Design of an Automated Decision Support System for Scheduling tasks in a Generalized Job-Shop

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Declaration

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

Signature: ______________________ Date: ______________________

Abstract

This thesis is a case study focusing on two problems that occur frequently at manufacturing facilities in general: determining an optimal factory layout (floor plan for machines or workstations) and streamlining the process of scheduling production tasks. The case study is based on the Loubser Wood Components facility, a manufacturer of high quality wooden components in the South African Western Cape.

Literature on both these problems are researched extensively in this thesis. The factory layout problem has appeared in literature from as early as the 1950s whereas the job–shop scheduling problem appears in literature since the early 1950s. A new notation for classifying factory layout problems is also developed and presented.

A decision support system, based on an underlying mathematical modeling approach, to solve the factory layout problem (approximately) at Loubser Wood Components is developed in this thesis. This decision support system uses a hybrid *tabu search* meta–heuristic to minimize the material–handling cost between machines or workstations on the factory floor while also incorporating the re–installation cost of machines in the factory. The actual factory layout at Loubser Wood Components prior to this study was based on the collective experience and intuition of management.

A decision support system is also developed to streamline day to day process scheduling of orders. This decision support system also uses a tabu search meta–heuristic to minimize the total net flow time of all orders in a job–shop scheduling problem by estimating the processing time on individual machines. Prior to this study the management at Loubser Wood Components based scheduling decisions on past experience.

The results obtained in this thesis are expected to be of a major benefit to the layout as well as scheduling practices at Loubser Wood Components. Both decision support systems will be delivered to Loubser Wood Components for possible future implementation.

Opsomming

Hierdie tesis is ’n gevallestudie wat fokus op twee probleme wat algemeen voorkom by vervaardigingsaanlegte: die opstel van ’n optimale fabrieksuitleg (vloerplan vir die plasing van masjienerie) en die verbetering van die produksietaak–skeduleringsproses. Die gevallestudie is gebaseer op die Loubser Wood Components aanleg, wat hoë kwaliteit houtkomponente in die Suid–Afrikaanse Wes–Kaap vervaardig.

Die literatuur vir beide hierdie probleme is deeglik in hierdie tesis ondersoek. Die fabrieksuitlegprobleem verskyn al vanaf die vroeë 1950s in die literatuur, terwyl die werkswinkel skedu-leringsprobleem vanaf die 1950s in die literatuur bespreek word. ’n Nuwe notasie vir die klasifisering van fabrieksuitlegprobleme is ontwikkel en word in hierdie tesis voorgestel.

’n Besluitnemingsteunstelsel, gebaseer op ’n wiskundige modelleringsbenadering, om die fabrieksuitleg probleem by Loubser Wood Components (benaderd) op te los, is in hierdie tesis ontwikkel. Die besluitnemingsteunstelsel maak van ’n aangepaste tabu soektog meta–heuristiek gebruik om die hanteringskoste van materiaal tussen masjiene of werkstasies op die fabrieksvloer te minimeer deur die herinstalleringskoste van masjiene in die fabriek ook in ag te neem. Die uitleg van die fabriek voor hierdie studie was gebaseer op die kollektiewe ondervinding en intuïsie van Loubser Wood Components se bestuur.

’n Besluitnemingsteunstelsel is ook ontwikkel om die dag–tot–dag skedulering van produksietake te bevorder. Die besluitnemingsteunstelsel maak ook van ’n tabu soektog meta–heuristiek gebruik wat die totale netto produksietyd van alle bestellings in ’n werkswinkel skeduleringsprobleem minimeer deur die individuele prosesseertye van masjiene te beraam. Voor hierdie studie het die bestuur van Loubser Wood Components skeduleringsbesluite op ondervinding gebaseer.

Daar word verwag dat die resultate wat in hierdie tesis vervat is ’n beduidende verbetering in die uitleg en skeduleringspraktyk by Loubser Wood Components teweeg sal bring. Beide besluitnemingsteunstelsels sal aan Loubser Wood Components gelewer word vir toekomstige implementering.

Terms of Reference

This thesis is a case study in the optimal layout and the optimal job–shop scheduling of a manufacturing facility. The Loubser Wood Components (LWC) factory, upon which the case study in this thesis is based, focuses on the manufacturing of high quality wooden components, typically used in the assembly of doors, cabinets, counters and furniture. It is a privately owned factory situated in the South African Western Cape Province.

LWC has a large number of competitors in the Western Cape. Hence the streamlining of its operations is deemed extremely important by the management of LWC in terms of its survival.

Mr Evert Loubser and Mr Hannes Loubser are the owners and managing directors of the LWC factory. Their brother, Mr Jaco Loubser, is responsible for the accounting side of the business and they employ a permanent secretary. Currently LWC also supplies jobs to 20 workers, of whom 7 can operate specialized machines.

A need for a scientific production scheduling process was identified in 2001 by Mrs Isabelle Nieuwoudt (Department of Applied Mathematics, University of Stellenbosch), a customer of Loubser Wood Components at that time. In November 2001 Mrs Nieuwoudt and Prof Jan van Vuuren (Department of Applied Mathematics, University of Stellenbosch) identified the possibility of a masters thesis containing a case study based on Loubser Wood Components.

Mrs Isabelle Nieuwoudt was the supervisor and Prof Jan van Vuuren the co–supervisor of this thesis. The first meeting between the author and the directors took place in February 2002. In December 2002 the facility layout problem was identified during a visit to Loubser Wood Components, by the author, Prof Van Vuuren and Mrs Nieuwoudt. This thesis is the first study conducted at Loubser Wood Components.

The factory was visited on various occasions during 2002 and 2003 for the purpose of data capturing as well as for meetings with the directors. The computing facilities of the Department of Applied Mathematics, Electrical & Electronical Engineering as well as private facilities, were used during the multiple iterations and instances of solving the models in this thesis, in order to obtain solutions to both the facility layout and production scheduling problems. Work on this thesis was completed in December 2005, and work emanating from this thesis was presented twice at annual conferences of the Operational Society of South Africa (ORSSA) in 2002 and 2003.

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Glossary

absolute deviation: The absolute value of the difference between the *due date* and the *completion time* of a *job* in a *production scheduling* problem.

absolute location: The actual location of a *centre* inside a production facility.

active production schedules: The set of all feasible *production schedules* in which no *global left–shift* may be made in such a way that the *production schedule* remains feasible (*i.e.*, no *task* can start earlier without delaying any other *task*).

activity network: A *graph* representing a *production schedule* where *precedence constraints* are indicated by presenting the *tasks* by the *graph arcs*.

acyclic graph: A *graph* with no *cycles*.

adjacent vertices: Two *vertices* in a *graph* joined by an *edge*.

algorithm: An ordered sequence of procedural operations for solving a problem within a finite number of steps.

arc: A directed *edge* in a *graph*.

arrival time: The *starting time* instant of a *job* on the first *centre* in its *processing sequence* (assuming a zero *lead–time*).

aspiration criterion: A condition in a *tabu search* heuristic where a tabu restriction is overriden when a better solution than any previously obtained solutions in the search was obtained.

asymptotic bound: A bound on a function that is valid for all values of the function argument greater than some fixed value.

attribute–based memory: A memory structure used in a *tabu search algorithm* that forces a certain attribute of a solution as *tabu–active* for a certain time interval.

block: A maximum sub–sequence of *tasks* on the *critical path* in a *graph* representing a *job–shop production schedule* that is processed on the same centre.

bottleneck: An accumulation of unprocessed *jobs* at a *centre*, which obstructs the flow of production material through that specific *centre*.

branch–and–bound procedure: An *exact optimization method* consisting of exhaustive *tree* search enumeration of the solution space to an integer optimization problem by means of problem relaxations. Branching occurs *iteratively* on non–integer components of relaxed sub–problems and bounding occurs when it becomes apparent that a sub–tree cannot contain an optimal solution.

buffer: The time interval allowed for a *job* in a production facility to wait before it is processed on the next *task* in its sequence.

capacity planning: The process of deciding how much of the production time of a machine should be allocated to each *job*.

centre: A specific workstation in a production facility where usually one machine/individual is located or a number of machines/individuals performing the same *task* are located.

chain: See *path*.

chipboard: A paperboard used for many purposes that may or may not have specifications with respect to strength, color, or other characteristics. It is normally made from paper stock with different densities.

class NP: Abbreviation for Non–deterministic Polynomial. The set of all *decision problems* which may be answered "yes" by a polynomial time algorithm given additional information (called a certificate to the problem instance at hand).

class NP–complete: The set of all *decision problems* $\mathcal{A}$ in the class $\mathcal{A}' \prec \mathcal{A}$ for all $\mathcal{A}'$ in the *class* **NP**.

class P: Abbreviation for Polynomial. The set of all *decision problems* that may be solved by a polynomial time algorithm.

closeness graph: A visual representation of the *layout* of *centres* at a production facility in terms of a *graph*, using the information in the *flow–chart* and *rel–chart*.

complete disjunctive graph: A *disjunctive graph* in which all the *disjunctive arc pairs* are *settled*.

completion time: The time (instant) when the processing of the last *task* in the sequence of *tasks* for a *job* terminates.

complexity theory: The theory of computation dealing with the resources required during computation in order to solve a given problem using an *algorithm*. The most common resources are time (how many steps are required to solve a problem) and space (how much computer memory is required to solve a problem).

computational steps: A step that is usually defined within the context of the computational problem to be solved. An example of a computational step might be any operation within the set {addition, subtraction, multiplication, division, exponentiation, boolean decision (if gate)}.

