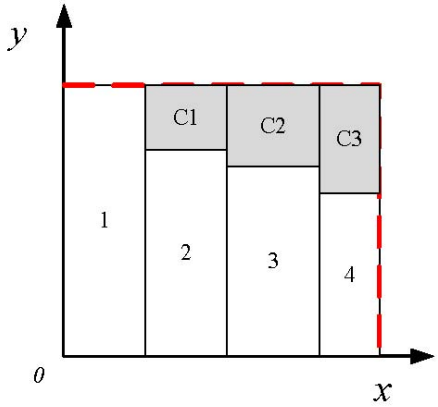

Figure 4: The Placement of Rectangle 4 and the Remaining Spaces

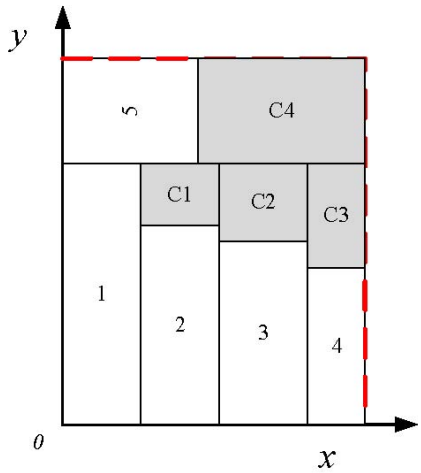

Figure 5: The Placement of Rectangle 5 and the Remaining Spaces

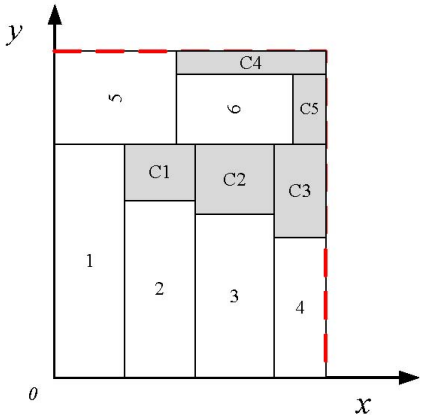

Figure 6: The Placement of Rectangle 6 and the Remaining Spaces

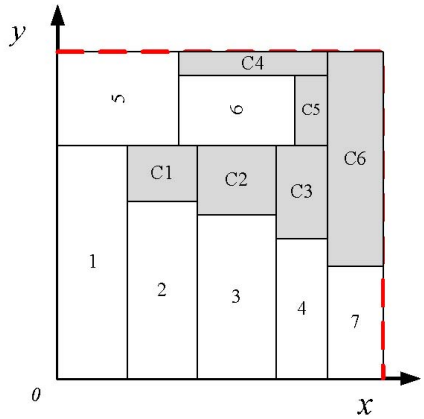

Figure 7: The Placement of Rectangle 7 and the Remaining Spaces

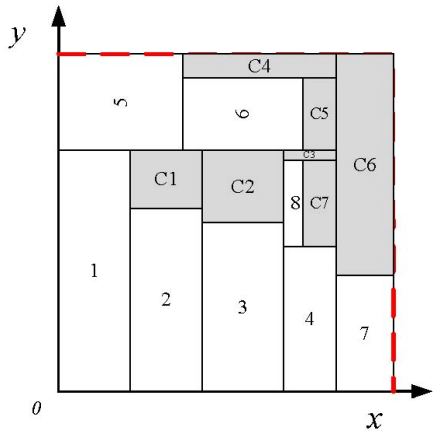

Figure 8: The Placement of Rectangle 8 and the Remaining Spaces

Tsai et al. (2013) proposed a deterministic approach to solve two-dimensional rectangular packing problems. Their method utilized a simple heuristic method to find the feasible area of the enveloping rectangle as follows:

$$\min\left((\sum_{i=1}^{n} p_i)(\max_i q_i),(\sum_{i=1}^{n} q_i)(\max_i p_i)\right)$$

To show the solution quality of the proposed algorithm, four problems (Problems 1 to 4) drawn from Tsai et al. (2013) are solved to compare the above heuristic method with the proposed algorithm. So as to treat the problem with additional small rectangles, problems 5 and 6 are extensions of problem 4. The sizes of the rectangles to be allocated in each problem are listed as follows:

Problem 1 with 5 rectangles: (33,10), (30,11), (25,15), (18,14), (18,10).

Problem 2 with 6 rectangles: (40,18), (36,12), (32,24), (25,20), (20,16), (20,13).

Problem 3 with 7 rectangles: (45,10), (40,18), (32,24), (25,5), (21,12), (20,16), (13,5).

Problem 4 with 8 rectangles: (50,15), (38,15), (35,17), (30,11), (26,20), (25,15), (24,12), (18,4).

Problem 5 with 9 rectangles: (50,15), (38,15), (35,17), (30,11), (26,20), (25,15), (24,12), (18,4), (15,12).

Problem 6 with 10 rectangles: (50,15), (38,15), (35,17), (30,11), (26,20), (25,15), (24,12), (18,4), (15,12), (10,8).

Table 3 lists the area of the enveloping rectangle solved by the heuristic method and the proposed algorithm. The proposed algorithm is able to obtain a smaller enveloping rectangle than the heuristic method in all problems except Problem 3. Additionally, the difference is more significant as the number of small rectangles increases.

Table 3: Comparison of the Area of the Enveloping Rectangle

Problem	Heuristic Method	Proposed Algorithm
Problem 1	1860	1692
Problem 2	4120	4020
Problem 3	4050	4402
Problem 4	4920	4900
Problem 5	5220	4900
Problem 6	5420	4900

4. Conclusions and Future Work

This study proposes a heuristic algorithm to solve two-dimensional open dimension rectangular packing problems. Since the NP-hard characteristic of the two-dimensional open dimension rectangular packing problem means the solution time required by the deterministic optimization techniques increases significantly, developing an efficient heuristic algorithm is more appropriate for treating large-scale problems in real applications. In this study, we propose a novel algorithm that balances the length and the width of the enveloping rectangle when allocating placing a set of

small rectangular items without overlapping.

In the future, the proposed algorithm can be modified by considering the combination of the remaining spaces. Since the area of the remaining space is the area of the enveloping rectangle subtracted from the total area of the given set of rectangular pieces, the minimal area of the enveloping rectangle results in the minimal area of the remaining spaces. However, the small rectangular items should be assigned across adjacent remaining spaces in the placement process. Additionally, the impact of placing the small rectangles with different sequences can be investigated for a possible improvement in the proposed algorithm. Finally, the solution obtained from the proposed algorithm may be further integrated into the deterministic optimization technique for two-dimensional open dimension rectangular packing problems. In the deterministic mathematical programming model, adding an inequality constraint that forces the minimal area of the enveloping rectangle to be less than the area of the enveloping rectangle found by the proposed algorithm may reduce the solution time of the deterministic model. Further experiments should be conducted to verify the effects of integrating the results from the proposed method into the deterministic technique so as to consider the solution efficiency and solution quality simultaneously.

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Optimal Multi-Degree Cyclic Scheduling of Re-entrant Electroplating Lines Including Multiple Hoists without Overlapping

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Abstract

Automated electroplating lines are typical integrated manufacturing systems consisting of processing machines and material handling devices, i.e. tanks and hoists respectively. Printed circuit boards, usually known as parts, are produced in a number of tanks following the given process flow. Reentrance will occur when a part is performed in the same tanks more than once due to the process requirement. Since parts are transported between tanks by hoists, the hoists usually create bottlenecks. Multiple hoists, instead of a single hoist, are largely used to balance the line and improve the throughput. Since hoists move along the same overhead track, they cannot cross over each other. This paper considers multi-hoist scheduling problems during the reentrance of automated electroplating lines. The objective is to maximize the throughput of the line, the equivalent to minimizing the cycle time, by obtaining optimal schedules. In order to tackle the collisions between the multiple hoists, the principle of non-overlapping is applied. Since identical parts are commonly arranged to be produced at the same time in a line during a period, cyclic scheduling is applied to deal with the scheduling problems due to easy implementation. This paper considers multi-degree cycles instead of a simple cycle, i.e. 1-degree cycles. In summary, this paper deals with the scheduling problems in a much more complicated scenario, where reentrance, multiple hoists and multi-degree cycles are included. To our knowledge, these complications have not been dealt with before. To obtain optimal schedules, the operations in the lines are analyzed in detail. Based on this, a mixed integer linear programming model is formulated to solve the scheduling problems in this scenario. This is the main contribution of this work. Finally, a numerical example, solved using the commercial software ILOG CPLEX, is applied to illustrate the model proposed and to show the benefits of multi-degree cycles compared with simple cycles.

Keywords: Multi-hoist scheduling problem, multi-degree cycles, reentrant electroplating lines, mixed integer linear programming, processing time window

1. Introduction

A typical integrated manufacturing system is the automated electroplating line for printed circuit board (PCBs) production. PCBs are knows as parts. A number of stages (i.e. stage 1, stage 2, …, stage n) are required to complete the parts in the lines, and the process stages are performed in related tanks, which are arranged in a line from left to right. A special condition in automated electroplating lines is where there are no buffers between the tanks. When a part completes its processing in a tank for a specific stage, the part should be picked up and transported to a tank for the next stage. Parts are transported between the tanks by hoists. Therefore, a part is

either being produced in a tank or held by a hoist for transportation.

Moreover, each tank can produce, at most, one part at a time, known as tank capacity constraints. Similarly, each hoist can only hold, at most, one part at a time. Hence, a hoist should be available when the hoist is scheduled to transport a part, known as hoist availability constraints. Since all parts are transported by a shared hoist(s), the hoists usually become the bottleneck resource. Therefore, more than one hoist is generally applied to the lines so as to balance the production and improve the throughput. In multi-hoist lines, these multiple hoists share and move on the same overhead track. Hoists cannot cross over each other. Therefore, more constraints are required to avoid any conflicts between the hoists. In addition, the practical processing times of the parts are within given time ranges, known as time window constraints. There are other scenarios relevant to the processing times. When the upper bound is infinite, time window constraints are not required. When, the upper bound is exactly equal to the lower bound, it is known as a no-wait scenario. These two scenarios can be viewed as special cases of scenarios with time window constraints.

Moreover, there are other more complicated lines. For instance, some tanks may need to be visited more than once in accordance with the process flow, i.e. the same tanks perform more than one stage. This is also known as reentrance. This paper considers multi-hoist lines with reentrance.

In practice, the production flow usually arranges identical parts to be produced during a specific period. Cyclic scheduling is commonly used due to its easy implementation. The time duration of a cycle is called the cycle time. The degree is used to describe the number of parts that are inserted and finished during a cycle. 1-degree cycles are also known as simple cycles. One part is inserted and is completed during a simple cycle. A K-degree cycle (i.e. multi-degree cycle) produces K parts. In order to compare a K-degree cycle with a simple cycle, the mean cycle time is defined and calculated based on dividing the cycle time of the K-degree cycle by K. The mean cycle time is the (mean/average) time required to produce a part. For a given degree, the objective is to obtain scheduling that minimizes the cycle time, i.e. maximizes the throughput.

Since hoists are applied in automated electroplating lines, scheduling problems in these lines are known as the hoist scheduling problem (Philips and Unger, 1976; Manier and Bloch, 2003; Lopez and Roubellat, 2008).

This paper deals with the hoist scheduling problem by considering multiple hoists and reentrance together. Time window constraints are also considered. In addition, multi-degree cycles are analyzed. To our knowledge, this is the first work focusing on this special scenario (i.e. multi-hoist, reentrance, and multi-degree cycles). The objective is to obtain schedules that will minimize the (mean) cycle time. To achieve this, the problem is modelled based on the mixed integer linear programming approach. Detailed operations of the lines are also analyzed. To deal with this complicated problem, a revised scenario without reentrance was analyzed first. This is the necessary condition of the complicated scenario. Then, the reentrance was analyzed. The problem is modelled by an MILP formulation. An instance of the model is solved using ILOG CPLEX.

The remainder of this paper is organized as follows. Section 2 reviews related work on the hoist scheduling problem. Section 3 describes the special scheduling problem dealt with in this paper. Corresponding notations are listed. Section 4 compares the scheduling problem considered in this paper with the revised scenario, where reentrance is relaxed. The revised scenario has been dealt with by Li and Fung (2013a). For completeness, constraints of the revised scenario are formulated based on Li and Fung's (2013a) work. Section 5 analyzes operations concerning

reentrance and develops corresponding constraints. In section 6, an example is used to illustrate the model proposed. Finally, this paper is concluded in section 7.

2. Literature Review

Philips and Unger (1976) proposed the first mathematical programming model (i.e. a mixed integer linear programming model) for the hoist scheduling problem. Shapiro and Nuttle (1988) developed a branch and bound approach to deal with the same problem. Since then, mathematical programming approaches, e.g. mixed integer linear programming (MILP) and branch and bound (B&B), have been increasingly applied to solve complicated scheduling problems in diverse scenarios.

Liu et al. (2002) proposed a comprehensive mixed integer programming model for the complicated lines with reentrance and parallel tanks in a simple cycle. Steiner and Xue (2005) reviewed scheduling problems in reentrant robotic cells, which have the same configuration as re-entrant electroplating lines. As for multi-hoist lines, Leung et al. (2004) developed the first mixed integer linear programming model in simple cycles. Middle-size instances (e.g. less than 20 tanks) can be solved using Leung et al.'s model with reasonable computational times. For large-size instances (e.g. 24 tanks), Zhou and Li (2009) proposed a new mixed integer linear programming model based on the no overlapping rule. In this way, the hoist assignment is determined first and final schedules are obtained using the MILP model. In fact, schedules with the no overlapping rule may not achieve global optimal solutions, but computational times are saved, i.e. large-size instances can be solved in reasonable time. Che et al. (2014) developed the MILP model to improve Leung et al.'s model. Jiang and Liu (2014) proposed a new MILP model and a B&B approach so as to deal with multi-hoist lines in simple cycles.

As for multi-degree cycles, Zhou et al. (2012) formulated the first MILP model for basic lines, i.e. the lines considered by Phillips and Unger (1976). Li and Fung (2014) developed a new MILP model for basic lines in multi-degree cycles. Then, Li and Fung (2014) extended their model to lines with reentrance. There is only one single hoist. For multi-hoist lines, Li and Fung (2013a) formulated the MILP model based on the no overlapping rule in multi-degree cycles. General multi-hoist lines were dealt with in Li and Fung (2013b) using the MILP model. In Li and Fung (2013a, 2013b), reentrance (or parallel tanks), were not considered with the multiple hoists at the same time. MILP models were also applied to deal with scenarios with multiple part types (Lei et al. 2014; El Amraoui et al. 2013b).

Heuristics and evolution algorithms have also been used to deal with the hoist scheduling problem. Zhou and Li (2008) proposed a heuristic algorithm to deal with two-hoist lines in simple cycles. El Amraoui et al. (2013a) developed a genetic algorithm for single-hoist scheduling problems with time window constraints. In addition, no-wait scenarios were solved in polynomial time (Che et al. 2002, Che et al. 2009, and Che et al. 2012).

Consequently, this paper deals with the multi-degree hoist scheduling problem and considers multiple hoists and reentrance together using mathematical programming (i.e. mixed integer linear programming). It extends Li and Fung's work (2013a, 2013b) which only deals with multi-degree hoist scheduling with multiple hoists without the occurrence of reentrance. Moreover, it is more complicated when compared with EI Amraoui's (2013a, 2013b) work that only deals with single hoist scheduling problems.