conjunctive arc: A single directed *arc* in a *disjunctive graph* indicating the precedence between *tasks* in a *production schedule*.

connected graph: A *graph* in which there exists a *path* between every *vertex* pair in the *graph*.

constructive algorithm: An *algorithm* that constructs solutions to a *production scheduling* problem, directly from problem data.

continuous layout: A production facility *layout* where the *centres* may be positioned at any (continuous) location on in the production facility floorspace.

critical path: A longest *path* (determined by the relevant *arc* weights) in a *graph*.

cut length: The sum of the lengths of cuts made at a particular centre to manufacture a component in a production facility.

cycle: An alternating sequence of at least three *edges* and adjacent *vertices* in a *graph*, in which the first and last *vertices* are the same and no other *vertex* is repeated.

deadline: A fixed real time (instant) limit by which a *job* must be completed, according to an agreed upon *due date* presented to a customer.

decision problem: A problem which takes the form of a question with a binary answer, usually interpreted as “yes” or “no.”

dedicated processors: A set of *processors* in a production facility, each with a specialized function.

discrete layout: A production facility *layout* where the *centres* may only be positioned at a finite number of (discrete) locations on the production facility floorspace.

disjunctive arc pair: Two *arcs* in opposite direction between the same two *vertices* in a *graph*.

disjunctive graph: An *edge–weighted graph* consisting of a *vertex* for each *task* and two dummy *vertices*, representing the start and end of a *production schedule*. Every two *tasks* of the same *job* are linked by a *conjunctive arc* whereas *tasks* that should be processed by the same *centre* are linked by *disjunctive arcs*.

diversification strategy: A strategy in a *tabu search algorithm* where the solution chosen is rather a solution that is visited for the first time than a solution with the greatest improvement in the *objective function* value.

due date: The time (instant) by which a *job* in a *production schedule* should be completed, as specified by the order.

earliness: The positive difference between the *completion time* and the *due date* of a *job*. If the difference is negative then the earliness is taken to be zero.

edge: The elements of the *edge set* of a *graph*.

edge set: A (possibly empty) finite set of two–element subsets of the *vertex set* of a *graph*.

edge–weighted graph: A *graph* with weighted *arcs* or *edges*.

effectiveness evaluation chart: A measure of the effectiveness of the nodal arrangement in a *closeness graph*.

efficient algorithm: An *algorithm* capable of solving a problem in polynomial time.

exact method: An optimization technique that is guaranteed to find an optimal solution to a combinatorial optimization problem.

fathomed branch: A branch in a *branch–and–bound procedure* where a sub–problem is encountered from which no further branching takes place.

flexible layout: A *layout* of a production facility that remains desirable even when significant temporary changes occur with respect to production material flow volumes.

flow–chart: A triangular matrix indicating the compound flow between *centres* in a production facility.

flow–shop: A manufacturing facility in which the *tasks* of a *job* are processed in a specific order and every *job* has the same number of *tasks*.

frequency–based memory: A memory structure used in a *tabu search algorithm* that uses a measure of frequency to determine whether a possible solution is tabu.

from–to matrix: A matrix indicating the flow (measured in number of trips, or volume of production material) between individual *centres* in a *production facility*.

Gantt chart: A line or block chart, in which time is represented on the horizontal axis and other quantities (such as *job* processing time) on the vertical axis.

genetic algorithm: An iterative meta–heuristic approach towards solving a multi–dimensional optimization problem. It may be described as a mechanism that mimics the genetic evolution of biological species. The main difference that distinguishes it from *simulated annealing* being that it deals with populations of solutions rather than with single solutions at each iteration. Solutions interact and produce solution offspring that hopefully retain the good characteristics of their parents, in terms of contributing to the optimality of solutions.

global left–shift: Said when a *task* is moved into a gap earlier on in a *production schedule*.

graph: An object $G = (V, E)$ consisting of a non–empty, finite set V of combinatorial objects called *vertices* as well as a (possibly empty) finite set E of two–element subsets of V called *edges*.

greedy algorithm: A *heuristic* search *algorithm* that selects the best solution to a *production scheduling* or *layout* problem at each iteration, disregarding possible future repercussions in terms of the optimality of the final solution as a result of choosing the best alternative at each step.

hessian: The matrix of second partial derivatives of a function of more than one variable (assumed to be twice differentiable).

heuristic algorithm: In *mathematical programming*, usually referring to a procedure that seeks an optimal solution, but it is not guaranteed to find one, even if one exists.

in–process inventory: The inventory of stock or raw material that is on hand in a production facility during processing.

integer programming problem: A *mathematical programming* problem in which some or all the variables are required to be integers.

intensification strategy: A strategy in a *tabu search algorithm* where the solution with the greatest improvement in terms of the *objective function* is chosen rather than a solution that has never been visited before.

job: An order placed by a customer, consisting of a fixed number of *tasks*.

job flow time: The amount of time required to complete a *job* in a *production scheduling* problem, assuming the job starts at time 0.

job net flow time: The amount of time required to complete a *job*.

job waiting time: The total time spent by a set of *jobs* in queues (at *centre*) in a production facility.

job–shop: A manufacturing facility where the *tasks* of a *job* should be processed in a specific order.

lateness: The *due date* of a *job* subtracted from the *completion time* of the same *job*.

layout: A positioning of resources (typically *centres* within a finite area, for example on a factory floor).

lead–time: The time interval that a *job* in a *production scheduling* problem has to wait for resources to become available before its processing commencement may be *scheduled*.

local left–shift: Said when a *task block* in a *Gantt chart* is moved to the left (*i.e.,* earlier in time), thereby adjusting the *starting time* of the *task*.

machine idle time: The total aggregated amount of time that *centres* were idle during the *makespan* of a *production schedule*.

makespan: The total amount of time required to complete a set of *jobs*.

material–handling: The movement or transportation of production materials.

mathematical programming: An optimization dicipline, in which the aim is to seek to minimize or maximize an *objective function* of real or integer variables, subject to constraints on the variables.

mixed integer linear programming problem (MILP): A *mixed integer programming problem* in which the *objective function* contains a linear combination of the *problem* variables.

mixed integer programming problem: An *integer programming* problem in which some, but not all, of the variables are required to be integers.

neighboring move: A set of trial solutions that may be reached from a given candidate solution by means of a single solution structure modification in a *tabu search* approach toward solving a combinatorial optimization problem approximately. Also called the solution *neighborhood*.

non–delay production schedules: The set of all feasible *production schedules* in which no *centre* is idle at a time when it could begin processing a *task*.

non–preemptive production schedule: A *production schedule* in which a *task* may not be interrupted.

objective function: A real–valued function of real or integer variables in a *mathematical programming problem* whose value is to be minimized or maximized.

open–shop: A manufacturing facility where the *tasks* of a *job* may be processed in any order and every *job* has the same number of *tasks*.

optimal production schedule: An *active production schedule* that processes minimum *makespan*.

parallel processors: A set of *processors* in a *production facility*, all performing the same function.

past due: The amount of time by which a *job* in a *production schedule* extends past its *due date*.

path: An alternating sequence of *edges* and *adjacent vertices* in a *graph*, both beginning and ending in a *vertex*, in which no *vertex* is repeated.

path length: The sum of the weights on the *edges* in a *path*.

positive definite matrix: A matrix A that satisfies $\underline{x}^T A \underline{x} > 0$ for all nonzero vectors $\underline{x}$.

precedence constraints: A constraint in a *production scheduling* problem indicating that some event must occur before another event .

preemptive production schedule: A *production schedule* in which a *task* may be interrupted at any time and restarted at a later stage.

process layout: The *layout* for a production facility that produces a large variety of different products, but a low volume of each product. For this *layout centres* are grouped together according to their functions.

processing sequence: The order in which the *tasks* of a *job* should be processed at different *centres*.

processing size: The space or area associated with a particular *machine* that needs to be available to process orders, including the space required by a worker to operate the *centre*.

processor: A *centre* or workstation in a manufacturing facility.

production scheduling: The assignment of *jobs* in a *production facility* to production machines at specific times.

quadratic assignment problem (QAP): A minimization problem consisting of a quadratic cost *objective function* together with a set of linear constraints in a set of binary variables.

quadratic integer programming problem: An *integer programming problem* with a quadratic *objective function*.

quadratic programming problem: A *mathematical programming* problem with a quadratic *objective function*.

recency–based memory: A memory structure used in a *tabu search* approach toward solving a combinatorial optimization problem approximately, that forces a certain solution to acquire a *tabu–active* status for a certain time interval.

relative location: The location of a *centre* relative to the other *centres* in a production facility.

rel–chart: Short for relationship chart. This chart consists of a qualitative measure of the closeness of different *centres* in a production facility.

scheduling: The allocation of resources (such as *centres*, or workers) to production *tasks* over time.

semi–active production schedules: The set of feasible *production schedules* in which a *local left–shift* may be performed in such a manner that the *production schedule* remains feasible.

set–covering approach: A technique towards solving a *layout* problem in which the set of feasible locations for *centres* is determined in advance.

settled disjunctive arc pair: Said about a *disjunctive arc pair* when one of the *arcs* has been selected to fix the precedence between the two particular *vertices*.

simulated annealing: A *heuristic* search *algorithm* that does not search for the best solution in the *neighborhood* of the current solution, but draws a random solution and accepts it as the next solution if it has a better *objective function* value.

squared deviation: The square of the *absolute deviation* in a *production scheduling* problem.

standard deviation: A measure of uncertainty of the dependent variable in a regression curve fit, defined as the spread of data around the mean.

standard error: A qualitative measurement of the error made for a regression curve fit, defined as the spread of data around the regression curve.

starting time: The time instant at which processing of a *job* starts at the first *centre* in its *processing sequence*.

tabu–active: The status acquired by a *neighboring move* at a certain iteration if it is in a *tabu search heuristic* implementation. Such a *neighboring move* is forbidden to be considered as a possible future candidate solution.

tabu list: A list containing information about recent choices with respect to *neighboring moves* (therefore having a *tabu–active* status) in a *tabu search* approach towards solving an optimization problem approximately.

tabu point: A *tabu–active* solution in a *tabu search* approach toward solving a combinatorial optimization problem approximately.

tabu search: A *heuristic algorithm* which is based on designing and exploiting adaptive memory structures in order to determine iteratively locally optimal solutions to an optimization problem.

tardiness: The positive difference between the *due date* and the *completion time* of a *job*, in a *production scheduling* problem. If the difference is negative, the *tardiness* is zero.

task: A process performed by a single *processor* at a *production facility*.

task–on–arc graph: A directed *graph* whose *vertices* represent time events and whose *arcs* represent *tasks* in a *production scheduling* problem.

task–on–node graph: A directed *graph* whose *vertices* represent *tasks* and whose *arcs* correspond to *precedence constraints* in a *production scheduling* problem.

total inventory: The sum–total of inventory units of stock or raw material required to process a set of *scheduled jobs* in a production facility.

total net flow time: The sum–total of the net *flow times* of each *job* in a predetermined set of *jobs* in the context of a *job–shop* schedule.

tractable: Said of a computational problem that belong to the *class* **P**.

tree: A *connected acyclic graph*.

uniconnected activity network: An *activity network* in which two *vertices* are connected by a direct *path* in one direction only.

unit penalty: A binary value that is equals to 1 if the *job* is completed after the *due date* of the *job*, and equal to 0 otherwise.

unrelated parallel processors: A set of *parallel processors* with different processing speeds depending on the *tasks* processed.

utilization: The percentage of work time productively spent by a *centre* or worker.

value chart: A conversion or decoding of a *rel–chart*, during which the quality measures of the different *centres* are converted to values.

veneer cover: Thin layer of wood or an artificial product (such as melamine) over the wood *chipboard*. These covers are produced in different colours and patterns.

vertex: A combinatorial object in terms of which the *vertex set* and *edge set* of a *graph* are defined.

vertex set: A non–empty, finite set containing the *vertices* of a *graph*.

weight priority: A weight assigned to a *job* that indicates its priority relative to the other available *jobs*.

work–in–process inventory: All *jobs* waiting in queue to be processed by *centres*.

worst–case complexity: A (possibly *asymptotic*) upper bound on the space [time] *complexity* of an *algorithm*.

List of Reserved Symbols

$\mathcal{A}$	the set of all conjunctive arcs.
B_i	a block, which is a maximum subsequence of the critical path u in a disjunctive graph, where all tasks in block B_i are processed on the same machine.
c_j	completion time of job J_j.
$C_{ik,jh}$	is the material–handling flow between centres i and j expressed as a product of the flow and the travel distance.
$C_{\max}$	the makespan of a schedule in other words the length of the longest path of the schedule.
C^v_{ij}	vertical movement cost between centre i and j,
d_j	due date; time instance by which job J_j must be completed according to the schedule.
d_{kh}	rectilinear distance from location k to location h.
$\mathcal{D}_k$	set of settled arcs such that $\mathcal{D}_k \subset \mathcal{E}_k$.
$\mathcal{E}_k$	set of pairs of tasks to be processed on processor k.
$\mathcal{E}$	set union of $\mathcal{E}_k$.
$\mathcal{E}(\pi)$	set of pairs of tasks according to the processing order π.
f_{ij}	material flow from centre i to centre j.
$f_{\max}$	the tabu list length.
$\mathcal{F}$	the tabu list.
F_{ik}	cost of placing centre i at location k.
F_j	the net flow time of job j.
$\mathcal{G}$	the total net flow time of all the jobs is a production schedule.
G	the cost per metre of the electrical cables required for the installation of centres,
$G(\pi)$	the graph with node set $\mathcal{T}$ and edge set $\mathcal{A} \cup \mathcal{E}(\pi)$.
H	floor height of all floors,
I_i	cost of installing centre i,
$\mathcal{J}$	a set of k jobs $\{J_1, \ldots, J_k\}$.
J_j	job; a set of n_j tasks $\{T_{1j}, \ldots, T_{n_j j}\}$.
K	number of potential factory floors.
$\ell_{\max}$	the length of the backtracking list $\mathcal{L}$.
$\mathcal{L}$	the backtracking list used in tabu search with backtracking.
$\mathcal{M}_k$	set of tasks processed by machine $P_k \in \mathcal{P}$.

m	Number of processors/machines available for processing.
n	Number of jobs available for processing.
$\mathcal{P}$	a set of m processors $\{P_1,\ldots,P_m\}$.
P_i	the processor numbered i.
$p_{ij}(k)$	the time needed by processor P_k to process task T_{ij}.
$\mathbf{p_{ij}}$	$[p_{ij}(1),\cdots,p_{ij}(m)]^T$: a vector of processing times for task T_{ij} on machines 1 to m.
π	an m–tuple representing the processing order of tasks on machines, $\pi=(\pi_1,\ldots,\pi_m)$.
π_k	the processing order of the tasks on machine P_k.
$\pi_k(i)$	denotes the task to be processed i–th by machine P_k.
Π_k	the set of all permutations of π_k.
$Q(\pi,v)$	the new processing order after move $v\in V(\pi)$ has been applied to processing order π.
r_j	arrival time; time at which job J_j is ready for processing.
$\mathcal{R}$	a set of s processors $\{R_1,\cdots,R_s\}$.
R_i	the resource numbered i.
s_j	the earliest starting time of job J_j.
T_{ij}	task T_i of job J_j.
$\mathcal{T}$	the set of all tasks $\{T_{11},\ T_{21},\ldots,T_{n_11},T_{12},T_{22},\ldots,T_{n_22},\ldots,T_{1j},\ldots,T_{n_jj},\ldots,T_{1k},\cdots,T_{n_kk}\}$.
u	the set of nodes on the critical path $u=(u_1,\ldots,u_w)$.
u_j	a node element of the critical path, an element of $\mathcal{T}$.
$V(\pi)$	the set of moves for the tabu search with processing sequence π.
w_j	the weight priority of job J_j.
$X^{\max},Y^{\max}$	dimensions of the available floorspace.

Chapter 1

Introduction

1.1 Layout & Scheduling Problems

Time and cost efficient production is becoming increasingly important in modern, global competitive markets [63]. Only an efficient and productive organization will survive in today's competitive market [185]. Scheduling production tasks at factories and planning factory floor *layouts* are examples of decisions that play a crucial role in the manufacturing industry. This leads to a continual re–evaluation of the facility layout as well as scheduling practices by production facility management. Failures to meet delivery dates lead to a loss in profit and goodwill. Another challenge is the various performance measures, involving multiple production activities, that should be optimized. Teamwork forms a crucial role — even though each member (designer, production worker, material–handler, etc.) of the team may be an expert in his or her own area, each person's work must achieve the overall objectives of the manufacturing plant. There are numerous decisions that affect manufacturing time and cost. *Scheduling* deals with the allocation of resources to production tasks over a specific time period. The resources may be for example machines, personnel, processing units, whereas tasks are individual operations performed by single resources. Re–evaluation of the *facility layout* deals with the possible repositioning of resources on the facility floor.

1.1.1 Why a Good Facility Layout?

Appropriate solutions to facility layout problems are important for three reasons. Firstly, *material–handling*[1] costs typically comprise between 30 and 75 percent of the total manufacturing costs at production plants [185] and hence an effective facility layout may reduce this cost significantly [192]. Secondly, material–handling leads to an estimated 50 percent of all industrial injuries [116]. A good layout may remove a considerable amount of the physical drudgery of material–handling [116], which may, in turn, lead to satisfied workers. Thirdly, the plant layout is a long–term, costly proposition, and subsequent modifications or rearrangements of an implemented plant layout typically incur a large cost and cannot be accomplished easily [185].

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[1] Material–handling is defined simply as the movement or transportation of material.

1.1.2 Why a Good Schedule?

The problem of scheduling jobs is widely encountered in manufacturing practice [186]. Scheduling in this context is the act of defining priorities or arranging activities to meet certain requirements, deadlines, constraints or objectives. Because time is a limiting resource, one typically needs to schedule activities, consciously or subconsciously, to utilize this limiting resource in an optimum manner [184].

Part of the difficulty in dealing with this problem is that the resources are, typically, interchangeable to some degree. More equipment and more employees (both at a larger cost) typically speed up throughput. A larger workforce may reduce the amount of overtime cost, but on the other hand, more overtime may enable a company to operate with a smaller work force. A suitable compromise of resources must therefore be found [62].

There are three kinds of schedules for manufacturing facilities. The first is *staff schedules*, where workers are assigned to time slots. Secondly, there are *production schedules*, where *jobs* (orders for products usually placed by customers) are assigned to production machines at specific times, and finally, there are *operation schedules*, where workers are either assigned to machines or jobs.