3. Problem Description and Notation

This paper deals with the multi-hoist line with reentrance, as shown in Figure 1. There are n stages indexed as $S_1, S_2, ..., S_n$ performed in n - 1 tanks numbered as 1, 2, ..., n - 1 from left to right. The indexes of the tanks increase from left to right. Except

for the reentrant stage, a later stage is performed in a tank with a larger index, i.e. a tank that is further to the left. Moreover, stages p-1 and p+1 are both performed in tank p-1 and stage p+1 is the reentrant stage. H hoists transport parts between tanks to complete the corresponding stages. S_{p-1} and S_{p+1} use the same tank p - 1. To avoid conflict between the hoists, the no overlapping rule is applied in this paper, i.e. hoist h picks up parts processed in stage $l_{h-1}+1$ to stage l_h. Moreover, it is assumed that tank p-1 and tank p are aligned with the same hoist.

In order to express the scheduling problem exactly and formulate the MILP model, the parameters and decision variables are listed as follows. These notations are adopted from previous work (Phillips & Unger, 1976; Liu et al., 2002; Leung et al., 2004; Zhou & Li, 2009; Li & Fung 2013a, 2013b, 2014).

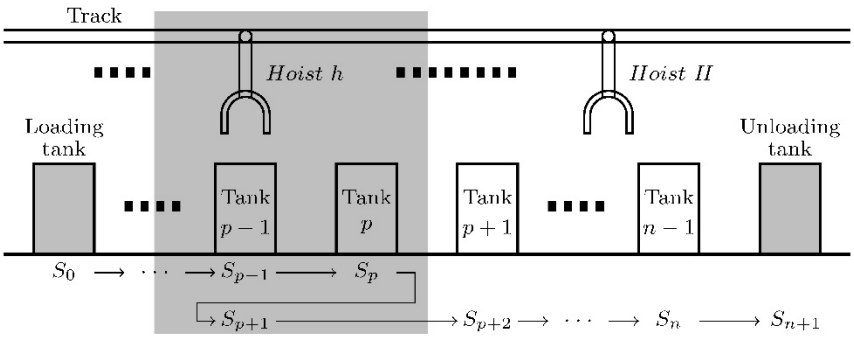

Figure 1: A Multi-hoist Line with Reentrance

3.1 Given Parameters

n: the number of tanks. The tanks are labeled 1; 2; …; n; the loading tank is numbered as 0 and the unloading tank is numbered as n + 1;

p: the stage p - 1 and stage p + 1 use the same tank p - 1;

H: the number of hoists;

K: the number of parts entering and exiting the line within a cycle, i.e. the degree of a cycle;

move (k,i): the hoist move when transporting a part from stage i to stage i+1 for the k-th time;

l_h: the parameter indicating the hoist assignment. Hoist 1 is responsible for moves from 0 to l_1 (to move out of tank 0 to l_1) and hoist h for moves l_{h-1} +1 to l_h;

L_i: the minimum amount of processing time a part requires in stage i;

U_i: the maximum amount of processing time a part is permitted in stage i;

a_i: the time required to unload a part from stage i corresponding to a *move(*, i)*;

b_i: the time required to unload a part from stage i + 1 corresponding to a *move(*, i)*;

d_i: the travel time for the hoist carrying a part from stage i to stage i+1 including the unloading time (a_i) and the loading time (b_i);

$e_{i,j}$: the travel time from stage i to stage j for an empty hoist;

Δ: a very small positive number;

M: a very large positive number

3.2 Decision Variables

T: cycle time;

$t_{k,i}$: the starting time of *move(k; i);*

$t_{min\ 1}$: the starting time of the last *move(K, i)* within a cycle for hoist 1;

$t_{min\ h}$: the starting time of the first move(1, i) within a cycle for hoist h, h = 2, …, H;

$t_{\max\ h}$: the starting time of the last move(K, i) within a cycle for hoist h, h = 2, …, H;

x_i: is equal to 1 if the move(K, i) is the last move for hoist 1; otherwise, it is equal to 0, where i = 1, 2, …, l_1;

z_i^h : is equal to 1 if the move(K; i) is the last move for hoist h; otherwise, it is equal to 0, where h = 2, 3, …, H and $i = l_{h-1}, l_{h-1}+1, \ldots, l_h$;

s_j^h : is equal to 1 if the move(1, j) is the last move for hoist h; otherwise, it is equal to 0, where h = 2, 3, …, H and $j = l_{h-1}, l_{h-1}+1, \ldots, l_h$;

$w_{i,j}^h$: is equal to 1 if the move(1, j) is the last move and the move(K i) is the last move for hoist h; otherwise, it is equal to 0, where h = 2, 3, …, H and $i, j = l_{h-1}, l_{h-1}+1, \ldots, l_h$;

$y_{r,i;u,j}$: is equal to 1 if $t_{r,i} \le t_{u,j}$; otherwise, it is equal to 0, where $h = 1, 2, \ldots, H$, $i, j = l_{h-1}, l_{h-1}+1, \ldots, l_h$ and $r, u = 1, 2, \ldots, K$;

$y_{r,i;u,i+1}$: is equal to 1 if $t_{r,i} + d_i - a_i < t_{u,j} + b_{i+1}$; otherwise, it is equal to 0, where $i = l_1, l_2, \ldots, l_h$.

4. Model the Revised Line

Assume that there was a virtual and additional tank $\tilde{p}$ performing S_{p+1}. Tank $\tilde{p}$ is placed between tank p and tank $p+1$, as shown in Figure 2. A revised scenario is formed, where the reentrance is relaxed compared to the original scenario shown in Figure 1. Moreover, constraints of the relaxed scenario, as shown in Figure 2, are necessary constraints of the original scenario shown in Figure 1. The operations in the revised scenario shown in Figure 2 should be analyzed and modeled first. Then, the operations concerning reentrance are analyzed, i.e. S_{p-1}, S_p and S_{p+1}. The revised scenario has been dealt with by Li and Fung (2013a). For completeness, the constraints of the revised scenario are formulated based on Li and Fung's (2013a) work. Simplified explanations are given as well.

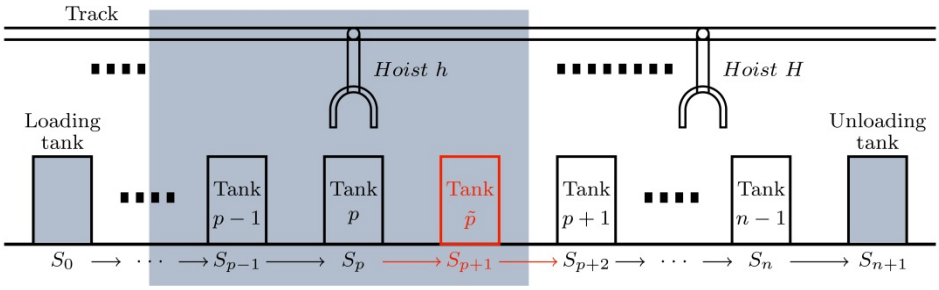

Figure 2: A Revised Multi-hoist Line without Reentrance

4.1 Constraints Concerning Hoist 1

4.1.1 Definitional and Initial Constraints

$$t_{\max 1} + \sum_{i=1}^{l_1} (d_i + e_{i+1,0}) x_i \le T \quad (1)$$

For $i = 0, 1, \ldots, l_1$,

$$t_{\max 1} \ge t_{K,i} \quad (2)$$

For $i = 0, 1, \ldots, l_1$,

$$t_{\max 1} \le t_{K,i} - (x_i - 1)M \quad (3)$$

$$\sum_{i=1}^{l_1} x_i = 1 \quad (4)$$

Constraints (2)-(4) guarantee that x_i and $t_{max\,1}$ are both well defined, i.e. $t_{max\,1}$ is the starting time of the last move performed by hoist 1. Constraint (1) guarantees that a cycle starting at hoist 1 picks up a part from stage 0. Hoist 1 comes back to stage 0 (i.e. loading tank) before the end of a cycle, for starting the next cycle.

4.1.2 Hoist Availability Constraints

For r, $u = 1, 2, \ldots, K$; $i < j$ and $i, j = 0, 1, \ldots, l_1$,

$$t_{u,j} - t_{r,i} \geq d_i + e_{i+1,j} - (1 - y_{r,i;u,j})M \quad (5)$$

$$t_{r,i} - t_{u,j} \geq d_j + e_{j+1,i} - y_{r,i;u,j}M \quad (6)$$

Constraints (5) (6) guarantee that the y's are well defined and that the hoist did not perform two moves simultaneously, i.e. moves performed by hoist 1 individually as a sequence.

4.2 Constraints Concerning Hoist h, Where h = 2, 3, …, H

4.2.1 Definitional and Initial Constraints

For $i = l_{h-1} + 1, \ldots, l_h$ and $h = 2, 3, \ldots, H$,

$$t_{\max h} \geq t_{K,i} \quad (7)$$

For $i = l_{h-1} + 1, \ldots, l_h$ and $h = 2, 3, \ldots, H$,

$$t_{\max h} \leq t_{K,i} - (z_i^h - 1)M \quad (8)$$

For $h = 2, 3, \ldots, H$,

$$\sum_{i=l_{h-1}+1}^{l_h} z_i^h = 1 \quad (9)$$

For $j = l_{h-1} + 1, \ldots, l_h$ and $h = 2, 3, \ldots, H$,

$$t_{\min h} \leq t_{1,j} \quad (10)$$

For $j = l_{h-1} + 1, \ldots, l_h$ and $h = 2, 3, \ldots, H$,

$$t_{\min h} \geq t_{1,j} + (s_i^h - 1)M \quad (11)$$

For $h = 2, 3, \ldots, H$,

$$\sum_{i=l_{h-1}+1}^{l_h} s_i^h = 1 \quad (12)$$

For $i = l_{h-1} + 1, \ldots, l_h$ and $h = 2, 3, \ldots, H$,

$$\sum_{j=l_{h-1}+1}^{l_h} w_{i,j}^h - z_i^h = 0 \quad (13)$$

For $j = l_{h-1} + 1, \ldots, l_h$ and $h = 2, 3, \ldots, H$,

$$\sum_{j=l_{h-1}+1}^{l_h} w_{i,j}^h - s_i^h = 0 \quad (14)$$

As constraints (2)-(4) are for hoist 1, constraints (7)-(9) guarantee that $t_{max\ h}$ and z_i^h are well defined. Similarly, constraints (7)-(9) guarantee that $t_{max\ h}$ and s_i^h are well defined. Constraints (13) and (14) make $w_{i,j}^h$ well defined.

4.2.2 Constraints for Cycle time T

For $h = 2, 3, \ldots, H$,

$$T \geq t_{\max h} \quad (15)$$

$$T + t_{\min h} - t_{\max h} \geq \sum_{j=l_{h-1}+1}^{l_h} \sum_{i=l_{h-1}+1}^{l_h} (d_i + e_{i+1,j}) w_{i,j}^h \quad (16)$$

Constraint (15) means that each move should start during the cycle. Constraint (16) guarantees that there is enough time for hoist h moving to the stage that is concerned with the first move from the stage concerned with the end of the last move.

4.2.3 Hoist Availability Constraints

For r, $u = 1, 2, \ldots, K$ and $i = l_1, l_2, \ldots, l_{H-1}$,

$$t_{u,j} - t_{r,i} \geq d_i + e_{i+1,j} - (1 - y_{r,i;u,j})M \quad (17)$$

$$t_{r,i} - t_{u,j} \geq d_j + e_{j+1,i} - y_{r,i;u,j}bM \quad (18)$$

Constraints (17) and (18) are similar to Constraints (5) and (6) concerning hoist 1.

4.3 Constraints to Avoid Conflicts between Hoists

For r, $u = 1, 2, \ldots, K$ and $i = l_1, l_2, \ldots, l_{H-1}$,

$$t_{u,i+1} - (t_{r,i} + d_i) \geq (y_{r,i;u,i+1} - 1)M + \Delta \quad (19)$$

$$t_{r,i} + d_i - b_i - (t_{u,i+1} + a_{i+1}) \geq -y_{r,i;u,i+1}M \quad (20)$$

Constraints (19) and (20) make the y's well defined and guarantee that there are no conflicts concerning tank l_{h+1}, i.e. there are no conflicts between the hoists.

4.4 Tank Capacity Constraints

For $k = 1, 2, \ldots, K$-1 and $i = 1, 2, \ldots, n$,

$$y_{k,i-1;k,i} = y_{k+1,i-1;k+1,i} \quad (21)$$

$$y_{k,i-1;k+1,i} \geq 1 - y_{k,i-1;k,i} \quad (22)$$

$$y_{k+1,i-1;k,i} \leq 1 - y_{k,i-1;k,i} \quad (23)$$

In a line, move(*,i-1) inserts a part into stage i and move(*,i) picks up a part from stage i. Because stage i (with only one tank performing the stage) can process, at most, one part at a time, move(*,i-1) and move(*,i) must alternate with each other. Constraints (21)-(23) guarantee this condition.

4.5 Time Window Constraints

For $k = 1, 2, \ldots, K$-1 and $i = 1, 2, \ldots, n$,

$$t_{k,i} - (t_{k,i-1} + d_{i-1}) \geq L_i - (1 - y_{k,i-1;k,i})M \quad (24)$$

$$t_{k,i} - (t_{k,i-1} + d_{i-1}) \leq U_i + (1 - y_{k,i-1;k,i})M \quad (25)$$

$$t_{k+1,i} - (t_{k,i-1} + d_{i-1}) \geq L_i - y_{k,i-1;k,i}M \quad (26)$$

$$t_{k,i} - (t_{k,i-1} + d_{i-1}) \leq U_i + (1 - y_{k,i-1;k,i})M \quad (27)$$

If the stage is empty at the start of a cycle, parts are inserted and completed within the current cycle. Constraints (24) and (25) guarantee that time window constraints are satisfied in this case. If the stage is occupied at the start of a cycle, the part being processed is inserted during the previous cycle. The last inserted part during this current cycle will be processed at the end of the cycle. Constraints (28) and (29) correspond to the parts in this case. K-1 parts are inserted and completed during the cycle. Time window constraints concerning these K-1 parts are formulated by constraints (26) and (27).

4.6 Binary and Non-Negative Constraints

$$t_{1,0} = 0 \quad (30)$$

For $k = 1, 2, \ldots, K$-1 and $i = 0, 1, \ldots, n$,

$$t_{k,i} \geq 0 \quad (31)$$

For $k = 1, 2, \ldots, K$-1 and $i = 0, 1, \ldots, n$,

$$t_{k,i} + d_i \leq t_{k+1,i} \quad (32)$$

For $i = l_{h-1} + 1, \ldots, l_h$

$$x_i \in \{0,1\} \quad (33)$$

For $i = l_{h-1} + 1, \ldots, l_h$ and $h = 2, 3, \ldots, H$,

$$z_i^h \in \{0,1\} \quad (34)$$

For $j = l_{h-1} + 1, \ldots, l_h$ and $h = 2, 3, \ldots, H$,

$$s_j^h \in \{0,1\} \quad (35)$$

For $i, j = l_{h-1} + 1, \ldots, l_h$ and $h = 2, 3, \ldots, H$,

$$w_{i,j}^h \in \{0,1\} \quad (36)$$

For $r, u = 1, 2, \ldots, K$; $i < j$; $i, j = l_{h-1} + 1, \ldots, l_h$ and $h = 2, 3, \ldots, H$,

$$y_{r,i;u,j} \in \{0,1\} \quad (37)$$

For $r, u = 1, 2, \ldots, K$; $i = l_1, l_2, \ldots, l_{H-1}$,

$$y_{r,i;u,i+1} \in \{0,1\} \quad (38)$$

5. Model Reentrance

As shown in Figure 1, stage p + 1 is performed in tank p – 1, where stage p -1 is also performed. When a part is completed in tank p for stage p, the part will be transported to tank p - 1 for stage p + 1. A conclusion of great significance is expressed by Lemma 1.

Lemma 1: It is infeasible that tank p - 1 and tank p are occupied at the same time.

Proof: Assume that part A and part B were being processed in tank p - 1 and p at the same time. Assume that part A was for stage p - 1. When part A is completed, it should be transported to tank p, which is occupied by part B. When part B is completed, it should be transported to tank p - 1 (for stage p + 1), which is occupied by part A. Hence, the deadlock occurs regardless of whether part A or part B is competed first.

Assume that part A is for stage p + 1. This means that part A entered the line before part B. When part A was transported from tank p to tank p-1 for stage p+1, tank p is empty. Moreover, tank p-1 started to process part A for stage p+1. It is infeasible to process part B at tank p - 1 for stage p - 1 at the same time and then to transport it to tank p.

Therefore, it is infeasible that tank p - 1 and tank p are occupied at the same time.

As a result, there are four feasible cases concerning Sp-1, Sp and Sp+1, based on the statuses of tanks p - 1 and p. These

cases are listed as follows with corresponding move sequences.

Case (1): Both tanks p - 1 and p are empty at the start of a cycle.

The sequence of corresponding moves should be move(1, p -2) → move(1, p - 1) → move(1, p) → move(1; p + 1) → ⋯ → move(k, p -2) → move(k, p - 1) → move(k, p) → move(k, p + 1) → ⋯ → move(1, p -2) → move(1, p - 1) → move(1, p) → move(1; p + 1).

Case (2): Tank p - 1 is occupied for stage p - 1 and tank p is empty at the start of a cycle.

The sequence of corresponding moves should be move(1, p - 1) → move(1, p) → move(1; p + 1) →move(1, p -2) → ⋯ → move(k, p - 1) → move(k, p) → move(k, p + 1) → move(k, p -2) → ⋯ → move(1, p - 1) → move(1, p) → move(1; p + 1) → move(1, p -2).

Case (3): Tank p - 1 is occupied for stage p + 1 and tank p is empty at the start of a cycle.

The sequence of corresponding moves should be move(1, p) → move(1; p + 1) →move(1, p -2) → move(1, p - 1) → ⋯ → move(k, p) → move(k, p + 1) → move(k, p -2) → move(k, p - 1) → ⋯ → move(1, p) → move(1; p + 1) → move(1, p -2). → move(1, p - 1).

Case (4): Tank p - 1 is empty and tank p is occupied at the start of a cycle.

The sequence of corresponding moves should be move(1; p + 1) →move(1, p -2) → move(1, p - 1) →move(1, p) → ⋯ → move(k, p + 1) → move(k, p -2) → move(k, p - 1) →move(k, p) → ⋯ → move(1; p + 1) → move(1, p -2). → move(1, p - 1) → move(1, p).

Table 1 shows the expressions of four cases by y's. Therefore, one more constraint is required to guarantee that one of these cases should occur, namely Constraint (39).

For k = 1, 2, …, K,

$$y_{k,p-2;k,p-1} + y_{k,p-1;k,p} + y_{k,p;k,p+1} - y_{k,p-2;k,p+1} = 2 \quad (39)$$

Until now, the MILP model is complete. The objective is to minimize cycle time T subject to Constraints (1)-(39).

Table 1: Express These Cases by y's

	yk,p-2;k,p-1	yk,p-1;k,p	yk,p;k,p-+1	yk,p-2;k,p+1
Case (1)	1	1	1	1
Case (2)	0	1	1	0
Case (3)	1	1	0	0
Case (4)	1	0	1	0

Table 2: Minimal and Maximal Processing Times (seconds)

Stage *i*	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Tank *i*	1	2	3	4	5	6	7	8	9	10	11	12
L_i	160	150	180	50	20	20	60	20	20	50	180	20
U_i	180	180	200	70	40	40	80	40	50	70	240	40
Stage *i*	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Tank *i*	13	14	15	16	17	18	19	20	19	21	22	23
L_i	80	30	50	100	70	70	140	50	60	30	70	150
U_i	120	50	80	130	100	90	180	70	80	50	90	180

6. Illustrative Example

A numerical example is used to illustrate the MILP model proposed in this paper. The example is modified from Zhou and Li's (2009) example. Using a personal computer with an i5-3337U 1.89GHz CPU and a 4GB RAM using the 64-bit Windows 8 OS, the commercial software CPLEX 12.6 under the default mode is used to solve the model with the example.

There are 2 hoists and 23 tanks performing 24 stages. Stage 19 and stage 21 are both performed in tank 19, i.e. p = 20. Moving times d_i = 14 seconds, where i = 0, 1, ..., 24. Empty moving time $e_{ij} = 6 + |i - j|$ seconds, where i, j = 0, 1, …, 25 and i ≠ j. a_i = 3 and b_i = 4, where i = 0, 1, …, 24. The processing times are listed in Table 2.

Tables 3, 4 and 5 list the results of the optimal schedules for 1-degree, 2-degree and 3-degree cycles respectively. Computation times are 1.52 CPUs, 130.52 CPUs and 1820.36 CPUs, respectively. Computation time around half an hour is viewed as an acceptable time, considering that the scheduling problem is off-line. Cycle times are 459s, 864s and 1259s respectively. Compared to 1-degree cycles, the improvements in the 2-degree cycles and 3-degree cycles are 3.79% and 6.53% respectively, i.e. (449-864/2)/449*100% = 3.79% and (449-1259/3)/449*100% = 6.53%. The results illustrate the benefits of multi-degree cycles.

Table 3: Result of 1-degree Cycle (l_1 = 12, T = 449s)

i	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
t_i	0	174	341	86	150	197	231	315	369	419	34	255	289
i		**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
t_i		405	0	64	182	266	350	87	151	226	290	374	111

Table 4: Result of 2-degree Cycle (l_1 = 12, T = 864s)

i	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
$t_{1,i}$	0	174	341	79	143	197	231	315	369	433	51	255	289
$t_{2,i}$	398	572	742	535	599	633	684	766	800	834	447	658	711
i		**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
$t_{1,i}$		419	483	64	178	262	346	136	211	305	369	453	110
$t_{2,i}$		811	864	547	671	755	839	507	571	645	696	780	621

Table 5: Result of 3-degree Cycle (l_1 = 12, T = 1259s)

i	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
$t_{1,i}$	0	174	361	59	143	197	251	335	389	453	31	225	276
$t_{2,i}$	309	483	647	555	619	669	703	785	834	885	527	760	809
$t_{3,i}$	730	914	1108	860	936	987	1038	1132	1179	1226	961	1155	1202
i		**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
$t_{1,i}$		52	96	160	274	27	131	325	409	459	560	0	194
$t_{2,i}$		383	436	523	637	358	496	613	690	764	828	664	858
$t_{3,i}$		943	1007	1078	1202	721	805	968	1037	1131	1175	912	1106

7. Conclusions

This paper considers multi-hoist scheduling with reentrance in multi-degree cycles. The no overlapping rule is applied and an MILP model is proposed based on this. The MILP model proposed is the first for this especially complicated scenario, i.e. multi-hoist lines with reentrance in multi-degree cycles. A numerical example is used to illustrate the model proposed. The results also show the benefits of multi-degree cycles.

This paper considers the special case of reentrance, i.e. stage p-1 and stage p+1 are performed in the same tank. For future work, a general case where stage q and stage v ($|v-q|>2$) are performed in the same tank will be investigated. Moreover, this paper applies the no overlapping rule to avoid conflict between the hoists. One direction is to pay more attention to the case where this rule is relaxed, which is a more general condition. Moreover, more attention will be paid to heuristic and/or meta-heuristic methods to deal with large-size instances.

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Framework on the Barriers to the Implementation of Automation and Robotics in the Construction Industry

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Abstract

Most countries have seen a rise in the use of innovative technologies in the construction industry, mostly in an attempt to address associated problems, such as decreasing quality and productivity, labour shortages, occupational safety, and inferior working conditions, especially on construction sites. One option is in the implementation of automation and robotics technologies, which have the potential to improve the industry in terms of productivity, safety and quality. However, this may not be suited to all countries. The research aim was to ascertain and explain the barriers to construction automation and robotics' implementation by exploring and establishing the barrier variables, the relationship between characteristics of the construction industry and the attributes of existing technologies in the form of ranking schemes based on data from three countries, Japan, Australia and Malaysia. Detailed quantitative (statistical) and qualitative (content) data analysis was performed, including cross-tabulations, and bivariate and multivariate analysis for investigating possible relationships between variables. In addition, the Kruskal-Wallis and Mann-Whitney U test of independent samples were used for hypothesis testing and for inferring the research sample to the construction industry population. A framework of ranking schemes produced for four key areas of, the construction attributes on level of usage; barrier variables; differing levels of usage between countries; and future trends, have established a number of potential areas that could have an impact on the level of implementation, both globally and for individual countries. The framework was also tested and validated on data from the Singaporean construction industry.

Keywords: Barriers to implementation, automation and robotics, construction industry

1. Introduction

Today, the use of innovative technologies has permeated across industries in most countries, including the construction industry. This is especially relevant for countries where the construction output is growing exceedingly fast due to high demands for infrastructure and buildings needed for development and growth of the nation. These newly industrialized countries, or NICs, are nations with economies more advanced and developed than those in the developing world, but without yet the full signs of a developed country, such as China or Malaysia. These economies have, in some cases, more than doubled their share of construction output and development, creating a rapidly developing industry that is bursting at the seams, and in need of more efficient and innovative solutions to increase productivity and the quality of the work produced (Bozyk, 2006; Mahbub, 2012).

As more countries embrace industrialization and the use of innovative technologies in their construction industry to address increasing demand and rising construction output, sometimes through the support of strong government policies, it is important to investigate how the countries' capabilities and characteristics fit in with

the attributes of the technologies and the barriers to implementation so as to measure their state of readiness. This paper describes a framework of ranking schemes that can be used to examine the state of readiness of countries intending to use automation and robotics technologies, specifically in terms of their construction attributes on level of usage; the barrier variables and differing levels of usage to gauge the relevancy of the technologies to the organizations and the countries in general. The framework could be useful in gauging the level of readiness based on core factors identified within the framework that may assist countries in finding the platform on which areas or technologies are most suited, given the countries' characteristics. The framework was produced initially based on data from three countries, Australia, Japan and Malaysia, and will subsequently be further developed using data from other countries, such as Singapore, China, Indonesia, Thailand, the Philippines and India.

2. Literature Review

The basis of the literature review for this research was to critically establish the extent and depth of existing knowledge on construction automation and robotics technologies in terms of definitions, range of technologies and the level of global implementation. The main characteristics of the construction industry and the likely automation and robotics technologies to be used throughout a construction project, from design to on-site application, were also examined to further explore the correlation and collaborate the relevancy of automation and robotics technologies to the construction industry. The issues underpinning the two key factors "construction characteristics" and "automation and robotics" can then be evaluated and investigated to produce the "barrier factors".

2.1 Construction Automation and Robotics Technologies

For this research, *construction automation and robotics* is defined as self-governing mechanical and electronic devices that utilize intelligent controls to carry out construction tasks and operations automatically. The construction work tasks and operations are regulated through programmable controls and sensors which are set up as a series of individual computer-controlled or robotic equipment with electro-mechanical links. (Mahbub, 2008)

Investigating ways where technologies can be adopted more easily in relation to the work process already in place can assist in identifying the areas where automation and robotics, in all probability, will be most relevant. These technology areas may include phases of construction, such as adopting a greater percentage of innovative technologies during the design phase, as compared to the construction phase, or it could be in terms of the construction process itself. Some construction processes, such as the installation of building components, are easier to automate as opposed to substructure or building foundation works. In this case, the drive to innovate is facilitated by the relatively straightforward technological processes that are already in place within this area. It can be construed from the characteristics and the overlapping of traditional and new technologies in terms of technology fusion that the prospect for implementation of automation and robotics technologies during the on-site phase of construction may be more widespread for some stages of the construction process compared to others (Hasegawa, 2006; Kajima, 2015; Obayashi, 2015; Shimizu, 2015 and Takenaka, 2015). However, these factors should not be looked at in isolation as other phases of a construction project, such as design, also play an important role in facilitating the adaptation of these technologies on the work site. For on-site construction, the six main stages identified that have the most potential for automation and robotics implementation were earthworks, structural steelwork, concreting, building assembly/lifting and positioning of components, painting/ finishing, and total automation of

the construction works, which involves the whole building process (Mahbub, 2012, IAARC, 2015).

2.2 The Construction Industry and the Global Development of Automation and Robotics Technologies

A shortage of labour is one of the factors behind the drive in many countries to mechanize production, by shifting from traditional craft methods to production of components in factories through prefabrication. This makes sense in economies where full employment is creating upward pressures on wages, or where labour shortages are acute.

Japan can be considered as the world leader in construction technology based on two interrelated factors: (1) the efforts toward technological innovation through research and development (R&D); and (2) a large domestic market and internalization of demand from Japanese investors in foreign countries. During the 90s, construction automation and robotics R&D activities were led by Japanese companies and universities, and were focused on the development of new robotic systems and in the automation of existing machinery. Nowadays, the focus is more on software and IT technologies, including on-site sensory data acquisition and processing, human operators' field safety and security, chip-based process controls, monitoring and many other aspects (Balaguer and Abderrahim, 2008).

In emerging economies, such as Malaysia, the need to improve the performance of the construction industry and address inherent problems, such as productivity and workmanship performance, inefficient construction processes and delivery, poor quality materials and products, ineffective organisation and supply chain management, have pushed forward the adoption of new construction methods and technologies in the industry. This has paved the way for the increasing use of innovative technologies in the Malaysian construction industry, as addressed under the Construction Industry Master Plan Strategic Thrust 5. This plan includes encouraging the use of industrialised building systems (IBS) and prefabrication, building information modelling (BIM), mechanisation, automation and robotics, and to a certain extent, modular construction (CIDB, 2015). R&D is mostly carried out by universities in Malaysia, sometimes in collaboration with the industry, and by CREAM, the R&D arm of the Construction Industry Development Board of Malaysia (CREAM, 2015).

3. Research Methodology

In the initial phase of the research, the barriers to implementation were investigated for Japan, Australia and Malaysia. These three countries were chosen because their construction industry characteristics provide a contrast in terms of culture, gross domestic product, technology application, organisational structure and labour policies. These countries also demonstrate a wide spectrum in terms of technology application, from high usage in a developed country (Japan), low usage in a developed country (Australia) and fairly low usage in a developing country (Malaysia). This phenomenon and the differing characteristics provide the general framework and were used to form the ranking schemes that would explore the different levels of implementation of automation and robotics globally.

This research adopted a mixed method approach of gathering data, both quantitative and qualitative, by using a questionnaire survey and an interview schedule to investigate respondents' attitudes towards the usage of automation and robotics in their construction firms. An Attitudinal Scale was developed following the Summated Rating or Likert Scale of five and seven-point numerical scales. A questionnaire was developed and distributed to construction firms, targeting contractors, specialist sub-contractors, developers and consultants to determine the extent of use and related value of the technologies. These companies were asked to provide

input regarding industry perception, benefits, barriers, and suggested practices for implementing construction automation and robotics technologies. The type chosen was a closed questionnaire, divided into five main sections: demographic information; the level of implementation and development of automation and robotics technologies; issues and concerns pertaining to the use of automation and robotics technologies; perceived barriers and their impact; and future trends and opportunities.