The construction of good schedules is therefore very important for several reasons. Every manufacturing facility typically aims to satisfy customers, indirectly implying they adhere to delivery dates. This can only be accomplished via efficient schedules. Inventory control problems and *bottlenecks*[2] may also be avoided or alleviated via good schedules. A satisfied worker is a good worker, and therefore satisfying the workforce is cardinal in manufacturing facilities. Good schedules ensure that workers know their working hours well in advance and that overtime is minimized, resulting in more satisfied workers.

1.1.3 General Characteristics of Manufacturing Problems

The general manufacturing problem may be stated as follows: Suppose that a number of *jobs* have to be performed, each of which consists of a number of *tasks*[3], utilizing a number of *resources*[4]. The problem is to determine the best production schedule for the jobs and tasks to be processed on/by the resources, and to change the layout of the resources to adhere to the overall objective of the manufacturing plant. Two kinds of feasibility constraints are typically encountered in scheduling problems. Firstly, there are limits on the capacity of available resources, in the sense that, for example, one machine may process only one task at any given time and that a factory worker may only work on one task at any given time. Secondly, there may be technological restrictions on the order in which tasks may be performed [9].

A manufacturing facility may be characterized by the number of machines in the facility, the number of tasks of each job to be completed, the processing times of the tasks, the demand patterns, the resource layout and workforce availability. The manager of a facility must decide how the layout of the facility should be designed and which scheduling methods should be used.

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[2] A *bottleneck* usually represents a pile up of jobs (orders) in front of a resource (machine), which obstructs the flow of production material through the facility.

[3] Each job consists of a fixed number of tasks, where a *task* is a process performed on a single production machine or workstation at the facility. All the tasks of a specific job have to be performed either in a fixed sequence or in any order, depending on the kind of *shop* represented by the manufacturing facility. If the manufacturing facility is a so–called *open–shop* the tasks may be processed in any order, but if it represents a so–called *job–shop*, the tasks must be processed in a specific sequence for each job.

[4] In manufacturing facilities the resources usually are the machines, workers and their production time.

In the layout problem there are a number of production machines or workstations that have to be positioned in such a way that a specific *objective* is minimized. The objective is usually to minimize the material–handling cost, but may also be to minimize occupied floorspace, maximize adjacencies of machines, ensure flexibility and accommodate potential expansion of the facility and thus minimize the cost of relocating machines. There are four general criteria to be considered in layout designs [185]:

- *Safety.* The facility layout should promote the safety of its workers and there should be sufficient precautions for hazardous situations.
- *Performance.* The benefit/cost ratio of the facility must be in order to show a profit.
- *Comfort.* Workers should be satisfied with their work situation and the layout of the area in which they work. The workers should also be able to move material comfortably within the facility.
- *Higher objective.* Some facilities design layouts in a way so as to promote social contact between workers.

In the production scheduling problem, the aim is usually to find the processing order of tasks on each machine such that a given cost function is minimized. The processing demand is not always constant and may change over time, depending on the industry. If, for example, the facility manufactures surfboards, the demand will be higher during summer, whereas if the facility manufactures paper, the demand will be approximately constant throughout the year. Many different performance measures may be used during scheduling decisions. The following list identifies and describes the more commonly used measures [9, 116]:

- *Job flow time.* The amount of shop time required for the completion of a job is called the job flow time. It is the difference between the *completion time*[5] (instant) and the time instant at which the job became available for its first processing task.
- *Makespan.* The total amount of time required to complete a *set* of jobs is the makespan of the set of jobs.
- *Past due.* The measure of past due may be expressed as the amount of time by which a job misses its *due date*[6], or the percentage of total jobs processed over some period of time that missed their respective due dates.
- *Work–in–process inventory.* Any job waiting in a queue is considered part of the work–in–process inventory. This measure may be expressed in production units, number of jobs, monetary terms, or weeks of supply.
- *Total inventory.* The sum–total of inventory units required to process a set of scheduled jobs is called the total inventory of the set of jobs.
- *Utilization.* The percentage of work time productively spent by a machine or worker is called the utilization of that machine or worker. It may be aggregated for more than one machine or worker. If there are fewer workers than machines, utilization is calculated separately for each relevant resource.

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[5] The *completion time* of a job is the time (instant) when the processing of the last task in the sequence of tasks of the job terminates.

[6] The *due date* of a job is the time (instant) by which the job should be completed, as specified by the order.

- *Job waiting time.* The total time spent in queues (in front of production machines or workstations) by the tasks of a job, is the job waiting time of that specific job.
- *Machine idle time.* The total machine idle time of a task schedule is the total aggregated amount of time that machines were idle during the makespan of the set of all jobs *i.e.,* the schedule.

All the above performance measures are usually minimized, except for *utilization*, which is typically maximized. Schedules may be grouped into preemptive and non–preemptive schedules. In a *preemptive schedule* a task may be interrupted at any time and restarted later at no additional cost. In a *non–preemptive schedule* this practice is disallowed.

1.2 The Loubser Wood Components Factory

The Loubser Wood Components (LWC) factory, upon which the case study in this thesis is based, focuses on the manufacturing of high quality wooden components, typically used in the assembly of doors, cabinets, counters and furniture. It is a privately owned factory situated in the South African Western Cape Province.

Wooden components are made to order at LWC, and typically these components comprise four parts: a chipboard or super–wood centre, solid wooden edges, a veneer cover and an acid catalyzed lacquer layer of varnish. LWC manufactures a large variety of wooden components, but mainly focuses on the above mentioned four products (in terms of order volumes). However, there is also a variety of routine contract work options on specific machines that have to be taken into consideration during the production scheduling process on the LWC factory floor. The factory floor consists of two equally sized warehouses connected by means of a tilted ramp. The ramp causes problems when materials are moved between machines on the different warehouse floors, because human resources are required to push trolleys carrying raw production material up or down the ramp without damaging the transported components. There are fifteen machines on the LWC factory floor. However, some products need to be processed at an external factory as part of their processing sequences.

LWC has a large number of competitors in the Western Cape. Hence the streamlining of its operations is deemed extremely important by the management of LWC in terms of its survival.

1.3 Informal Problem Description

The facility layout at LWC is of concern to its management in terms of the large number of machines that could cause bottlenecks when moving raw material between machines on the factory floor.

There is a large variety of products that LWC offers and because products are made to order, the management of LWC does not know in advance which type of order will be requested. Scheduling is therefore a day to day task. Due to the large variety of components manufactured by LWC, the multiple functions of some machines and the external facilities that need to be visited in some machine processing sequences, the scheduling of orders on the machines causes bottlenecks on the factory floor, resulting in possible delays in the dispatch dates of orders.

Four objectives were set for this thesis:

I: To investigate and determine any mathematical method that may be used to improve the LWC facility layout.

II: To investigate and determine any mathematical method that may be used to improve the scheduling at LWC.

III: To develop a computerized decision support system (DSS) by implementing the mathematical method(s) of Objective I in order to assist LWC in solving its layout problem.

IV: To develop a computerized DSS by implementing the mathematical method(s) in Objective II in order to assist LWC in resolving its day to day scheduling problem.

These objectives will be pursued throughout this thesis.

1.4 Thesis Preview

A concise survey of the literature on the facility layout problem and the job–shop scheduling problem will follow in Chapter 2. The complexities of these two problems in a general scenario are also considered in Chapter 2. A number of exact and heuristic facility layout and job–shop scheduling methodologies that were specifically applied to the LWC case study are reviewed in detail in Chapter 3. This is followed by a detailed discussion of the processes, objectives and problems of the case study facility in Chapter 4. The methodologies discussed in Chapter 3 are then applied to the case study described in Chapter 4 and the results obtained for the facility layout problem and the job–shop scheduling problem at LWC are presented in Chapter 5 and Chapter 6 respectively. Two DSSs were designed in order to assist the LWC management in their decision making process concerning facility layout and scheduling. Discussions of the functionalities of these DSSs, are provided in Chapter 7. The DSSs may also be accessed via the compact disc included in the back cover of this thesis. The thesis closes in Chapter 8 with a review of what has been achieved in terms of the objectives stated in §1.3 as well as some suggestions for future areas of research.

Chapter 2

Concise Survey of Literature

The facility layout and production scheduling problems described in general terms in §1.1.3 and experienced by Loubser Wood Components (LWC) in particular, as outlined in §1.2, are well known problems in the manufacturing industry. Operations researchers have conducted extensive research on both these problems from as early as the 1950s [106, 114]. However, before solutions to the factory floor layout and production scheduling problems at LWC are attempted, it is necessary to review the methods typically used to solve these problems — this is the objective in this chapter. However, in such a review the notion of computational complexity plays a central role. The chapter therefore opens with a brief discussion of the basic terminology in computational complexity theory. This is followed, in §2.2 by a review of the methods typically used to solve manufacturing facility layout problems and we conclude this chapter in §2.3 with a discussion of the different methods typically used to solve job–shop scheduling problems.