For any research, the required sample size depends on two key factors: the degree of accuracy required for the sample and the extent to which there is variation in the population with regards to the key characteristics of the study. Other than accuracy, cost and time are key factors in working out the sample size. Taking into consideration the large geographical area covered for the research, and the inherent cost and time implications, the sample size for the questionnaire survey of this research was selected to be 80 for each country, with a total number of 240 construction companies in the sample group. This was based on judgement sampling of the top 80 companies operating in the Japanese, Australian and Malaysian construction industries, specifically contractors, specialist sub-contractors, developers and consultants. Also, due to the large geographical area covered involving the three countries of Japan, Malaysia and Australia, it was found that mail only questionnaires would be impractical. Therefore, the respondents were given the option of either responding by mail, or through a web-site. The web questionnaire was designed to be as user-friendly as possible - respondents were required to "scroll down, click and point" to select the appropriate response to each question; before submitting the completed questionnaire directly via e-mail by clicking the "submit" button. The questionnaire for each country was separated on different web pages to facilitate data coding, handling and analysis. The total response rate was 105 (44%) with 48% from Australia, 29% from Japan and 23% from Malaysia.

The interviews conducted were semi-structured and one-to-one to allow for additional probing and the opportunity to gather more in-depth information on the subject in order to supplement the data gathered from the questionnaire. Due to the geographical distribution of the study population, the sample size for the interviews was relatively small, about 7 per country, with a total number of 21; as a larger sample might prove to be expensive and inconvenient. The results of the interviews were used to support and cross-validate the questionnaire findings. This research therefore employed the mixed methods strategy where data were collected sequentially, with the questionnaire survey providing a broad information base, whilst the interviews provided a specific focus on certain characteristics or areas, specifically the factor regarding barriers to implementation. A summary of the demographic information of the sample is depicted in Table 1 below.

In administrating both the questionnaire and interview, English was used for all three countries. In Malaysia, as English is spoken widely, there were no critical issues for respondents in understanding the questions. However, for Japan, to address this, the respondents were also given the option of whether they would prefer the language to be Japanese. Additionally, in cross-cultural data collection, there were also other issues to be considered, especially in terms of relationships and social frameworks, time and power distance (Reynolds and Valentine, 2004).

Table 1: Summary of the Demographic Information of the Sample

VARIABLES	GROUPING	JAPAN (FREQ %)	MALAYSIA (FREQ %)	AUSTRALIA FREQ %)
Business Type	Contractor	40	38	55
	Sub-contractor	7	8	7
	Consultant	43	16	27
	Developer	10	38	11
Sector of Industry	Residential	10	25	5
	Non-residential	0	0	34
	Civil engineering Works and Infrastructure	20	25	12
	All of the Above	60	38	34
	Residential & Non-residential Only	10	12	15
Number of Full-time Staff	1-50 people	0	26	8
	51-100 people	3	12	6
	101-250 people	3	8	23
	251-500 people	33	21	27
	501-1000 people	33	21	26
	More than 1000 people	28	12	10
Number of Branches Outside the Country	None	30	90	78
	1-5	40	10	4
	6-10	20	0	18
	16-20	10	0	0

In Australia, people place great importance on individuality, independence and self-reliance, and therefore communication tends to be direct, explicit and personal. In contrast, collectivism is common in most Asian countries, such as Japan and Malaysia, and in this context communication tends to be intuitive, complex and impressionistic, and attention should be given to implicit, non-verbal messages and body language. The order in which information is presented is also different. In Western cultures, important information tends to be given first, with less important items left towards the end, whilst in Asian cultures, less important items are spoken of first, setting the stage for the important information, which comes at the end. To ensure the reliability of the data collected in terms of cultural differences, there is a need for sensitivity on the part of the interviewer, especially in reconfirming points that have been raised but have not been directly disagreed upon.

The need to maintain reliability and validity throughout the research process so as to ensure all the components of the research being conducted measured up to the elements under study; and to make certain the most suitable methods, instruments, techniques and procedures have been selected and implemented, were addressed through several means including conducting pre-testing and a pilot study. Pre-testing addresses the face and content validity whilst the pilot study, to a certain extent, addresses the criterion validity of the research. A pilot study was carried out for a small sample of 75 i.e. 25 for each country, and the response rate was 35%. Improvements were made to the research instrument based on the pilot study, including the method of administering the questionnaire to improve response rate (by including a website option in the actual survey) and the minor re-phrasing of items to improve comprehension. The internal reliability of the research instrument was also assessed using Cronbach's Alpha (α), which is an index of reliability associated with the variation accounted for by the true score of the underlying construct. The values of Cronbach's Alpha for all related items in the questionnaire were duly computed and analyzed; and the value for the total items at 0.875 and 0.894 indicated high internal consistency of the instrument.

The findings from the survey were useful in providing a better understanding of the range and level of construction automation and robotics technologies that are currently in use and in ascertaining a pattern of usage for the three selected countries, Australia, Japan and Malaysia. This was then used to develop a framework to further investigate the barrier variables under study based on the characteristics of the technologies in use, the three countries' construction industries and their patterns of implementation.

4. Data Analysis and Findings

Data becomes meaningful only after analysis has provided a set of descriptions, relationships, and differences that are of use in addressing the research objectives. In the case of this research, the purpose of data analysis was both to uncover phenomena that may describe or be related to a situation in some way, such as looking at the possible relationship between the level of use of automation and robotics and the size of company (cross-tabulations, bivariate and multivariate analysis), and relating the research sample to the construction industry population of Japan, Malaysia and Australia (inferential statistics and hypothesis testing; through tests conducted such as Kruskal-Wallis and Mann Whitney U test of independent samples). The two data sets analysed under Phase 1 (the questionnaire) and Phase 2 (the interviews) were then integrated in that the findings from phase two were used to elaborate and extend the analysis results of phase one. The process of synthesizing and integrating the results of both phases were discussed and placed in context with the literature review concerning barriers to the implementation of automation and robotics in construction.

4.1 Questionnaires

For the questionnaire data, numerical measures of location and variability using mean and standard deviation were only applied on a limited basis to the analysis of the interval variables in the demography section, whereas descriptive statistics in the forms of graphical presentations and tables (frequency distributions) were employed more extensively. Frequency counts were used for univariate analyses of the variables whilst cross-tabulations were used for bivariate or multivariate analyses of the variables involving nominal or ordinal scales. The other frequently used analysis for this research was inferential statistics in the form of non-parametric tests, such as the Kruskal-Wallis and Mann-Whitney U-statistic tests. As the frequencies represent ordinal measurements with many points on the scale, the Kruskal-Wallis test, a rank-order test of significance, was used to interpret the data. Cases were ordered from lowest to highest according to the "score" each case received on the scale, and then assigned a ranking that indicated where in the list it appeared. Here, the descriptive statistics for the ranking of the means were performed using the Kruskal-Wallis test for the three country sample, and the results are as shown in Tables 4 and 5. The Mann-Whitney U test was then performed as an independent check and to cross-validate the results from Kruskal-Wallis. The statistical analysis for the questionnaire data was performed using SPSS (Statistical Package for the Social Sciences) software.

4.2 Interviews

The analysis of qualitative data in Phase 2 was facilitated by the use of NUD*IST (Non-numerical Unstructured Data Indexing Searching and Theorizing) Vivo. The document file holds all the documentary data and interview transcripts, as well as memos regarding these. The nodes represent categories of data that are important to the research project, and memos of the researcher's ideas can be attached to these. (Richards, 2005; Richards, 2006). For this research, the categories were mainly coded under Tree Nodes (stored in hierarchical catalogues) and Cases. The categories that emerged from the code note headings of the interviews formed the basic framework that constituted core materials for answering this study's

research questions. The core materials for analysis were formed by comments and notes categorised under these headings, which were found to be useful in explaining or interpreting the findings of the research.

4.3 Analysis of Data

This paper will describe only selected areas of the quantitative and qualitative data analysis that are useful in highlighting the development of the framework of ranking schemes for the implementation of automation and robotics technologies.

4.3.1 Area of Implementation

The majority (90%) of Japanese companies used automation and robotics, whilst in Australia, 65% used the technology and 50% in Malaysia. However, a more useful indication would be to look at the areas within which the technologies are used, as most of the companies may only use automation at the design stage in the form of design software, such as Computer Aided Design (refer to Figure 1).

Overall, Japan used the technology across the board, although with less usage in on-site construction compared to the other areas. However, there was still a greater percentage of on-site application in Japan (on-site usage: Japan 70%, Malaysia 12% and Australia 22%), compared to Malaysia and Australia. The prevalent areas of usage for Malaysia and Australia are in scheduling/planning, design and costing/tendering, with some applications in project management. Australia, however, used the technology slightly more on-site compared to Malaysia.

4.3.2 Why the Technologies are Used More Predominantly in Certain Areas of Construction

This question involved respondents choosing what, in their opinion, are the reasons automation and robotics are used more predominantly in certain areas of construction, such as design, but not others. The most popular reason chosen by respondents at 24% was that the type of work done by the company reflects the areas of usage.

Table 2: Reason for Use in Certain Areas

Why used predominantly in certain areas?	Frequency of Use
Type of work done by company reflects areas of usage	48(24%)
High costs associated with application in certain areas	30(15%)
Availability of technologies differs across the areas	36(18%)
Ease of use (easily understood during implementation)	27(14%)
The technologies can be used repetitively for a range of projects	27(14%)
Differing levels of awareness (exposure) across areas	30(15%)

4.3.3 Perceived Barriers to Construction Implementation

The barriers to implementation are interconnected with a number of factors, including the main problems associated with technology use and areas of usage within the construction phases. For the questionnaire, a list of eight statements relating to barriers to implementation was provided and respondents were requested to indicate their opinion of each statement ranging from the least to the most significant. The variable and value label codes and summary of analysis results for the statistical analysis are presented in Tables 3 and 6, whilst the results of the content analysis are presented in Table 7 below.

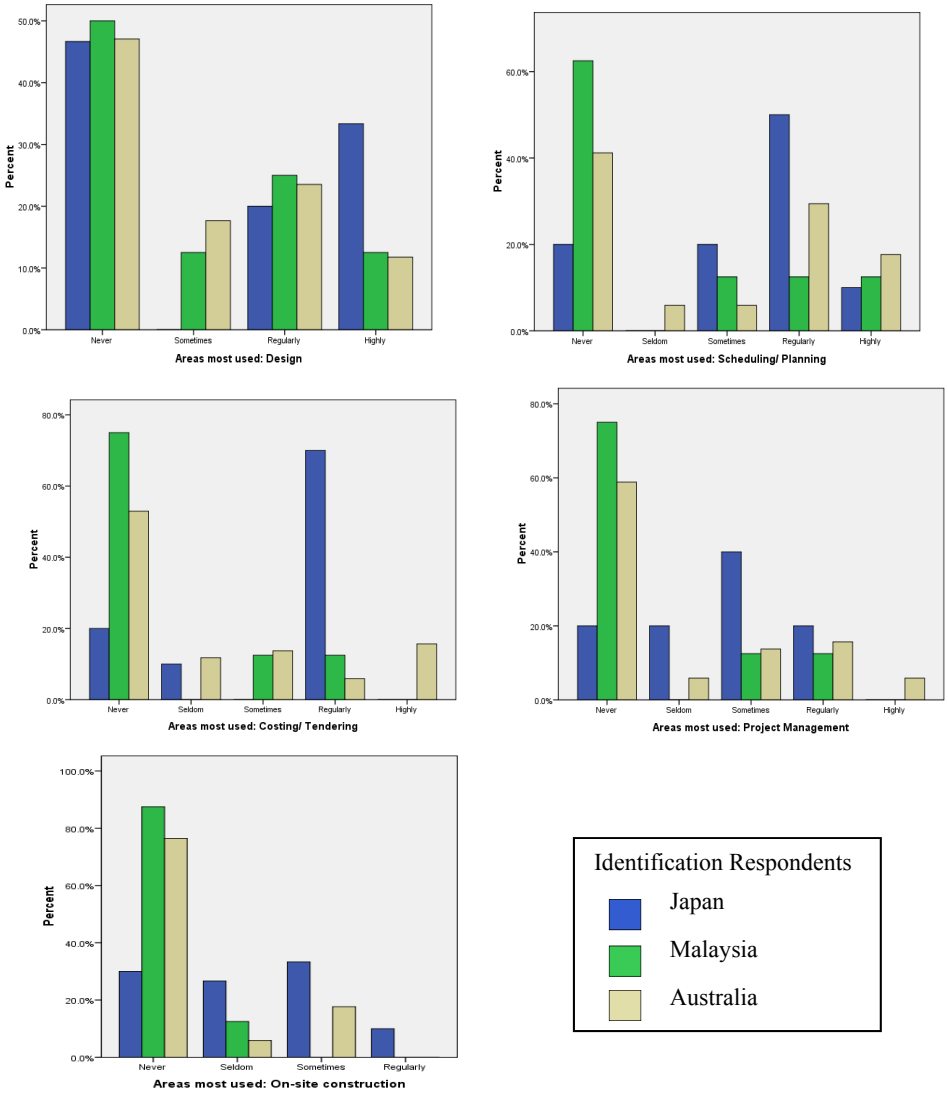

Figure 1: Level of Use of Automation and Robotics Technologies in Different Areas of Construction (Design, Scheduling and Planning, Costing and Tendering, Project Management and On-site Construction)

Table 3: Variable Codes and Description

Code	Variable Description of Barriers: Questionnaire statement
B1	High costs / substantial financial commitment in acquiring the technologies
B2	Automation and robotics technologies are expensive to update and maintain
B3	Incompatibility of the technologies with existing practices and current construction operations.
B4	The fragmentary nature and size of the construction industry makes the technologies difficult to implement
B5	Automation and robotics technologies are difficult to use and not easily understood
B6	Automation and robotics technologies are unavailable locally or difficult to acquire
B7	The technologies are not easily accepted by the workers and workers' union
B8	Low technology literacy of project participants / need for the re-training of workers

Table 4: Barrier Variables: Kruskal-Wallis Test Statistics and Descriptive Statistics

DESCRIPTIVE STATISTICS							TEST STATISTICS GROUPING: COUNTRIES		
Variable	N	Mean	Rank	Std. Dev.	Min	Max	Chi-square	*df*	Asymptotic Significance (2-tailed)
B1: Cost to acquire	105	4.69	1	1.625	1	7	1.800	2	.407
B4: Fragmented	105	4.29	2	1.392	1	6	9.652	2	.008
B5: Difficult to use	105	4.03	3	1.348	1	6	4.499	2	.105
B2: Cost to update	105	3.97	4	1.213	1	6	16.374	2	.000
B3: Incompatible	105	3.97	4	1.390	1	6	2.362	2	.307
B8: Low literacy	105	3.83	6	1.471	1	7	17.826	2	.000
B6: Unavailable	105	3.71	7	1.758	1	7	19.439	2	.000
B7: Not accepted	105	3.60	8	1.685	1	7	26.208	2	.000

Table 5: Barrier Variables: Kruskal-Wallis Test and Mean Ranks

VARIABLE	COUNTRY	N	MEAN RANK	VARIABLE	COUNTRY	N	MEAN RANK
B1: Cost to acquire	1 Japan	30	56.15	B5: Difficult to use	1 Japan	30	60.95
	2 Malaysia	24	57.50		2 Malaysia	24	43.81
	3 Australia	51	49.03		3 Australia	51	52.65
B2: Cost to update	1 Japan	30	71.30	B6: Unavailable	1 Japan	30	32.90
	2 Malaysia	24	46.81		2 Malaysia	24	57.31
	3 Australia	51	45.15		3 Australia	51	62.79
B3: Incompatible	1 Japan	30	45.95	B7: Not accepted	1 Japan	30	35.00
	2 Malaysia	24	56.00		2 Malaysia	24	43.44
	3 Australia	51	55.74		3 Australia	51	68.09
B4: Fragmented	1 Japan	30	51.65	B8: Low literacy	1 Japan	30	34.70
	2 Malaysia	24	38.00		2 Malaysia	24	53.94
	3 Australia	51	60.85		3 Australia	51	63.32

Table 6: Barrier Variables: Summary of Analysis Results

Variable	Descriptive Statistics			*Accept*	
	Rank	Mean	Std. Dev.	H_O	H_A
B1: CostAcq	1	4.69	1.625	√	
B4: Fragment	2	4.29	1.392		√
B5: Difficult	3	4.03	1.348	√	
B2: CostUpd	4	3.97	1.213		√
B3: Incomp	4	3.97	1.390	√	
B8: Low Lit	6	3.83	1.471		√
B6: Unavail	7	3.71	1.758		√
B7: NotAccpt	8	3.60	1.685		√

For the interviews (Table 7), almost all participants (92.1%) agreed that the barriers are very much influenced by the different phases of construction, with the majority agreeing that barriers to automation and robotics technologies being implemented within on-site construction are much greater compared to barriers to implementation during the design phase. With regards to cost, the wider scope of the quantitative analysis that separated initial and updating costs was consolidated and incorporated under one variable, i.e. “cost”, after triangulation with the qualitative results and the literature.

Table 7: Summary of Content Analysis: Barrier Variables

Rank	Barrier variables	Freq.	% of Response	
			Positive	Negative
1	Different Construction Area Usage	43	92.1	7.9
2	Cost	39	87.7	12.3
3	Fragmented Industry	28	72.6	27.4
4	Difficult to Use	23	58.5	41.5
5	Incompatibility	18	57.3	42.7
6	Re-training	15	48.0	52.0
7	Unavailable	11	50.3	49.7
8	Not accepted	8	32.9	67.1

4.4 Framework of Ranking Schemes for the Core Factors

The main categories reviewed pertaining to the technologies implementation were economics and cost, structure or organisation, products and processes, technology, and culture or human factors; which were then elaborated in parallel to the construction characteristics and barrier variables. Through the research instruments, namely the questionnaire and interviews, and the data collected, analysed and synthesised with the literature, a simple framework of ranking schemes was developed which incorporated the key factors and variables that had been identified. This framework allowed for the comparison and ranking of these factors and variables in terms of their application or significance.

4.4.1 Ranking Scheme 1: Correlation between the Characteristics of the Construction Companies and Industry to the Level of On-site Usage of Automation and Robotics Technologies

Areas of construction play a significant role in influencing levels of usage, with the core factors under investigation showing a stronger correlation with the level of usage for on-site construction, when compared to other stages, such as design. As such, it can be deduced from statistical evidence that there is no significant relationship between the level of implementation and the core factors for the earlier stages of construction, especially in design and planning/scheduling. Following these facts, the ranking scheme produced below is applicable specifically for on-site construction only, as this area is also the main focus or scope of the research.

Table 8: Ranking Scheme 1: Correlation Between Core Factors and Level of Usage

Ranking	Characteristics of Company and Industry
1	Size of Company
2	Type of Business
3	Market Share
4	Construction Sector

4.4.2 Ranking Scheme 2: Barrier Variables

One important aspect that was ascertained from the examination of the barrier variables was that the ranking of all seven variables corresponds with each other for both the statistical and content analyses. Another aspect that should be mentioned is that the barrier variables were, again, very much related to the areas of usage, but as far as possible, the ranking scheme produced for this area is specific to on-site construction.

Table 9: Ranking Scheme 2: Barrier Variables

Ranking	Barrier Variables
1	High Costs / Financial Commitment
2	Fragmented Nature of the Construction Industry
3	Difficult To Use/Not Easily Understood
4	Incompatibility With Existing Practices and Current Construction Operations
5	Low Technology Literacy of Project Participants/Need For Re-Training Of Workers
6	Unavailable Locally and Difficult to Acquire
7	Not Accepted By Workers

From the ranking scheme, it can be concluded that the high costs and financial commitment associated with automation and robotics application is the most significant factor whilst the least significant is the technologies not being accepted by workers. It can be deduced from this that the construction industry is fairly cost sensitive towards technology utilisation, and for there to be greater implementation of the technologies, the purchase, operating and maintenance costs need to be affordable and offered at a more competitive price to the industry.

4.4.3 Ranking Scheme 3: Comparison of Differing Levels of Usage between Countries

The differing levels of usage of the technologies were investigated between Japan, Malaysia and Australia for comparison purposes; evolving around six core factors including: the individual countries' construction characteristics; the labour situation; cultural and societal acceptance of the technologies in general; companies' market share composition; government and company policies; and the countries' construction management and workers' unions.

In answering the question of "why there is a greater use of the technologies in one country compared to another", no attempt was made to rank these factors and only a list of reasons were provided as it was deemed as more suitable in answering "why" a phenomenon occurs. The ranking scheme provided here is based on the content analysis ranking derived from the three sample countries.

Table 10: Ranking Scheme 3: Comparison of Differing Levels of Usage between Countries

Ranking	Core Factors Influencing Level Of Usage Between Countries
1	Construction Characteristics
2	Labour Situation
3	Cultural and Societal Acceptance of Technologies
4	Companies' Market Share Composition
5	Government and Company Policies
6	Construction Management and Workers' Union

Construction characteristics play a vital role in determining the level of implementation of the technologies, as can be deduced from the higher level of usage by the Japanese. The Japanese construction industry comprises mostly of large conglomerates operating under one roof and involved in fairly large and competitive markets; compared to Malaysia and Australia where the construction industry comprises of fairly small businesses.

4.4.4 Ranking Scheme 4: Future Trends and Opportunities

The future trends and opportunities were statistically analysed under a broader group of ten categories whilst the content analysis provided a focus by directing the topic area into a smaller group of five categories. However, for ranking purposes, the

statistical analysis will be used so as to provide a broader information base and better clarity in terms of the significance placed by the participants on each trend stated.

It can be concluded from the ranking scheme that an increasing awareness of the technologies within the construction industry community is the most probable future scenario for automation and robotics technologies. The least likely scenario, of there being greater integration within the construction industry, is to be expected and is generally supported by literature evidence. As the industry is usually composed of small companies specializing in different areas of construction; with different responsibilities and control within their own area, it is very unlikely that we will see greater integration within these smaller companies in the near future.

Table 11: Ranking Scheme 4: Future Trends and Opportunities

Ranking	Future Trends and Opportunities
1	Greater awareness of the technologies within the construction industry community
2	The number of construction companies using automation and robotics technologies will increase significantly
3	Automation and robotics technologies will be cheaper to acquire and operate
4	There will be a significantly larger range of automation and robotics technologies available for use in construction
5	There will be greater standardisation of the design and construction processes
6	The use of automation and robotics technologies will enable firms to operate more efficiently and competitively
7	The technologies will be easily available across the world
8	The technologies will be readily accepted by the workers and the industry
9	Automation and robotics technologies will be easier to install and operate
10	There will be greater integration within the construction industry in terms of control and responsibility for design and construction

4.4.5 Discussion on the Findings

The contributions made through the ranking of the key categories identified within the four areas were realised in terms of establishing the groundwork for research on the global application of construction automation and robotics technologies. The key categories identified under ranking schemes 1 and 3 can be employed to determine the potential for any country in terms of adopting the technologies; in that the schemes can be used to gauge whether a country is more likely to use the technologies based on their construction industry attributes.

For example, these ranking schemes can be used to investigate which country is more likely to adopt such technologies, for instance Yemen or Singapore, given the characteristics of the construction industry in each country and the foreseeable advantages to be gained in adopting the technologies.

Ranking scheme 1 can be employed to gain a better understanding of the construction companies' composition in these countries with regard to the technologies. In Yemen, the construction industry is mostly made up of small companies operating in a fairly localised market, so the ranking for its potential use of technologies would be fairly low. These facts can then be juxtaposed with ranking scheme 3, and it is found that the labour costs in Yemen are quite low, with less cultural and societal acceptance of technologies in general. Therefore, it can be concluded that Yemen rates low in terms of the adoption of the technologies. The same procedure can be applied to Singapore, and from there the rankings can be used to determine whether the potential for the technologies' adoption by each country is ranked high or low, whilst allowing comparisons to be made.

To be more precise and to provide better clarity, the ranking schemes need to be expanded to allow for weightage of rankings between countries to be evaluated, which is an area for future research work.

Ranking scheme 2 can be used to investigate the barriers to implementation for a country that is found to be likely to adopt the technology but currently is not. As evidenced by the findings of the literature, for some countries, the best solutions to their labour or other construction problems are not seen to be the adoption of innovative technologies, especially if there are high costs involved. The ranking scheme can allow researchers to study the reasons why these technologies are not used, and if it is generally because of high costs or unavailability, there may be potential in examining selected areas of use where these barriers do not present such a high level of hindrance. Ranking scheme 4 can provide the researcher with the background on the predicted value and use of the technologies in the future. Where there is an area that is discovered to gain advantages from the use of the technologies, then future trends can assist in predicting the likely scenario of the technologies' application in these areas. A summary of the framework of the ranking schemes is shown in Figure 2.

5. Current and Future Research

In order to test, validate and build the database for the framework of ranking schemes, subsequent research data was collected from Singapore, via an on-line questionnaire distributed in January 2014. Preliminary analysis of the research data from Singapore has indicated that the results correspond with the factors under the framework of ranking schemes as previously described. For research on Singapore and other subsequent target countries such as Indonesia, China, Thailand and India, the focus will be on core factors under ranking schemes 1, 2 and 3 only; as it is within these areas that the framework would be most applicable and useful for gauging the level of use of automation and technologies globally.

6. Conclusions

From the literature and analytical data findings, there is clear evidence that the implementation of automation and robotics in the construction industry is influenced by the characteristics of the construction industry and the attributes of individual companies in parallel to consideration of their barrier variables. Findings and conclusions arising from the research work, including the ranking schemes produced for the four key areas of construction attributes on the level of usage, barrier variables, differing levels of usage between countries, and future trends, have established a number of potential areas for further research that could have an impact on the level of implementation both globally and for individual countries. The research also sets out and provides various perspectives of the construction industry and advanced technology applications from the three countries studied, namely Japan, Malaysia and Australia. This establishes the groundwork for further research into the global application of automation and robotics technologies; in terms of extending the ranking schemes to address a wider application and expanding the database to include countries such as Singapore, Indonesia, China, Thailand and India.

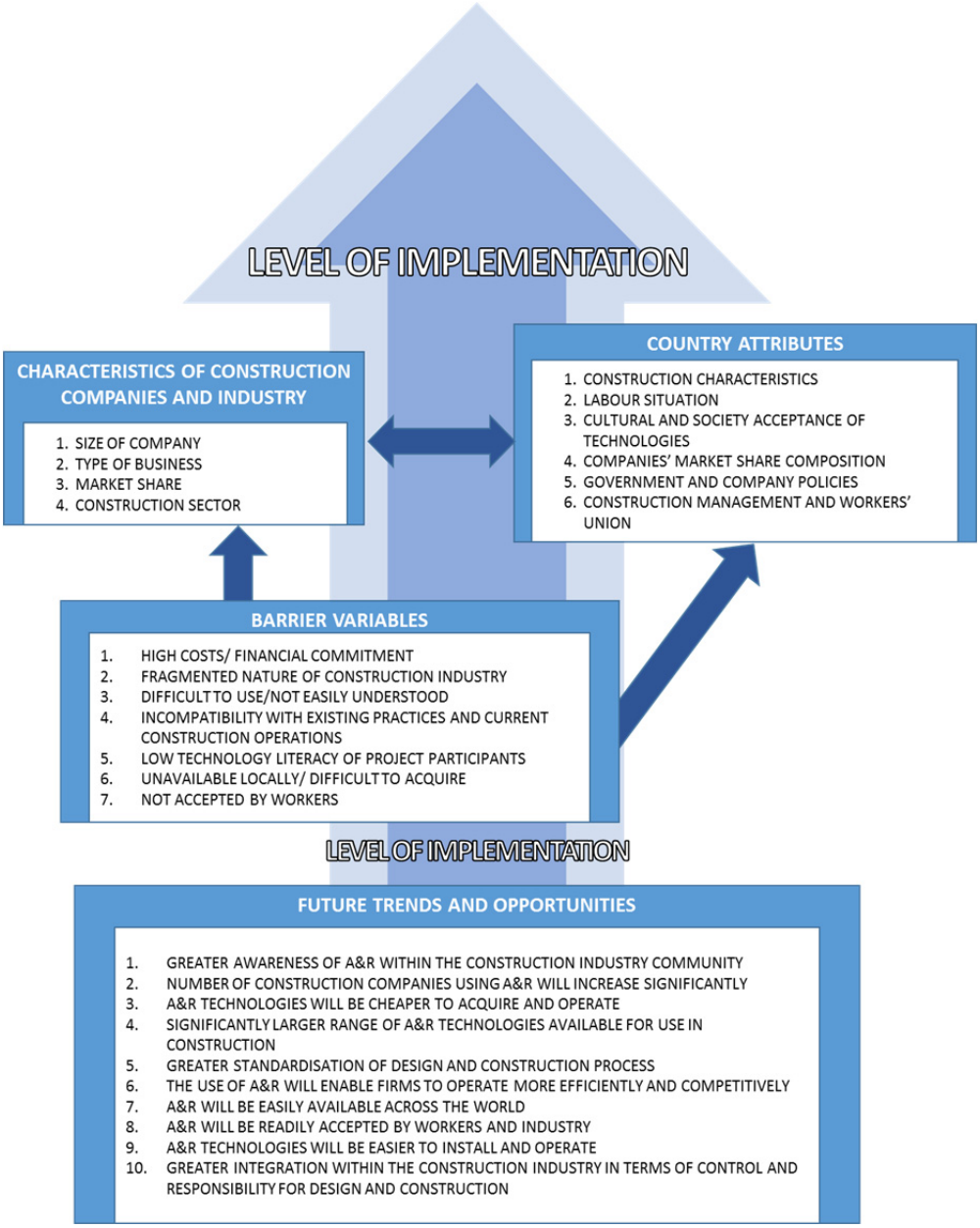

Figure 2: Framework on Construction Automation and Robotics Implementation

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IT Enabled Global Operations in the Textile Industry

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Abstract

This study, based on a case of an international textile group, demonstrates the change process and change content of an IT enabled global operations model in the textile industry. This textile group has restructured its operation network via a Global Operations System (GOS) to obtain maximum resource utilization at the network level. The findings indicate: (1) in the absence of the required trust and commitment among transaction parties, global operations require a governance mode that is more vertically integrated than virtually integrated. NWTextile Taiwan adopted a cross-holding strategy to obtain control power and increased ownership of their global operations, ensuring there was sufficient information exchange and good quality information for operation decisions; (2) a centralized decision center should be created to organize global resources from a global viewpoint; (3) clarifying the benefits of a GOS and providing related support as well as financial incentives are the keys to successful implementation.