2.1 Computational Complexity

Informally, *complexity theory* provides a mathematical framework by which computational problems may be classified as either "hard" or "easy." For the purpose of this thesis a *computational problem* is defined as follows:

Computational problem $P(f, X)$:

INSTANCE: *A real–valued function f and a feasible domain X.*
OBJECTIVE: *To compute the minimum value of $f(x)$ over all $x \in X$.*

An *algorithm* capable of solving a computational problem $P(f, X)$ approximately within a tolerance $\epsilon \geq 0$, for error, is denoted by $A(P(f, X), x_0, \epsilon)$ and is assumed to be a set of rules by which $P(f, X)$ may be solved to within the tolerance specified. In order to be useful from a practical point of view, such an algorithm is usually *constructive*, in the sense that it not only approximately solves $P(f, X)$, *i.e.,* finds the minimum value of f over X, but also produces an extremal point $x \in X$ at which the approximate minimum value of f is attained. A constructive algorithm capable of solving the computational problem $P(f, X)$ approximately usually requires an initial feasible solution $x_0 \in X$ in order to initiate execution; hence the triple notation for an algorithm. An algorithm of the form $A(P(f, X), x_0, 0)$ is said to solve $P(f, X)$ *exactly.*

One of the main components of complexity theory is the quest to measure the performance of an algorithm $A(P(f, X), x_0, \epsilon)$ in terms of the computational time required to implement the algorithm. The worst–case computational performance measure of an algorithm $A(P(f, X), x_0, \epsilon)$ is measured by an upper bound, denoted $T(A(P(f, X), x_0, \epsilon))$, on the number of *computational steps*[1] required by the algorithm, expressed in terms of ϵ and the size of some encoding of the initial solution x_0, denoted by $|x_0|$. For most meaningful computational problems $P(f, X)$ in the field of operations research, the precise form of a tight upper bound $T(A(P(f, X), x_0, \epsilon))$ is typically very difficult to evaluate, for any algorithm $A(P(f, X), x_0, \epsilon)$, that solves $P(f, X)$ approximately. For this reason the function $T(A(P(f, X), x_0, \epsilon))$ is usually replaced by some asymptotic upper bound on $T(A(P(f, X), x_0, \epsilon))$ as $|x_0| \to \infty$ and $\epsilon \to 0$. We write, in particular, that $T(A(P(f, X), x_0, \epsilon)) = O(g(|x_0|, \epsilon))$ if there exist a real constant $c > 0$ and a non–negative integer n_0 such that $T(A(P(f, X), x_0, \epsilon)) \leq cg(|x_0|, \epsilon)$ for all $|x_0|$, $\frac{1}{\epsilon} \geq n_0$. In such a case $T(A(P(f, X), x_0, \epsilon))$ is said to be asymptotically bounded from above by the function $g(|x_0|, \epsilon)$.

Although operations researchers are primarily concerned with solving computational problems, it is beneficial to reduce computational problems to so–called *decision problems*, which take the form of a question with a binary answer, usually interpreted as "yes" or "no." With any computational problem $P(f, X)$ a decision problem of the form

Decision problem $P_D(f, X, k)$:

INSTANCE: *A real–valued function f, a feasible domain X and a real number k.*
QUESTION: *Is $\min_{x \in X}\{f(x)\} \leq k$?*

may be associated.

The set of all decision problems has been divided into a number of so–called complexity classes, the simplest of which is the *class* **P** (acronym for Polynomial). A decision problem $P_D(f, X, k)$ is a member of the class **P** if there exists an algorithm $A_D(P_D(f, X, k), x_0)$ [2] capable of answering the binary question in $P_D(f, X, k)$, for which $T(A_D(P_D(f, X, k), x_0)) = O(g(|x_0|))$, where g is a polynomial in $|x_0|$.

If $A_D(P_D(f, X, k), x_0)$ is an algorithm capable of answering the decision question in $P_D(f, X, k)$ exactly, then an algorithm $A(P(f, X), x_0, \epsilon)$ may, in fact, be derived which is capable of solving the corresponding computational problem $P(f, X)$ approximately (under suitable continuity conditions on f and compactness conditions on X) if a pair of real numbers $k_L^{(0)}$ and $k_R^{(0)}$ can be found for which the answers to the decision question in $P_D(f, X, k_L^{(0)})$ and $P_D(f, X, k_R^{(0)})$ are "no" and "yes" respectively. Such an algorithm, called the interval halving algorithm, is given

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[1] The notion of a computational step is usually defined within the context of the computational problem to be solved. An example of a computational step might be any operation within the set {addition, subtraction, multiplication, division, exponentiation, boolean decision}.

[2] The tolerance factor ϵ does not make any sence in decision problems that only has a "yes" or "no" binary answer and will therefore be omitted.

as Algorithm 1.

Algorithm 1 Interval halving algorithm.

Input: The computational problem $P(f, X)$, an initial solution x_0 and an error tolerance of ϵ.
Output: The answer to the computational problem $P(f, X)$ within an error tolerance of ϵ.

```
1:  $i \leftarrow 0$.
2:  let $k_L^{(i)} \in \mathbb{R}$ such that the answer to $P_D(f, X, k_L^{(i)})$ is "no".
3:  let $k_R^{(i)} \in \mathbb{R}$ such that the answer to $P_D(f, X, k_R^{(i)})$ is "yes".
4:  $k \leftarrow (k_L^{(i)} + k_R^{(i)})/2$.
5:  if ($P_D(f, X, k)$ = "yes") then
6:      $k_L^{(i+1)} \leftarrow k_L^{(i)}$ and $k_R^{(i+1)} \leftarrow k$.
7:  else
8:      $k_L^{(i+1)} \leftarrow k$ and $k_R^{(i+1)} \leftarrow k_R^{(i)}$.
9:  end if
10: if ($k_R^{(i+1)} - k_L^{(i+1)} > \epsilon$) then
11:     $i \leftarrow i + 1$ and go to 4.
12: end if
13: stop.
```

It is clear that if the algorithm $A_D(P_D(f, X, k), x_0)$ is constructive, in the sense that it produces a *certificate*[3] $x^* \in X$ when producing an affirmative answer, then the corresponding algorithm $A(P(f, X), x_0, \epsilon)$ will also be constructive.

Since the uncertainty interval width, $x_R^{(i)} - x_L^{(i)}$, halves each time i is incremented, it follows that $x_R^{(i)} - x_L^{(i)} = 2^{-i}(x_R^{(0)} - x_L^{(0)})$. Hence, to solve $P(f, X)$ to within a tolerance ϵ, it follows that

$$\left\lceil \log_2 \frac{k_R^{(0)} - k_L^{(0)}}{\epsilon} \right\rceil$$

iterations of algorithm $A(P(f, X), x_0, \epsilon)$ are required. If $T(A_D(P_D(f, X, k), x_0)) = O(g(|x_0|))$, it therefore follows that $T(A(P(f, X), x_0, \epsilon)) = O(g(|x_0|, \log_2 \frac{1}{\epsilon}))$. Hence the algorithmic complexity of the algorithm $A(P(f, X), x_0, \epsilon)$ does not add significantly to that of $A_D(P_D(f, X, k), x_0)$ if g is, for example, a polynomial (in the sense that if the worst case performance measure of $A_D(P_D(f, X, k), x_0)$ is asymptotically bounded from above by a polynomial in $|x_0|$, then the worst case performance measure of $A_D(P(f, X), x_0, \epsilon)$ will be asymptotically bounded from above by a function which is a polynomial in both $|x_0|$ and in $\frac{1}{\epsilon}$). It therefore makes sense to classify a computational problem $P(f, X)$ as a member of the class **P** whenever its corresponding decision problem $P_D(f, X, k)$ is a member of **P**, for all $k \in \mathbb{R}$.

Example 2.1 *Suppose we take $X^{(a)} = \mathbb{R}^n$, the n–dimensional real space, and that $f^{(a)}$ is a twice continuously differentiable function on $X^{(a)}$, whose hessian is positive definite on $X^{(a)}$. Then the computational problem $P(f^{(a)}, X^{(a)})$ is an example of a problem in the class* **P**. *Here we may take $|x_0^{(a)}| = n$. It is well–known that the orthogonal directions method is capable of solving $P(f^{(a)}, X^{(a)})$ within n iterations [177], each iteration consisting of $\frac{n^3}{2} + \frac{5n}{2} + 6n + 6$ elementary operations from the class $\{+, -, \times, \div\}$. Hence the orthogonal directions method is an algorithm of the form $A(P(f^{(a)}, X^{(a)}), x_0^{(a)}, 0)$ for which $T(A_D(P_D(f^{(a)}, X^{(a)}, k), x_0^{(a)})) = O(n^3)$.* ■

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[3] A *certificate* in this context is a feasible point $x^* \in X$ for which $f(x^*) \leq k$.

Perhaps the next simplest complexity class is the *class* **NP** (acronym for Non–deterministic Polynomial). A decision problem $P_D(f, X, k)$ is a member of the class **NP** if there exists an algorithm $A_D(P_D(f, X, k), x_0)$ which is capable of answering the binary question in $P_D(f, X, k)$ in the affirmative, given additional information (called the certificate to the instance of $P_D(f, X, k)$), such that $T(A_D(P_D(f, X, k), x_0)) = O(g(|x_0|))$, where g is a polynomial in $|x_0|$. Now suppose $P_D^{(1)}(f^{(1)}, X^{(1)}, k^{(1)})$ and $P_D^{(2)}(f^{(2)}, X^{(2)}, k^{(2)})$ are two decision problems. If an algorithm $A_D(P_D^{(1)}(f^{(1)}, X^{(1)}, k^{(1)}))$ exists that is capable of answering the binary question in $P_D^{(1)}(f^{(1)}, X^{(1)}, k^{(1)})$ and if this algorithm is a sub–routine of an algorithm $A_D(P_D^{(2)}(f^{(2)}, X^{(2)}, k^{(2)}))$ that is capable of answering the binary question in $P_D^{(2)}(f^{(2)}, X^{(2)}, k^{(2)})$ then we write $P_D^{(1)}(f^{(1)}, X^{(1)}, k^{(1)}) \preceq P_D^{(2)}(f^{(2)}, X^{(2)}, k^{(2)})$. Informally, if $P_D^{(1)}(f^{(1)}, X^{(1)}, k^{(1)}) \preceq P_D^{(2)}(f^{(2)}, X^{(2)}, k^{(2)})$, then $P_D^{(2)}$ may be viewed at least as hard to solve as $P_D^{(1)}$ form a computational perspective. A decision problem $P_D^{(1)}(f^{(1)}, X^{(1)}, k^{(1)})$ is called **NP**–*complete* if $P_D^{(1)}(f^{(1)}, X^{(1)}, k^{(1)}) \in$ **NP** and $P_D(f, X, k) \preceq P_D^{(1)}(f^{(1)}, X^{(1)}, k^{(1)})$ for all $P_D(f, X, k) \in$ **NP**. Informally, the class **NP**–complete problems may therefore be viewed as the set of hardest problems within the class **NP**, from a computational point of view. A computational problem is called *tractable* if it falls within the class **P**. Finally, a decision problem $P_D^{(1)}(f^{(1)}, X^{(1)}, k^{(1)})$ is called **NP**–*hard* if $P_D(f, X, k) \preceq P_D^{(1)}(f^{(1)}, X^{(1)}, k^{(1)})$ for all $P_D(f, X, k) \in$ **NP** but $P_D^{(1)}(f^{(1)}, X^{(1)}, k^{(1)})$ is not necessarily a member of the class **NP** [108].

Prompted by a similar argument to that for the class **P**, a computational problem $P(f, X)$ is called **NP**–complete [**NP**–hard, respectively] if its corresponding problem $P_D(f, X, k)$ is **NP**–complete [**NP**–hard, respectively].

Example 2.2 *The* quadratic assignment problem *(QAP) in this context is a minimization problem consisting of a quadratic cost objective function $f^{(b)}$ together with a set of linear constraints in a set of binary variables, which depend on a discretization of the floorspace into a set of candidate locations for departments. Each binary variable corresponds to the possibility of assigning a specific department to a specific location on the floorspace of the facility. The objective of the problem is to minimize the transportation cost of material moving between departments and therefore the objective function is quadratic. A finer discretization typically leads to a better solution, but at the cost of increased computational effort and hence time required to solve the model. The problem has two sets of constraints, the first set of m (number of departments) constraints ensures that each department occupies only one location and the last set of n (number of discretized locations) constraints ensures that there is no more than one department assigned to a specific location. There are $m \times n$ binary variables in total. The solution space $X^{(b)}$ is defined by the $m + n$ linear constraints. In 1976, Sahni & Gonzalez [162] showed that the computational problem $P(f^{(b)}, X^{(b)})$ is a member of the* **NP**–*complete class.* ■

2.2 The Layout Problem

The facility layout problem is concerned with the placing of departments on a plane in order to minimize the total cost associated with material flow between departments on that plane. A facility may be a company with offices and workstations, or a factory with different machines, depending on the specific application considered. In this thesis a facility will be taken as a production facility or factory in which the placement of machines has to be determined.

2.2.1 Different Types of Layouts

There are four basic layout types in factories, namely *process layouts*, *product layouts*, *hybrid layouts* and *fixed layouts*. The distinctions between these types of factory layouts are discussed briefly in this section.

2.2.1.1 Process Layout

When a factory produces a large variety of different products, but a low volume of each product, the plant usually calls for a *process layout*, where machines are grouped together according to their functions. A process layout is typically very flexible, and equipment utilization is very high, because the requirements of all *jobs* may be pooled together, in the sense that there is usually no more than one machine that performs the same type of task and hence all jobs that require that specific task have to be processed on that specific machine. However, the machines or groupings of machines are usually almost never idle in a process layout. The main disadvantage of this type of layout is that the processing rate is low, because of the production time that is lost when changing between jobs (products). The machines typically also exhibit variation in their output rates, usually resulting in a large number of jobs having to wait in queues before they can be processed on a specific machine — this, in turn, leads to an increase in storage space requirements and more capital being tied up in inventory. Material–handling tends to be costly in such a layout and various transport devices are typically employed, such as carts or trolleys, rather than conveyor belts, because of the diversity of routings [107, 116, 204].

2.2.1.2 Product Layout

A *product layout* involves a number of linear production paths, in which machines and resources are assigned to successive tasks of an individual type of job. An automated car wash is a popular example of a service facility with a product layout. Product layouts typically rely heavily on specialized, capital–intensive resources and are therefore risky when jobs (products) are manufactured for a short or uncertain time interval. The advantages of a product layout are mirror images of the disadvantages of process layouts [43, 116, 204].

2.2.1.3 Hybrid Layout

More often than not, a positioning strategy combines elements of both a product and process layout to form a *hybrid layout*. A factory has a hybrid layout if some portions of the factory have a process layout and others a product layout. Hybrid layouts are created when introducing group technology (GT) cells[4], one–worker–multiple–machines (OWMM) centres, or flexible manufacturing systems (FMS)[5]. In factories having both production and assembly tasks, the production tasks tend to call for a process layout and the assembly tasks tend to call for a product layout [23, 116, 204].

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[4] Group technology refers to the concept of identifying and grouping together production or assembly of similar parts of a product to take advantage of their common characteristics in design and production methods.

[5] The reader is referred to Krajewski [116], p. 165–170 for an in–depth discussion of GT, OWMM and FMS.

2.2.1.4 Fixed–Position Layout

In this case products are fixed in space. Workers (along with their tools and equipment) come to the product to work on it. This approach aims at minimizing the number of times a product has to be moved, and may only be applied if the resources and machines are small and easily moved [116, 204]. An example of a fixed–position layout is a factory building ships. The ship remains stationary and the workers come to various parts of the ship to work on it.

2.2.2 Classification and Notation for Layout Problems

There exist a large variety of facility layout problem types. However, the author could not find a unifying classification notation in terms of which general layout problems could be expressed. In this section a basic classification scheme, that will be used throughout this thesis, is presented, and is a contribution by the author.

The floorspace of a facility may be considered to be *discretized* or *continuous*. In the former case the available floorspace of the facility is divided into a fixed set of potential locations for the placement of departments in the facility, whereas in a continuous facility layout one considers the floorspace to be continuous, in the sense that departments may be located anywhere on the floorspace.

The notation to classify layout problems consists of four fields, denoted $\boxed{\alpha \mid \beta \mid \gamma \mid \delta}$. The first field, α, characterizes the type of layout problem:

$$\alpha \in \begin{cases} proc & : \text{ process layout,} \\ prod & : \text{ product layout,} \\ H & : \text{ hybrid layout,} \\ F & : \text{ fixed}-\text{position layout.} \end{cases}$$

The second field, β consisting of the ordered pair β_1, β_2, describes the floorspace of the facility, where β_1 indicates the type of floorspace:

$$\beta_1 \in \begin{cases} D & : \text{ discretized floorspace,} \\ C & : \text{ continuous floorspace.} \end{cases}$$

In some cases a facility may consist of more than one floor. The parameter β_2 denotes the number of different floors in the facility.

The third field, γ consisting of the ordered 3–tuple γ_1, γ_2, γ_3, describes the departments in the facility. The parameter γ_1 indicates the number of departments that have to be positioned in the facility:

$$\gamma_1 \in \begin{cases} \varnothing & : \text{ there is a variable number of departments}^6, \\ n & : \text{ there are exactly } n \text{ different departments.} \end{cases}$$

The parameter γ_2 indicates whether the departments of the facility may have different orientations:

$$\gamma_2 \in \begin{cases} \varnothing & : \text{ the departments each have a fixed orientation,} \\ orient & : \text{ the departments may have different orientations.} \end{cases}$$

The parameter γ_3 indicates whether or not the departments all have the same size:

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[6] In this notation, $\varnothing$ denotes an empty symbol which will be omitted in the remainder of this thesis, in accordance with general practice in classification notation schemes for other problems.

$$\gamma_3 \in \begin{cases} \varnothing & : \text{ the departments have different sizes,} \\ equal & : \text{ the departments all have the same size.} \end{cases}$$

The last field denotes the optimality criterion or performance measure to be employed when solving the layout problem. The performance criteria for floor layouts at production plants that receive the most attention in the literature are *capital investment*, *material–handling* and *flexibility*. Floorspace, equipment requirements, and inventory levels depend in part on whether the management of the facility selects a process or product layout. If an existing layout is to be revised, renovation costs may be significant. Relative locations of departments should allow for large production material flows to proceed short distances, which minimizes material–handling costs. A good layout must be very flexible in the sense that the layout remains desirable even when significant temporary changes occur with respect to production material flow volumes, possibly due to a stochastic demand for product types. A layout is called *performance flexible* if it is designed to minimize the cost of changing it at a later stage to meet new demands or to satisfy new constraints. Other performance criteria include *labour productivity*, which may be affected by the layout, as well as *equipment maintenance* which may be rendered difficult by an undesirable layout. The parameter δ indicates the performance measure of the layout problem, where:

$$\delta \in \begin{cases} \varnothing & : \text{ a variable performance measure,} \\ Cap & : \text{ capital investment,} \\ MH & : \text{ material}-\text{handling,} \\ F & : \text{ flexibility,} \\ LP & : \text{ labour productivity,} \\ EM & : \text{ equipment maintenance.} \end{cases}$$

In some cases there are more than one optimality criteria, and each criterion may have a different priority. In these cases two or more δ–values are used consecutively in descending order of priority.