Keywords: Global operations, textile, global sourcing, global operations systems, operation network

1. Introduction

To date, textiles remain an important industry for many developed and developing countries, and have served as a key source of employment and export growth (US Department of State 2008). Since the 1990s, textile companies have been aware of the trend of globalization. As fashion is merchandised and sourced from across the world, textile businesses face a widely fragmented supply chain. A single item of clothing may be made by numerous raw material suppliers and garment manufacturers, resulting in complicated operation processes. Because of quota limitations and complicated global material management, it is more difficult for textile companies to leverage among various manufacturing factors and achieve optimal solutions for all the parties in their supply and production network. The ability to virtually integrate operation activities has become more of an issue in the textile industry. As Cudahy et al. (2008) observed, a 'multi-polar' world has been created due to the increase in economic interdependence across multiple centers of economic power. This is true for textiles, especially when substantial shifts in the worldwide textile trade happened because of the uncertainty induced by the changes to quota policy of the US and the European Union (EU).[1]

There is now a need for textile companies to upgrade their operation activities and move up along the value chain. In contrast to other industries, for which the

[1] Although textile quotas were abolished from the beginning of 2005, in May 2005 the US government decided to re-impose a special quota restriction on China's exports of several types of textile products. Meanwhile, the EU resumed the setting of quotas on China's textile exports to the EU (US Department of State, 2008, Chowdhury, 2005).

most obvious reason for globalization is to reduce production costs, globalization in the textile industry has different considerations. Different from other globally-operated industries, such as the high-tech machinery and paper industries, the textile industry utilizes a great variety of non-standardized materials which are produced worldwide. Therefore, companies from more than a hundred countries have to co-operate with each other along the whole supply chain. Textile companies need to balance various complicated factors, such as structural restrictions (e.g., quotas and tariffs), labor costs, transportation costs, quality, delivery times, and so on, so as to optimize efficiency and establish an effective worldwide operation.

Although textile companies have traded worldwide for decades, many companies have dealt with their operating activities (e.g. procurement, production, marketing, and manufacturing) separately and have not yet adopted a comprehensive approach to operate globally (Monczka et al. 2008). Recently, more and more leading textile companies have realized that effective operations in the global market requires an integrated operation network in which all operation activities and parties are taken into consideration. Traditional supply chains in the textile industry need to be restructured to form an integrated perspective so as to eliminate any inefficiency in global resource management and to leverage the capabilities of all divisions.

Nevertheless, global operations pose several challenges, including such issues as restructuring the decision-making process, redesigning operation procedures, sharing information among network parties, and the management of conflicts of interest between local sites and central offices. This paper is an attempt to provide a case study for a better understanding of these issues. We examined a Taiwanese textile group that had developed an integrated global operations model through a global operations system (GOS) to deal with imbalances of capacity and resource management among the group members

2. Global Operations

2.1 Evolution of Global Operational Modes

As the textile market is greatly fragmented with thousands of material suppliers from all over the world, global operations play an important role in the operation process. To take on and manage such complex operations globally, there should be a key issue that can determine exactly what the most efficient form of a global operation is. There are several feasible alternatives for global operational modes.

First, firms can be tied to upstream suppliers and downstream customers with regards to the aspects of materials, information, finances and services to form a supply chain (Larson and Halldorsson 2002, Menzer 2001). Recently, such simple one-way exchanges in a traditional supplier-buyer relationship have evolved into a more flexible 'supply network'. A supply network encompasses the complexity of exchanges and coordination from a broad, strategic view for the purposes of resource acquisition and network management (Harlan et al. 2001).

For a more efficient supply network design, both the physical and information aspects of the supply chains are treated separately in a governance structure of virtual integration. Virtual integration substitutes direct ownership with partnership and emphasizes information sharing among vertical parties that leads to increases in manufacturing flexibility and adaptability (Wang et al. 2006). By outsourcing organizational functions and concentrating on the core area of competence, virtual integration allows firms to make decisions and coordinate actions quickly (Guisinger and Ghorashi 2004). Virtual integration, therefore, is considered to be the most flexible governance structure of a supply chain. Nevertheless, without a high degree of trust and commitment among the parties, high transaction costs could offset

production costs, leading the supply structure to become unstable and collapse (Maropoulos et al. 2008).

A production network is another type of network. A common challenge suffered in production planning is deciding on the inventory level, production venues and workforce size required so as to meet with fluctuating demands (Hax and Candea 1984). Companies that share the same market and that have targeted customers and suppliers may find there are redundancy, incapability and insufficient resources among themselves. An exchange of information and resources can provide these companies with the opportunity for better production planning (Wiendahl and Lutz 2002). Therefore, companies cooperate with other companies in a production network and reinforce horizontal partnerships in a long-term and stable relationship (Maropoulos et al. 2008).

In textile markets, numerous factors might have an impact on operation decisions, such as costs, quotas, quality, capacity, lead times, industrial infrastructure, and delivery times. It is essential to leverage these factors in an integrated manner in order to improve product quality and manufacturing flexibility to ensure an economic portfolio (Ettlie and Sethuraman 2002, Monczka et al. 2008). Both production networks and virtual integration are run with a market system rather than a central planning system. In a competitive market system, key information, such as resource availability, consumer preferences or technological opportunities, are not necessarily transmitted (Milgrom and Roberts 1992). However, determining an efficient allocation of global resources requires detailed information about the entire network, and the optimized solutions of operation should take all this information into consideration. As Min and Eom (1994) state, operational decisions in different working units should be consistent and based on the strategic operation plans of a central office. Unlike virtual integration, global operations emphasize both horizontal and vertical integrations in a network. In global operations, the structure of the network is built through the effective integration of operational activities including R&D, sourcing, manufacturing, sales, marketing, logistics, delivery, and supporting services (Cudahy et al. 2008). Resource allocation is planned as a centralized process for both local and global demands. In their study, Cudahy et al. (2008) observed firms with highly effective global operations, typically favoring globalization of the entire value chain of product lines or business units, rather than the globalization of specific functions. By so doing, firms can manage a balanced portfolio of local, regional, and global resources and leverage their abilities for all network parties to realize maximum profits for the whole network rather than individual companies within the network.

2.2 Global Operations Design

A big challenge of a global operations model is how to effectively coordinate and leverage worldwide requirements while remaining responsive to the needs of regional business units and operation sites (Monczka et al. 2008). Dealing with various problems separately within an individual unit or from a local viewpoint usually results in the sub-optimization of global operations, and this can lead to poor customer service, distribution inefficiencies, cost wastage and low employee morale (La Londe et al. 1993, Bendiner 1993). Such sub-optimization is caused by the interrelated nature of logistical activities, and these, in turn, damage global logistics (Capacino and Britt 1991). Accordingly, constructing a fully integrated model, rather than building smaller sub-models separately, is required to effectively manage capacity and resources in global operations (Min and Eom 1994).

Cudahy et al. (2008) proposed setting up a central office or a staff head to account for global operations and deal with the inevitable conflict among local, regional and global divisions. A center-led and coordinated decision-making function is called ‘Centers of Excellence’ (CoE),

which is a small, center-led group of experts within an organization who focus on standardizing processes, leveraging eSourcing technology, adopting the best practices, sharing information, and streamlining procurement activities (Hochman and Dorf 2008). Decisions that involve broader and more centralized strategies require resource alignment and information sharing between the locals and a central office to balance local requirements with overall network goals (Colotla et al. 2003). There must be a 'positive tension' and a balance must be made between corporate, regional, and local sites, with the process and principal decisions made on the central level, as well as daily operating decisions. Therefore, operational practices are best performed at the local sites (Cudahy et al. 2008, Monczka et al. 2008). Consequently, once grounded in resource integration and information visibility, global operations demand a strong and controlling power for decision-making and information acquisition. By so doing, a global operational model can reduce the total costs of ownership and leverage abilities and the resources of the entire operational network, thereby increasing manufacturing flexibility.

2.3 Global Operations System

Global operations emphasize the functions of identifying and evaluating alternative options for operation activities and the ability to structure complex managerial goals, constraints and variables. Information technology (IT) thus plays a critical role in global operations as it provides timely connection, collection, access to and analysis of information produced in interrelated operation activities from numerous operation sites. An early study by Eom and Lee (1990a) indicates that marketing and logistics are the predominant fields when adopting decision support systems (DSS). The application of DSS to solve a variety of operating problems in operations areas includes tactical and operational planning, strategic planning, manufacturing logistics management, monitoring and controlling manufacturing flow, transport management, planning/scheduling, and so on (Eom and Lee 1990b). Considering the complexity of global decision-making, Min and Eom (1994) thus proposed an integrated DSS framework for multinational corporates to enhance the effectiveness and efficiency of worldwide communications based on an information-network that could overcome geographical, cultural and legal barriers extant in the foreign market. They argued that the implementation of specific DSSs to aid specific logistical decisions should be designed for both cross-functional and cross-border operations and must build a network-based system that directly delivers information from foreign countries to the corporate headquarters (Min and Eom 1994). An integrated DSS which coordinates operation activities, shares a central communication network and evaluates trade-offs throughout the entire operation process is called a Global Operations System (GOS). More specifically, parameters, such as price, transportation fees, labor costs, lead time, quality and the available capacity of candidate factories, will be taken into consideration at the same time, using a mathematical algorithm model to obtain an optimal solution. A GOS should be designed with an effective flow of information across the entire operation network to eliminate duplicated effort and to successfully link activities from sourcing, production and marketing to logistics. As Min and Eom (1994, p.37) described, "The assimilation of up-to-date information and knowledge from different countries and fields can provide a "macroscopic" or "bird's eye" view to the operation planner to make better plans and decisions". Integrated operations enabled by such IT allow manufacturers to substitute 'information for inventories' so as to improve resource utilization and production flexibility for the whole network (Dudley and Lasserre 1989).

IT can not only provide greater information processing and communication ca-

pabilities, but also better controlled feedback mechanisms. However, it could be a challenge for trading partners using IT to achieve greater inter-firm collaboration and information exchange. Without the autonomy of administration, the quality and precision of shared information may be a problem. Therefore, the adoption of a GOS requires a restructuring of the operation network in which both the controllability and adaptability of manufacturing are high.

3. A Case of Global Operations in the Textile industry

3.1 Research Method

The purpose of this study is to suggest a qualitative case-based method to provide an insight into a particular area rather than to validate the existing theory. Both qualitative and quantitative data were collected.

Table 1: Interview Questions

Interview Questions
1. The purpose of GOS adoption.
2. Difficulties and problems encountered in the old business model.
3. The interviewee's role in business model change and GOS implementation.
4. The process of GOS implementation (project members and their roles, implementation method, steps etc.)
5. The role of MIS in GOS implementation.
6. GOS usage in NWTextile.
7. Difficulties and challenges for GOS implementation and business model change
8. Reasons for approving a GOS and global operations model.
9. The evaluation of GOS performance.
10. Functions of GOS.
11. Solutions for business model change and SBUs' resistance

One of the authors of this study was the consultant for this company's GOS implementation from the beginning of the project. Semi-structured interviews with key personnel, including the CIO and CEO involved in the GOS project, were conducted and a sample of the interview questions is illustrated in Table 1. During the interviews, extensive notes were taken and these notes were then written up as soon after the interviews as possible, often on the same day of the interviews. In addition to interviews, related information (such as GOS project documents including system analysis and design, budgets, project members, and a Gantt chart), and secondary data (annual NWTextile reports, newsletters, local newspapers and historical reports on the textile industry) were available for the authors as references. A system demonstration of the GOS was also provided by NWTextile and this allowed the authors a better understanding of the proposed functions of the system. However, for confidentiality, NWTextile requested that some information was not revealed. Participant observation and informal conversations with key personnel were also used by the author, who was the consultant of the company. These personnel included several senior managers of foreign SBUs (Strategic Business Units). Conversations with these key personnel helped the authors to understand the feelings of the different groups and attitudes toward the GOS implementation. On the basis of the collected data and literature, a rich organizational context has been developed in which the story of the adoption of GOS takes place.

3.2 NWTextile Group

NWTextile was established in the late 1970s by five good friends who had been awarded BA degrees from the same textile engineering department. They became the main stockholders of NWTextile. NWTextile started as a trading converter and fabric supplier, coordinating between textile traders and manufacturers. Despite a successful history, the textile industry in Taiwan has been put under pressure by the rise of China's textile industry and higher labor costs that came with economic development. It was inevitable that garment manufacturers would spread their manufacturing and marketing operations offshore. NWTextile also found it was getting more difficult and more competitive as a trading converter in Taiwan's textile industry. With changing markets and the trend of globalization in Taiwan's textile

industry, NWTextile started to expand its business from material manufacturing to apparel trading and manufacturing. From the 1990s to early 2000, NWTextile expanded its territory through reinvestment and developing joint ventures with Chinese and Mexican dyeing, weaving, and apparel trading companies, becoming an apparel OEM. NWTextile also invested in three apparel trading companies in the US (New York, Los Angeles, and Dallas) to evaluate US markets. The NWTextile group's businesses now include yarn spinning, dyeing and finishing, fabric sales, garment production, and other sales departments. In 2007, NWTextile group's global turnover was about USD 1.3 billion (over 70% from garments, approximately 15% from yarn-dyeing, and 10% from weaving). All of NWTextile's important apparel customers are in North America, including K-Mart, Wal-Mart, and Alfred Dunner. NWTextile group has a few factories in Africa and Central America. It also has joint-ventures and subcontracting material suppliers in Southeast Asia. During the expansion process, each stockholder was in charge of one or two companies and was responsible for a broad set of decisions relevant to his/her own units. NWTextile Taiwan undertook very few management roles within other units, and found it difficult to coordinate activities within the growing firm operated over broad geographical areas.

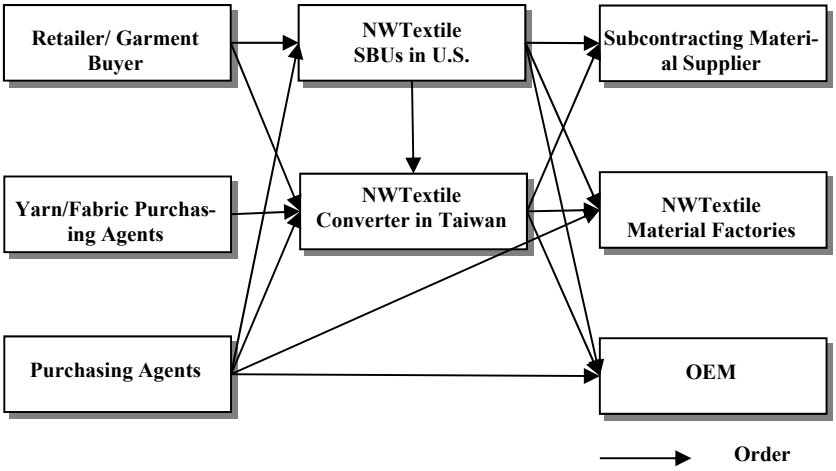

Figure 1: Operation Model of NWTextile before 2003

3.3 Unbalanced Resource Arrangement in the Decentralized Operation Model

The original operation model used by NWTextile is illustrated in Figure 1. Every local division within NWTextile served as a SBU, operated as a self-contained planning unit and was financially self-sufficient. SBUs in North America were in charge of marketing, sales, channel management, and apparel customer service, SBUs in the Asian Pacific region were in charge of dyeing, fabric and weaving, sourcing, marketing, and trading tasks, with an SBU in Mexico in charge of both material and garment manufacturing and trading.

The managers of each SBU had a large degree of autonomy. Each SBU developed its own business strategy, goals and operational plans that could be different to other SBUs. Most SBUs had purchase and sales staff who were responsible for their own SBU's purchasing and orders. Given that NWTextile was run as a decentralized collection of entirely separate units, it was not necessary for the sales and marketing SBUs to pass garments or material

orders with reference to the production, dyeing, or weaving SBUs within the NWTextile group. However, purchasing agents and sales personnel in the U.S. SBUs might choose suppliers from markets to enhance the profitability of their own units. NWTextile Taiwan, as a trading converter, had a set of external customers. Additionally, the material factories in Southeast Asia were not just run as internal material suppliers within the NWTextile group. NWTextile Taiwan, thus viewed itself as a customer of NWTextile New York and NWTextile Los Angeles, and the contrary was true for weaving SBUs and dyeing SBUs in Taiwan. All SBUs make their own decisions from a more local perspective, and some elements of the practical programs and facilities are shared among them. As the CIO and CEO of NWTextile Taiwan said:

"The purchase function was not independent in the old business model and every SBU could make its own purchase decisions. A manager could make decisions on fabric orders from tens to thousands of yards that could amount to millions of US dollars. He could also make decisions on outsourcing because he had to be responsible for the delivery date" (Quoted by the CIO).

"We used to view NWTextile US as our customers. We needed to compete with other (companies) to obtain orders from the US (SBU)" (Quoted by the CEO).

As Figure 1 describes, both NWTextile Taiwan and NWTextile U.S. would take garment orders from the customer first, and would then pick a manufacturing facility for their own consideration. The facilities were not necessarily NWTextile members. Manufacturing factories were independent from each other, meaning that they had separate manufacturing arrangements, sourcing, equipment and inventories. Once the orders were forwarded, the manufacturing process became an independent task of that SBU. Such arrangements virtually divided the whole NWTextile group into many smaller independent companies and the entire NWTextile group was unable to generate economies of scale and overall utility.

Given that commercial information is handled separately, the independent operations of each SBU decentralized the process of operational information flow and this created difficulties with the integration of information and resources among these SBUs. This model seriously impaired the decision makers' ability to quickly harmonize business units for global operations since they could not receive quick and integrated information from the other members. Functional activities spread over many SBUs resulted in inconsistent information and redundant efforts made by different unit managers. Strategies focusing on one site optimization also prohibited the NWTextile group from achieving overall optimization of the whole group. Consequently, this caused low efficiency and business conflict, and even competition among the SBUs. This decentralized operation model introduced an imbalance among the NWTextile manufacturers and meant that "some units had overcapacity and some had few orders" (Quoted by the CIO).

Table 2: Analysis of NWTextile Global Operations Layout

Regions	Regional Strength	Function	Affiliates	Quotas	Labor Costs	Delivery Speed	Industry Integration
Taiwan	1. Good at R&D 2. Complete integration of supply chain	Operations center, finance, strategy planning, R&D	Yarn dyeing, Weaving, Plain, Garment Factories	End by 2005	High	Medium	High
China	1. Mature textile industry 2. Good at producing complex products 3. Massive domestic market	Global sourcing, manufacture of garments, sweaters	Shanghai Sourcing Agent, Shenzhen Purchasing Agent	Uncertain	Medium	Medium	High
Southeast Asia	1. Good at producing complex products 2. Incomplete integration of supply chain	Manufacturing	Vietnam Garment Factories	End by 2005	Low	Slow	Medium
North America	1. The biggest apparel market 2. Fast response to customer requirements 3. Communication with customer is easy.	Sales and marketing	New York, Los Angeles, and Dallas companies	No	High	Fast	Low
Mexico	1. Duty free and no quota limitations 2. Quick response 3. Near to North America	Manufacturing	Dyeing, knitting, and garment factories	No	High	Fast	Low
Africa	1. Duty free and no quota limitations 2. Low labor wages 3. Reciprocal benefits from local government	Manufacturing	Garments, Dyeing, Weaving, Yarn spinning, Spinning factories	No	Low	Medium	Low

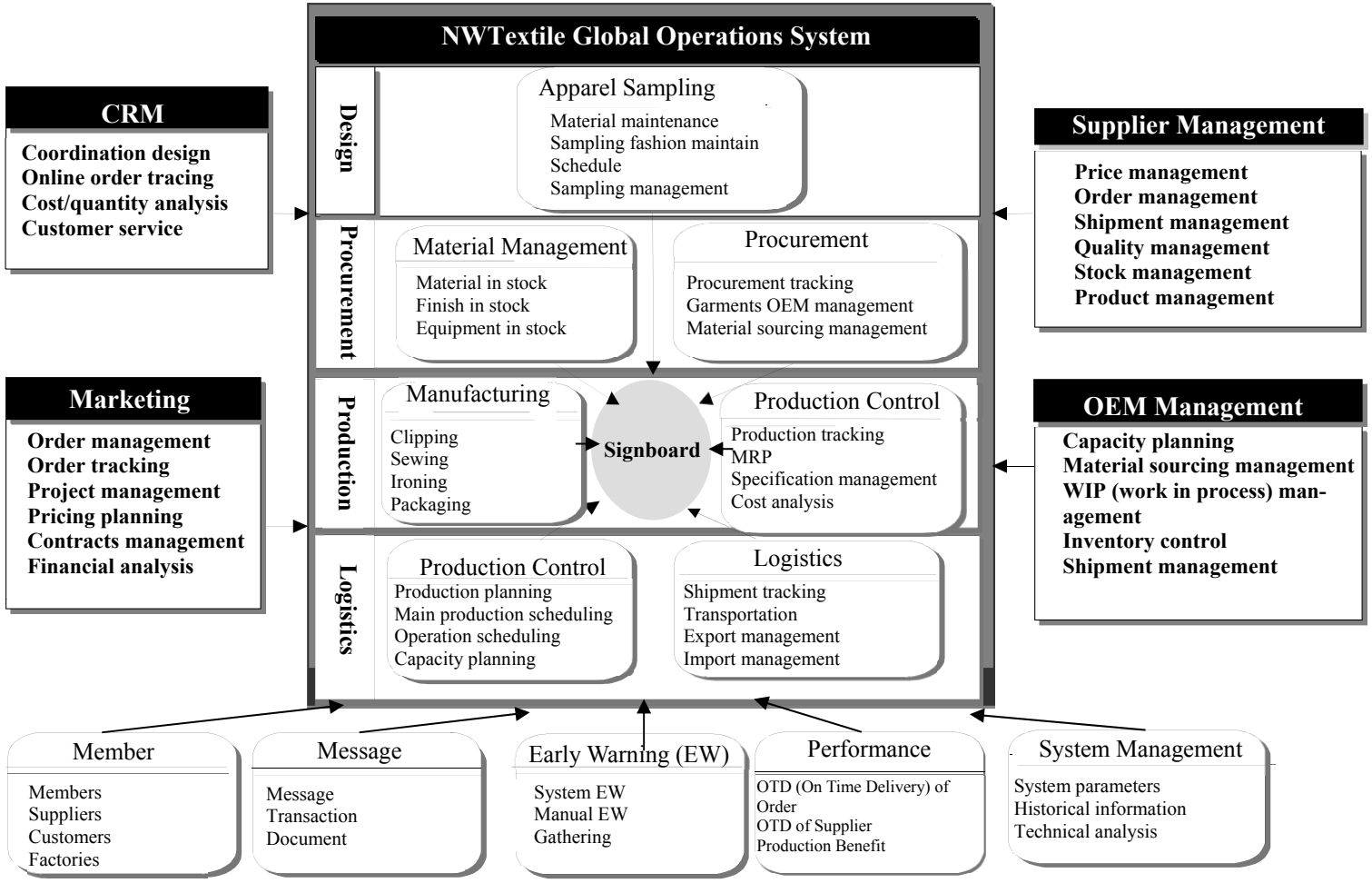

Figure 2: Functions of Global Operations System

4. Discussion

4.1 Changes to the Global Operations Model

With the increase in competition, NWTextile was forced to find its own competitive edge and niche market to respond to the economic challenges of costs, lead time, and trade restrictions. The CEO of NWTextile Taiwan recognized that the limitations and insufficiencies of its current operation structure where dragging down the performance of the entire group. NWTextile Taiwan thus began to transform its business model in 2002 to build a more integrative and globally-operated framework.

A global operations model requires appropriate operations and planning, according to the characteristics of each geographic region, which can quickly respond to the market and develop an optimal operational plan at the network level. To reach this goal, real-time information is vital in synchronizing and coordinating the different facilities. NWTextile Taiwan decided to build a comprehensive global operations network through a GOS that integrates information from all SBUs, OEM, joint-ventures and subcontractors that is relevant to the whole operational process. The analysis of NWTextile for global operations design is shown in Table 2 and the functions of its GOS are illustrated in Figure 2.

The goals of the GOS initiative are to (1) centralize decision-making and planning by managing operational information through a single nerve center, so as to better organize resources and the competence of all network members; (2) integrate resources and the abilities of all operation sites to provide operation strategies with a global perspective.

4.2 Organization Restructuring

The first step in the organization restructuring process was to redefine the roles and functions of each working site according to each SBUs' regional characteristics and competitive edge.

Southeast Asia and South Pacific: Although the largest clothing market is in North America, higher wage costs preclude manufacturers from establishing a labor-intensive plant there. Countries in Southeast Asia and the South Pacific, such as Vietnam, Cambodia, and Indonesia are more suited to fabric production and garment assembly because of lower wage costs. However, the application of certain complicated textile techniques requires not only low wages but also technical support and external resources from the whole textile industry. NWTextile, therefore, looked for OEMs and subcontractors in China, taking into consideration the increased development of China's textile industry as well as the massive domestic market. China is a member of the WTO, and there have been no quota limits on China since 2005. As a result, material suppliers in China, the South Pacific and Southeast Asia became the best choice for material sourcing and manufacturing.

Africa: Considering labor costs and quota limits, NWTextile chose Africa as their base for garment production . Because of the African Growth and Opportunity Act (AGOA), garments made in Africa were free from tariffs and quota limitations when exported to the U.S. before 2005. Additionally, since many countries in Africa were economicaly under-developed, as defined by the AGOA, NWTextile were also able to import materials from other regions to its African factories to maintain its duty-free status. Therefore, NWTextile built two new garment factories in Africa in 2001 and 2002.

Central America: For a garment manufacturer, on-time delivery is more important than quality control of the products. NWTextile found that the production systems in China and Southeast Asia were unable to service quickly the orders from North-American customers.

To solve this problem, NWTextile used Central America as a manufacturing

base. This region is a party to the North American Free Trade Agreement (NAFTA), which makes textile goods exported from this region duty free. Also, this region is close to the U.S. and the short communication distance makes lower labor costs feasible. NWTextile finally established garment factories, fabric factories, and dyeing factories in Mexico.

North America: North America is the biggest fashion market and has been the largest importing market of garments (The U.S. imported large quantities of clothing to the value of almost $90 billion in 2005, 80% of which was controlled by the big four retailers: J.C. Penney, K-Mart, Wal-Mart and GAP). Because of the short life cycle of apparel and the changing nature of fashion, marketing and manufacturers located in regions close to the U.S. are important in order to quickly respond to customers' changing demands. Taiwan is geographically far away from the Western world, thus it is difficult for Taiwanese manufacturers to have a good grasp on fashion trends in the U.S..

To obtain orders from the major U.S. retailers and to remain profitable, it is essential to provide a better service and be more active in maintaining a good working relationship. Since most of NWTextile's customers are located in North America, it was necessary for NWTextile to set up several branches in the U.S. to gain better access to their customers. For example, NWTextile can create value for customers by providing the newest information and innovative materials or samples, or by suggesting new production technology. Nonetheless, garment manufacturers still have to suffer cut-throat competition to survive in the market. A late delivery can be sufficient to destroy a thirty-year relationship. Therefore, the regions close to the U.S. are definitely important, considering speed-to-market for marketing and sales functions.

Taiwan: First, the textile industry in Taiwan is mature with a highly flexible supply chain. Second, related industries, such as yarn-spinning, weaving, and dyeing, are more prominent compared to other countries. Third, advanced production technologies for, textiles such as a computer assisted color match system has been pioneered in Taiwan and NWTextile Taiwan has developed strong R&D capabilities over a long period. Engineers in the R&D team have rich experience in yarn-dyeing, finishing, weaving, and garment production. NWTextile finally chose Taiwan as its operating center to manage information and determine sourcing, producing and manufacturing plans for the entire network. Based on the information passed from all units, suppliers, and OEM, the Taiwanese operation center can produce production plans and manufacturing schedules for its global operations in a more integrated way. The tasks and decisions of each unit can be found in Figures 2 and 3.

Table 3: Effectiveness of Global Operations

Performance	Before, 1st quarter, 2001	After, 1st quarter, 2003	Growth rate
On time delivery of orders	76.92%	89.21%	12.29%
On time delivery of suppliers	63.42%	79.12%	15.70%
Average lead time (days)	71 day	62 day	12.68%
Sales growth of NWTextile group (USD)	157 millions	242 millions	53.41%

As shown in Figures 3 and 4, sales, sourcing and production processes are integrated to leverage resources to reach a better arrangement for all network members. In the global operations model, resource management and planning functions are now regrouped by the global operation center in Taiwan. NWTextile Taiwan essentially acts as a full-service center to engage, integrate and coordinate global operation activities across the worldwide locations. In many respects, this center ena-

bles global operations planners to have a worldwide footprint. The optimization of global operations considers variables including quality, production costs, inventory costs, transportation costs, lead time, duty, and tariffs in a more holistic view enabled by the decision support function of the GOS (Figure 2 and Figure 3). Hence, global demand can be satisfied more efficiently, resources can be reallocated to different facilities more quickly, and large scale production can be planned and estimated more precisely.

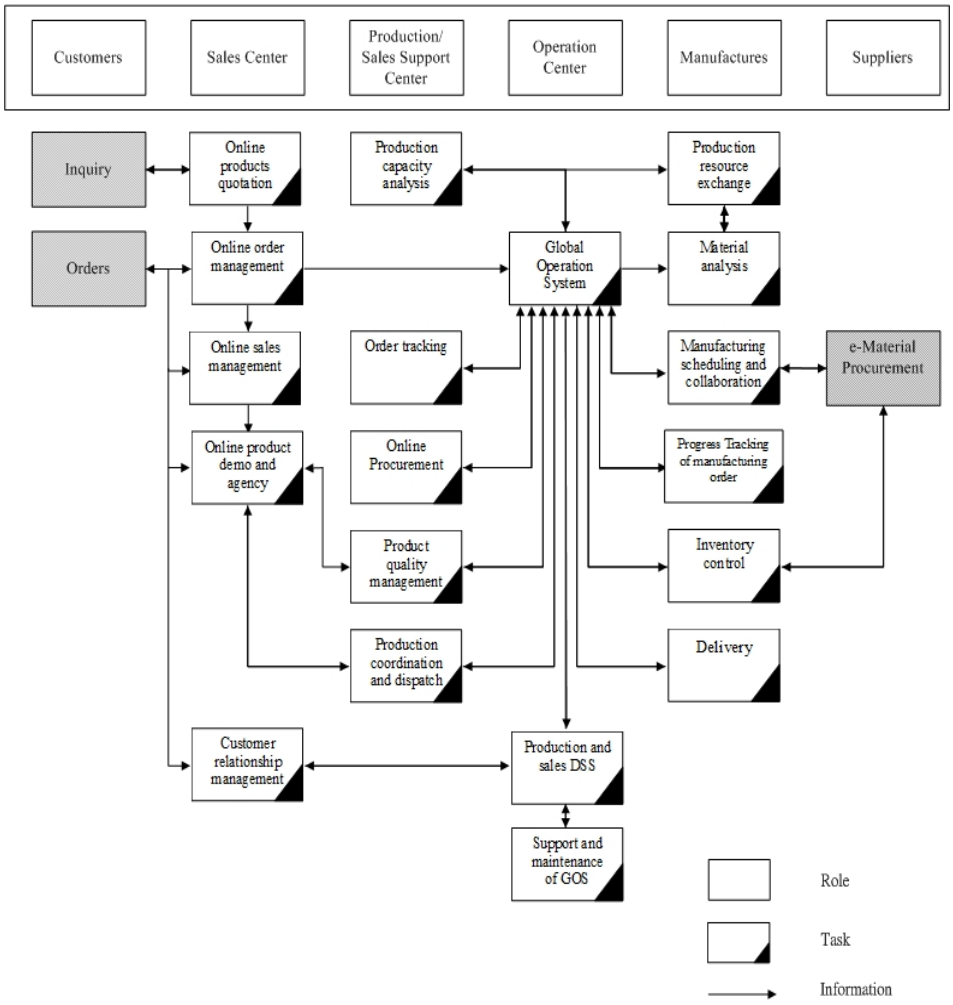

Figure 3: Global Operations Processes

Table 4: Financial Effectiveness of Global Operations

Year	Profit Ratio	Inventory Turnover	Average Days in Sales	Ratio or return on share-holder's equity
1998	4.01	5.57	65.53	7.61
1999	unavailable			
2000	0.04	11.94	30.56	0.11
2001	0.94	9.9	36.86	1.5
2002	2.37	11.27	32.38	4.92
2003	5.13	11.14	32.76	10.92
2004	5.44	9.8	37.24	8.43

The financial data is cited from the annual report of NWTextile Taiwan
Inventory turnover=cost of goods sold/average inventory
Average days in sales=365/inventory turnover
Profit ratio=net income/net sales

4.3 Transformation Process and the Difficulties Encountered

Before running global operations, NWTextile's global strategy was similar to a 'multinational strategy' (c.f. Bartlett and Ghoshal 1989). To quickly respond to diverse local needs and national opportunities, the Taiwanese headquarters managed its foreign subsidiaries as a loose federation, and each SBU operated its own business autonomously. The need for efficient communication with customers and for local responsiveness was the main driving force behind the old business model. Following the multinational strategy, manufacturing facilities within NWTextile were independent from each other and they were even financially independent. In such circumstances, the advantage of this kind of arrangement is that each facility can be flexible in determining its marketing and manufacturing-related matters. Conversely, the physical distance hindered information flow and high coordination costs all served to preclude optimal production and marketing arrangements. Consequently, the multinational strategy was unable to deal with orders of small quantities and great variety in an economically viable way as the entire NWTextile group was expanding.