Example 2.3 *The above classification scheme is illustrated by means of two simple examples:*

(a) The layout problem $\boxed{proc \mid D, 1 \mid 10 \mid MH}$ *is the problem of determining a best process layout of 10 departments, with unequal sizes which all have a fixed orientation, on one level of descretized floorspace, where a best layout minimizes the material–handling cost.*

(b) The layout problem $\boxed{proc \mid C, 2 \mid 21,\ orient \mid F}$ *is the problem of determining a best process layout for a facility with two levels of continuous floorspace, 21 departments of unequal sizes in which it is possible to vary the orientation of departments, and where a best layout maximizes performance flexibility.*

■

2.2.3 Exact Methods for Layout Problems

There is a large body of literature on facility layout problems. Facility layout problems are typically solved using *mathematical programming* or *graph theoretic* models. Koopmans & Beckman [114] were the first to introduced mathematical programming models to solve layout problems of the form $\boxed{proc \mid D, 1 \mid n, equal \mid MH}$ in 1957. They modelled the facility layout problem as a QAP. Although there are methods available that solve the QAP optimally, they are currently only computationally feasible for very small problems and are only applicable to special cases of the QAP [205]. A significant disadvantage of the quadratic assignment model is that all the departments have the same size in the prototype model. This restriction was overcome in 1975 by Bazaraa [21], who introduced a generalized QAP to solve facility layout problems of the form $\boxed{proc \mid D, k \mid n \mid MH, Cap}$. Because of the complexity of the latter QAP, the facility layout problem with varying size departments has not been solved for more than 15 departments [109], even as late as 2003, using computing facilities that were then state–of–the–art. Papageorgiou & Rotstein [149] introduced a *mixed integer linear programming problem*[7] in 1988, to solve the facility layout problem of the form $\boxed{proc \mid C, k \mid n \mid MH}$, but this model was also not efficient for large problems.

2.2.4 Heuristic Methods for Layout Problems

The large computational time complexity of exact methods for solving facility layout problems has led operations researchers to concentrate on *heuristic*[8] methods to solve approximately facility layout problems of the form $\boxed{proc \mid D, k \mid n \mid MH}$. The heuristic methods employed in this regard may be classified into two broad groups, namely *construction methods*[9] and *improvement methods*[10]. Examples of construction methods include CORELAP (Computerized Relationship Layout Planning) [124], ALDEP (Automated Layout Design Program) [166] and MAT (Modular Allocation Technique) [67]. CORELAP is a manually performed heuristic procedure, which may be utilized to convert so–called *rel–chart*[11] (relationship chart) information to a schematic layout diagram, which may, in turn, be converted to a physical layout. The basic inputs required by CORELAP are the rel–chart and the area or floorspace requirements for each department. CORELAP begins by selecting the most critical department and placing it in the centre of the layout. Then, by selecting the departments having the highest production material–flow relationship with the departments already placed, CORELAP grows intermediate layouts like a crystal from the centre outwards to develop the final floor layout [192]. ALDEP requires the same basic data inputs as CORELAP. The procedural difference between CORELAP and ALDEP is that CORELAP utilizes the so–called *total closeness rating*[12] as criterion for the order in which placements are made, whereas ALDEP selects a department randomly for placement. The basic philosophical difference between CORELAP and ALDEP is that CORELAP attempts to produce one good layout, whereas ALDEP produces many layouts, leaving

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[7] The mixed integer linear programming problem in this context is a minimization problem, consisting of a linear objective function, together with a set of linear constraints in a set of binary and continuous variables. The objective function measures the production material–handling cost of a layout, but instead of assigning variables to points on the discrete floor, this problem considers a continuous floor and therefore variables which indicate the distances between two separate departments are used. A binary variable is a variable that can only take the value of 0 or 1 whereas a continuous variable can take any real value. If m is the number of departments in the facility and k is the number of floors, then there are $3m^2 + (1 + k)m$ binary variables and $7m^2 + 5m$ continuous variables and $8m^2 + 7m + 4$ linear constraints.

[8] A heuristic algorithm does not guarantee an optimal solution to an optimization problem, but rather attempts to find a feasible, near–optimal solution. The sacrifice of solution quality often comes with a significant reduction in computational cost.

[9] In construction methods the facility layout is constructed from an empty floorspace and departments are assigned to locations, one at a time.

[10] Improvement methods start out from an initial facility layout, which is often randomly generated, and attempt to improve upon this layout in an iterative fashion.

[11] A rel–chart is an 2D array that is used to indicate *qualitatively* the importance of two departments being close to each other in a facility layout.

[12] An individual closeness rating between two departments is a *quantitative* measure of the importance of two departments being close together. The total closeness rating of a department is the sum of the individual closeness ratings of a department with all other departments.

the evaluation and comparison of the layout alternatives produced, and the selection of a final layout, to the facility designer [192]. MAT utilizes the distance between all pairs of locations and the material–loads transported between all pairs of departments per unit time to approximate an optimal allocation of the departments to a set of candidate locations. The MAT procedure orders the distances between the locations in a decreasing order as well as the flow between the departments in an increasing order and then the procedure is based on a theorem that states that the sum of pairwise products of two sequences of real numbers is minimized if one sequence is arranged in non–decreasing order and the other in non–increasing order [67].

Based on a given initial solution, systematic exchanges of department locations are made by improvement heuristics and the results are then evaluated. CRAFT (Computerized Relative Allocation of Facilities Technique) is an example of an improvement method, developed in 1964 by Buffa, *et al.* [42] and is capable of solving layout problems of the form $\boxed{proc \,|\, D,\, 1 \,|\, n \,|\, MH, F, LP}$. CRAFT is a *greedy algorithm*[13] that is *path dependent*[14]. The algorithm performs two–way and/or three–way exchanges of department centroids to identify those exchanges that potentially reduce the layout cost, which is a function of the flow between the departments multiplied by the *rectilinear distance*[15] between the centroids of the departments. At each iteration, the exchange that leads to the largest estimated reduction in total cost is selected. The improvement process is repeated until there are no two–way or three–way exchanges that reduce the estimated layout cost [32]. Other improvement methods are COFAD (Computerized Facilities Design) [193], which is a modification of CRAFT [42], and (the more recent) FACOPT (Facility Layout Optimization System) [13] that uses *simulated annealing*[16] and a *genetic algorithmic*[17] *approach* to improve the layout of an initial facility iteratively. COFAD is basically a modification of CRAFT that allows realistic inclusion of transportation costs for all material–handling equipment alternatives (for example trolleys, forklifts and conveyor belts). To include such transportation costs, the methods and costs of material–handling have to be determined for each alternative facility layout design. COFAD, therefore, is a model that simultaneously considers the layout and the material–handling system when making layout decisions. The inputs required by COFAD are alternative material–handling equipment capable of performing specific transportations, the costs of these alternatives, so–called *from–to charts*[18] for each equipment

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[13] A *greedy algorithm* repeatedly selects the immediate best choice from a set of alternatives at each step of its execution, disregarding possible future repercussions in terms of the optimality of the final solution of choosing the best alternative at each step.

[14] An algorithm for solving a multi–dimensional optimization problem is called *path dependent* if the initial solution and the subsequent changes afforded to the solution throughout every iteration of the search procedure largely determines the quality of the final solution.

[15] The *rectilinear distance* between two points with Cartesian coordinates (a, b) and (x, y) in the plane is defined as $d = |x - a| + |y - b|$.

[16] Błażewicz [27] mentions that *simulated annealing* was proposed by Kirkpatrick, *et al.* [111]. It is based on a procedure originally devised to simulate the annealing (or slow cooling) of solids after they had been heated to their melting point. A simulated annealing algorithm does not search for the best solution in the *neighborhood* of the current solution x_n, but draws a random solution x and accepts it as the next solution if it has a better objective function value. If the randomly drawn solution's objective function value is worse than that of the current solution, the random solution x is selected with a probability $p(n)$, or the current solution is reselected with a probability $1 - p(n)$. The probability function $p(n)$ typically decreases with time, n, to increase the probability of finding a global optimum.

[17] A *genetic algorithm* is also a heuristic, iterative approach towards solving multi–dimensional optimization problems and may be described as a mechanism that mimics the genetic evolution of biological species. The main difference that distinguishes it from simulated annealing is that it deals with populations of solutions rather than with single solutions at each iteration. Solutions interact, mix together and produce solution offspring that hopefully retain the good characteristics of their parents, in terms of contributing to the optimality of solutions.

[18] A *from–to chart* is a 2D array that is used to indicate quantitatively the amount of material transported between two departments in a facility layout.

alternative and an initial layout. COFAD utilizes these data in an effort to develop a layout and material–handling system, which hopefully approximates a minimal cost material–handling system. In extremely general terms, the following steps may describe the iterative functioning of COFAD:

1. Determine a layout.
2. Select a material–handling system.
3. Divide the costs of the
   handling system to the individual transportations.
4. Return to step 1.

These four steps are repeated until a steady–state solution is reached, at which point either the model is terminated or sensitivity analysis may be performed on the from–to chart. FACOPT is a user friendly software package which runs behind a Visual Basic interface in a Windows environment, and employs either simulated annealing or a genetic algorithm to obtain a good solution to a facility layout problem of the form $\boxed{proc \mid D, 1 \mid n \mid MH}$ with $n \leq 30$. The user may employ more than one algorithm and specify parameter values other than the default values. A *space–filling curve*[19] may be inserted manually or may be created automatically. A set of 10 possible solution layouts are obtained after each run and the user may compare them and select one, which may be fine–tuned and used as the final layout.