The global operations model is closer to a 'transnational strategy' as the Taiwanese headquarters conducts most operational activities from a global perspective. Bartlett and Ghoshal (1989) argue that the goal of a transnational strategy is to retain local flexibility while simultaneously achieving global integration and efficiency as well as the worldwide diffusion of innovations. In this sense, the design of global operations aims to optimize supply and demand by utilizing the most competitive resources from each region. As Bartlett and Ghoshal (1989, p. 69) state, "dynamic interdependence is the basis of a transnational company - one that can think globally and act locally".

However, changing from a multinational strategy to a transnational strategy connotes the change in decision-making structures and thus requires the redesign of organizational structures to facilitate the implementation of new strategies. Therefore, the first problem faced by NWTextile is to rearrange its power and decision-making structure. Further, in the transformation process, NWTextile changed the location of its headquarters three times and finally chose Taiwan as its 'Center of Excellence (CoE)'. NWTextile also increased the stock holdings of its African SBUs (one factory from 60% to 100% and another from 30% to 80%) and continued to invest in U.S. SBUs (nearly 6 million USD in 2003 and 2004). Some SBUs had little willingness to join the new business model and NWTextile finally decided to sell a U.S. SBU and reduce the stockholding from 47% (in 1999) to 13% (2003) to 0% (in 2004).

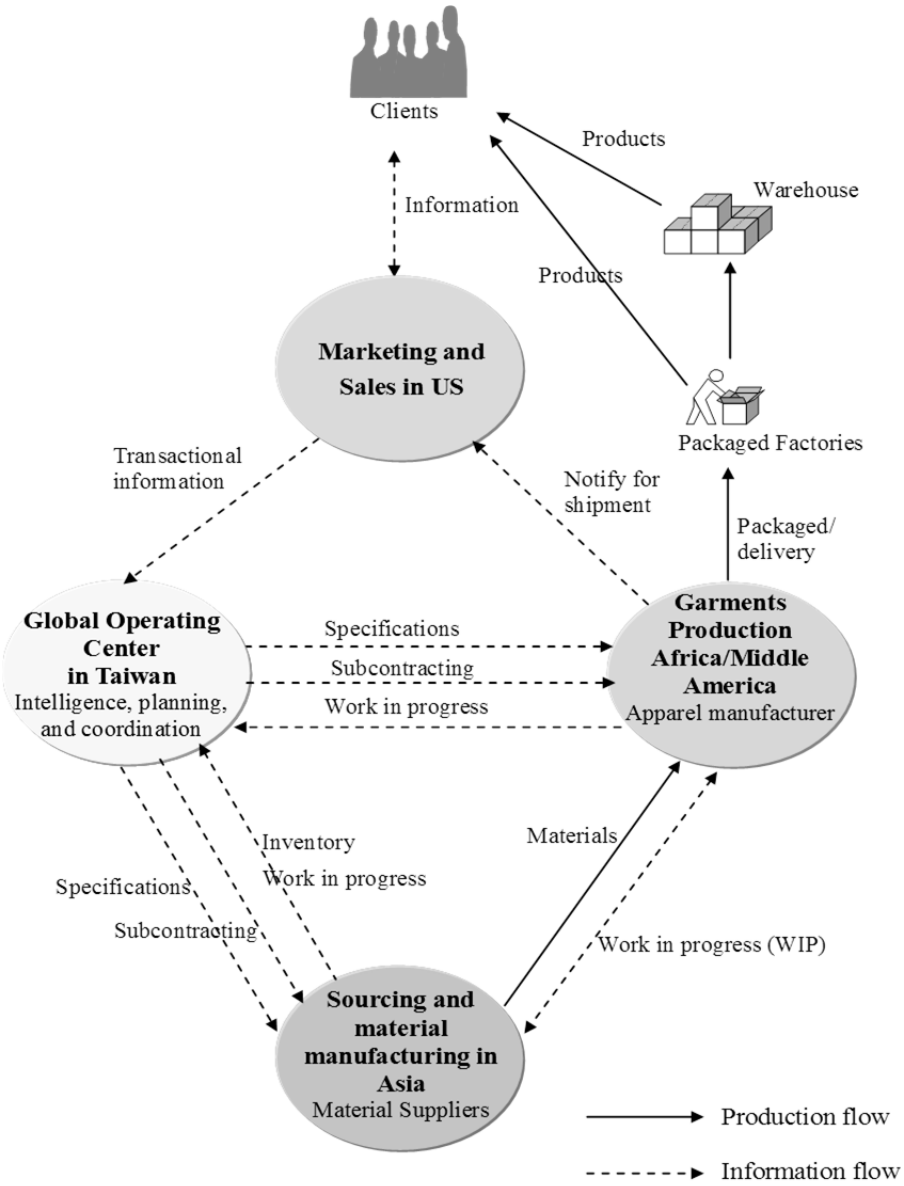

Figure 4: Global Operations Model of NWTextile

The changes to this global operation model took NWTextile a full five years to complete. The most important factors when introducing a business change are the top leader's determination and the clarity of their strategic goals (Ives and Jarvenpaa, 1991).

"Because of the GOS project, I was promoted to Vice General Manager. In this position, I could discuss business procedures with the directors of other SBUs in a fairer way" (Quoted by the CIO).

"Communication is an on-going process, even now. Collaboration with some factories has actually stopped and we no longer give them orders, while with some units it stopped in the middle of the collaboration. However, we are constantly re-

structuring and making changes all the time, since restructuring is an on-going process" (Quoted by the CIO).

By recognizing the importance of a leader's determination during a business change, the NWTextile's CEO himself handled the fear and anxiety emanating from structural change.

"As long as you can help factories with their business and reduce their costs, they are willing to discuss this with you. It might not be obvious that sometimes we had to rush people to two places during one day in order for the communication to go smoothly. It takes more than ten hours by airplane from the northern-most part of Guangdong to Shenzhen (in China)" (Quoted by the CIO).

"Sometimes when factories were not willing to provide production information, we had to talk directly to their managers. However, it had to be direct contact between the President and their managers; still I am not able to do that. Matters like this can be extremely complicated" (Quoted by the CIO).

"We had to go everywhere to communicate with them (SBUs) and explain the benefits of this model to them. I had even flown to ten places within seven days to do this" (Quoted by the CEO).

To reduce resistance from employees in the transition process, NWTextile first clarified the benefits of GOS to the top managers of every SBU, and arranged positions, career paths, training and education for employees at the same time. As a willingness to cooperate from all network parties is essential for the successful initiation of global operations, the NWTextile headquarters provided financial incentives to all SBUs to work towards the common goal of global operations. To align the incentives between local sites and the entire network, NWTextile Taiwan increased the commission ratio for SBUs on the total revenue of the headquarters and also increased employee stock bonuses.

NWTextile Taiwan was responsible for the fees, design, and development of GOS to encourage the SBUs, clients, suppliers and manufacturers to cooperate. Since the GOS could have had a great impact on all parties, the change was undertaken in phases.

5. Conclusions

In this study we demonstrate how the international textile group, NWTextile, responded to the challenges faced in the new post-quota era with organizational transformation. Over the past decades, NWTextile had grown by encompassing increasingly diverse business activities in textile trading and the manufacture of fabric, cotton yarn, and apparel. NWTextile used to adopt a multinational model to run its expanding businesses across broad geographical areas. Each SBU had full control of its own functional activities, including resource allocation, supplier selection, production line scheduling, new product development, and strategic direction making. With the multinational model, each regional unit was autonomous, and unit managers would seek to maximize their own unit interests, which could damage the interests of the entire NWTextile company. As the CIO of NWTextile Taiwan said:

"In the old model, we found that some units faced serious drought, and others were flooded."

Competing instead of cooperating and the difficulties of undertaking planning on a global scale motivated NWTextile Taiwan to frame its transnational strategy. In the IT-enabled global operations model, the functional activities that traditionally belonged to each unit were regrouped as an integrated system. Decisions regarding a global operations model considered the interplay and interdependence of manufacturing factories and the whole network at the same time in order to align local resources and capabilities with the network goal (Colotla et al. 2003). A planning and R&D center is now centralized in Taiwan, a sales and marketing center is located in the U.S., manufacturing is decentralized in Africa, South-East Asia, Mexico, and Chi-

na, whilst China is also responsible for sourcing activities. This model helps NWTextile eliminate inefficiencies and decrease the imbalance of resources and capacity allocation among network parties. Global planning in this transnational model made global economies of scale easier for NWTextile.

The GOS model helps NWTextile to centralize its coordination and control powers and achieve global integration and national responsiveness. With the support of the GOS, the corporate headquarters serves as a nerve center and manages all planning tasks. Thus, it can make day-to-day management decisions efficiently. Production and sourcing planning are separated from the manufacturing facilities. The nerve center can plan and arrange the production process according to the order price, delivery time, quality requirements, factory capacity, costs, distance, and so on. With respect to material sourcing, the nerve center makes decisions on 'where to buy' and 'from which suppliers' with the exception of some cheap local materials. Theoretically, the visibility is enhanced as the nerve center controls the orders, manufacturing capacity, inventory, and production progress via the GOS.

To implement the global operations model successfully and reduce the resistance from SBU stakeholders, NWTextile not only redesigned its operational process and integrated information flow across different SBUs, but the CEO of NWTextile also provided good incentives for the SBU owners, which included an increase in the commission ratio and employee stock bonuses for the stakeholders and top management. NWTextile Taiwan adopted a cross-holding strategy to gain support and control from the SBUs. In so doing, the relationship between NWTextile Taiwan and the SBUs changed from virtual integration to vertical integration. NWTextile Taiwan absorbed all tasks and fees for the GOS development, and provided training and education to the SBU staff. The chairman of NWTextile clarified the advantages of global operation by directly communicating to every stakeholder of each SBU continuously.

The findings of this study are provided to assist with the development of global operations in the future. First, when the general circumstances are uncertain and there is a lack of trust and commitment among the transaction parties, global operations may be performed through a governance mode that is more vertically integrated than virtually integrated.

As mentioned earlier, some firms struggle to build an operation network that will achieve higher manufacturing flexibility and cost advantages that enable them to survive in a globally competitive environment. To achieve the above objectives, some researchers argue that the structure of traditional vertical integration should be replaced with a virtual integration. Vertical integration is criticized for its low manufacturing flexibility, low adaptability, and high administrative inefficiency, even though it provides higher continuity and controllability over the whole production process (Dwyer and Oh 1988, Mahoney 1992). Conversely, in the governance structure of virtual integration, firms can outsource production activities and members if a virtually integrated production network can cooperate tightly and share manufacturing information through inter-organizational systems. In such electronic hierarchies, both collaboration and information sharing are enhanced, and both manufacturing flexibility and controllability are increased because of higher information visibility. However, virtual integration has its own challenges when sharing information among inter-organizations. Building on a transactional inter-organizational relationship, the extent and quality of information shared among firms may be inadequate and problematic. Given that this governance structure substitutes ownership with partnership, virtual integration requires very high levels of trust, commitment and a mutually-dependent relationship for sharing key

information (Ramsay, 2001). In an uncertain environment and a transactional relationship, information that is harmful toward self-interest may not be exposed sufficiently to other parties.

Both virtual integration and global operations are enabled by integrated information systems which synchronize material flow and allow firms to have greater upstream and downstream visibility. When implementing such integrated information systems, business models should be restructured for leveraging the benefits of the system (Ives and Jarvenpaa 1991). On the one hand, enhanced IT capability increases the scope that a firm can control and make decisions about. That is, with proper IT support, a firm can lower both its transaction costs and agency costs. On the other hand, a GOS is developed as a central system whereby the activities of all parties within an entire operation network are fully integrated. It requires a centralized governance structure to ensure the gathering of information and the follow-up on decisions is made by the headquarters. By increasing the level of the cross holdings of its SBUs, NWTextile Taiwan participated more fully in upstream manufacturing and downstream marketing. The cross holding strategy enabled the NWTextile headquarters to obtain information concerning demand, inventory buffers, work in process, and production capacity from its network members. With the increased ownership, the NWTextile headquarters gained greater control of the SBUs and was able to ensure sufficient information exchange and information quality.

Second, central to the new business model is the integration of all operational activities from a global perspective so as to consider the comparative advantages of the different regions, allocate resources and spread risks accordingly. As Taylor (2009) states, the operating practices of a firm are that it is usually retained or modified piecemeal when a firm extends its business and there is a need to develop a systematic and strategic view of the global supply chain management. In the GOS model, a centralized decision center should be created to arrange global resources from a global viewpoint. However, the execution of production, sales, and marketing practices are given to offshore parties and subcontractors. Such a design is meant to overcome the inherent differences that exist across different regions and to prevent individual sites from preceding their self-interests over the entire group's interests. Centralized planning with decentralized practices allows NWTextile to coordinate all its operational activities on a borderless basis in order to meet speed-to-market, production quality, and manufacturing flexibility.

Finally, when implementing a GOS, clarifying the benefits of the new business model, providing related training and education to all related persons, and providing financial incentives are key to reducing resistance and increasing individual parties' willingness to cooperate. Corporate restructuring, information integration, incentive alignment, centralized decision-making, and decentralized operations are all essential factors in the success of the global operations of NWTextile. Since the GOS might affect and restructure the costs and profits of an operation network, these changes should be undertaken gradually and should obtain stakeholders' buy-in to avoid employee resistance.

This paper contributes to the body of work on supply chains by demonstrating a paradigm shift in the operational model of the textile industry. We show that a centralized decision structure is the key to leveraging decentralized resources distributed globally. Global operations need greater centralized decision-making power for allocating all the network resources and administrative power in order to control the entire production process. Since IT reduces the administrative costs within firms, and also transaction costs between firms, researchers should rethink the issue of inter-organizational governance concerning the flexibility, adaptability, controllability

and the risks of vertical integration and of virtual integration for global operations.

Like the old Chinese saying: *'Strategies are devised in a military camp, battles are won thousands of miles away.'*

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