In 1987, Wilhelm & Ward [205] and in 1990 Connolly [55] also showed how simulated annealing could be used in an improvement method to solve the layout problem. They assumed that the cost of production material–flow between two departments on a discrete floor layout is the same for flow in both directions. The algorithm selects two departments randomly and computes the change in the objective function to be obtained should the move be executed. The move is then executed with a probability depending on the change in the objective function if the objective function does not improve, whilst it is always accepted if the objective function improves. The results found by Wilhelm & Ward was comparable to results obtained by CRAFT.

As mentioned, graph theoretic methods have also been used traditionally to model and solve facility layout problems. These models focus on determining a weighted *maximal planar*[20] sub–graph of a graph $G = (V, E)$, whose *vertex set*, V, represents the departments to be placed on a plane and whose *edge set* and associated weights, E, represent adjacency and flows of production materials between departments respectively. When developing a facility layout, using graph theoretic techniques, one usually follows three steps [109, 167, 168]:

1. A weighted maximal planar graph is constructed from a so–called *department relationship graph*[21] in order to determine which departments should be adjacent.

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[19] A *spacefilling curve* is used to ensure that a department is not split into distinct parts when placed on the facility floor. The curve visits each square of the discrete facility floorspace by visiting the neighbors of a square before visiting other squares. Each department's assignment squares have to be chosen from adjacent squares on the curve.

[20] A graph is called *planar* if it may be drawn in the plane in such a way that none of its edges intersect, except possibly at vertices. A planar graph is called a *maximal* planar graph if no edges can be added to the graph, without intersecting some existing edge of the graph. The *dual* of a planar graph (called the primal graph) may be constructed by placing a dual vertex in each face of the primal graph and by joining vertices corresponding to two faces in the primal graph that share a common boundary edge. The dual of a planar graph is again a planar graph [109].

[21] A *department relationship graph* is a graph in which two vertices are joined by means of an edge if there

2. A dual graph is constructed from the maximal planar graph in step 1 to represent the departments as adjacent regions having specific boundaries.
3. The dual graph in step 2 is converted to a block layout, where departments have regular shapes and specific areas.

The main draw–back of this method is the requirement of repeatedly testing the planarity of the graph in step 1. In 1978, Foulds & Robinson [77] developed two alternative heuristics, which deal with maximal planar graphs at all times and therefore have no planarity testing requirements. Boswell [31] developed a greedy heuristic in 1992, called TESSA, that also avoids the planarity testing which caused significant computational complexity limitations in previous graph theoretic heuristic methods. Leung [129] also avoided planarity testing by means of a greedy heuristic approach, developed in 1992, that starts by creating a deltahedron and repeatedly adds single vertices, or triplets of vertices to selected faces of the graph in step 1 above.

Kim & Kim [109] focused on facility layout problems of the form $\boxed{proc \mid D, 1 \mid n \mid MH}$ in 1995. They used a construction heuristic to determine a planar graph and then improved it by modifying the *adjacency graph*[22]. They found that this method gave better results than the CRAFT method, which is one of the most popular methods for solving varying department size facility layout problems. Hasan & Osman [90] studied steepest ascent, simulated annealing and tabu search methods for layout problems. They found that the simulated annealing and tabu search methods outperformed all other methods and recommended that these methods be used in real life situations. Goldschmidt, *et al.* [84] showed in 1996 how a *biconnected spanning sub–graph*[23] may be used to construct a layout for a facility. They showed that the problem of determining a biconnected spanning planar sub–graph is **NP**–complete and developed a heuristic to construct a biconnected spanning planar sub–graph using a depth–first search algorithm developed by Tarjan [190] in 1972.

Most of the research on the facility layout problem, using graph theoretic techniques, focuses on the first and second steps mentioned above in developing a block layout via graph theoretic techniques. Watson & Giffen [203], however, focused in 1997 on the third step and developed an approach for finding a facility layout block plan from an arbitrary maximal planar graph.

All the methods mentioned above were developed for static layout problems. However, in 1997 Lacksonen [119] focused on the dynamic nature of layout problems. Since the production volumes and a manufacturing system may be changing constantly, there may be a need for a flexible layout, which is able to accommodate alternative future scenarios. If one may reasonably accurately estimate the future flow of production materials between departments, the problem may be solved as a dynamic layout problem. Lacksonen combined a quadratic assignment approach and a continuous layout modelling approach in a two–stage algorithm for facility layout problems of the form $\boxed{proc \mid D, 1 \mid n, orient \mid MH}$. Stage 1 models the dynamic layout problem as a QAP in order to find approximate department arrangements. The algorithm uses a cutting plane heuristic and an exchange routine to minimize a combination of total flow

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exists a flow of production material between the departments corresponding to the vertices. The department relationship graph is not necessarily planar.

[22] The *adjacency graph* of a facility is a graph in which departments are represented by vertices and in which two vertices are adjacent if the corresponding two department are physically adjacent.

[23] A graph $G = (V, E)$ is *connected* if there exists a *path* between every pair of vertices in the vertex set V. A graph $G' = (V', E')$ is a *sub–graph* of G if $V' \subseteq V$ and $E' \subseteq E$. If $V' = V$, then G' is called a *spanning sub–graph* of G. G is called *biconnected* if it requires the removal of at least two vertices before the resulting graph is split into more than one component.

and re–arrangement costs. Stage 2 models the dynamic layout problem as a *mixed integer programming problem*. The complexity of this model prohibits the solution of problems with more than 12 departments and 3 time periods, primarily due to the number of binary variables present in the model. Lacksonen used a preprocessing method to reduce the complexity of the mixed integer programming problem and solved the problem with a revised *branch–and–bound*[24] strategy, where some branches are *fathomed* due to probabilities computed in the preprocessing stage. This was the first algorithm to find efficient layouts for realistic sized dynamic layout problems with varying department sizes.

The majority of the research conducted on layout problems considered problems of the form $\boxed{proc \mid 1 \mid n \mid}$. However, Bozer, *et al.* [32] developed a heuristic method in 1994 called MULTIPLE (Multi–floor Plant Layout Evaluation), which uses space filling curves to find a good multi–floor layout — it may, of course, also be used for single floor layout problems. When working with multi–floor layout problems it is important to consider the limited capacity of lifts (Matsuzaki, *et al.* [136] showed in 1999 how this may be achieved). Papageorgiou [150] also developed a method in 2002 that incorporates multiple floors and uses mixed integer linear programming methods to for solving the continuous layout problem, but this method is only suitable to solve small problem instances.

In Figure 2.1 the reader is presented with the development of literature concerning manufacturing facility layout problems. A more detailed discussion on how some of the methods cited above are used to solve the layout problem at LWC follows in Chapters 3 and 5.

2.3 The Scheduling Problem

Research in scheduling started at the beginning of the 20th century, largely inspired by the work of Henry Lawrence Gantt (see Figure 2.2), an industrial engineer and a disciple of Fredrick W. Taylor, who was a mechanical engineer and the founder of system engineering. Taylor's writings on efficiency and scientific management were widely read at the turn of the 20th century [191]. However, the first publications on scheduling practice only appeared during the early 1950's [152].

The notation commonly used in scheduling problems, and also used throughout the remainder of this thesis, as well as a discussion on the different types of schedules and a classification of the different types of scheduling problems that occur in practice are the topics of this section.

2.3.1 Basic Notation in Scheduling Theory

In general, scheduling problems are characterized by three sets: a set $\mathcal{T} = \{T_1, T_2, \ldots, T_n\}$ of n *tasks*, a set $\mathcal{P} = \{P_1,\ P_2, \ldots,\ P_m\}$ of m *processors* (*machines*) and a set $\mathcal{R} = \{R_1,\ R_2, \ldots,\ R_s\}$ of s types of *additional resources*. Scheduling, generally speaking, entails an assignment of

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[24] As indicated by the name, the branch–and–bound method consists of two procedures: branching and bounding. *Branching* is the procedure of partitioning a large minimization problem into two or more, usually mutually exclusive, sub–problems. The sub–problems are, in turn, further divided into two or more sub–problems, in a similar way, and so on. A tree structure, representing the partitioned solution space, is constructed dynamically. The initial (relaxed) problem represents the *root* of the tree and a solution at the lowest level corresponds to a *leaf* of the tree. Solutions are found on the lowest level. *Bounding* is the procedure of calculating a lower bound on the optimal solution to the original minimization problem for each sub–problem generated by the branching procedure. This lower bound dictates whether a branch is fathomed. For more information on the branch–and–bound method the reader is referred to Blazewicz, *et al.* [27].

Mathematical programming (Koopmans & Beckman, [114]) : 1957	
CORELAP (Lee, [124]) : 1963	1964: CRAFT (Buffa *et al.*, [42])
ALDEP (Seehof & Evans, [166]) : 1967	
	1970: MAT (Edwards *et al.*, [67]), general graph theory concepts (Seppanen & Moore, [167])
QAP (Bazaraa, [21]), graph theory (string processing) : 1975 (Seppanen & Moore, [168])	1976 : Proof QAP is NP–complete (Sahni & Gonzalez, [162]), COFAD (Tompkins & Moore, [193]) and depth–first search and linear graph algorithms (Tarjan, [190])
	1978 : Graph theory (improvement of the string processing method) (Foulds & Robinson, [77]) and CORELAP (Tompkins & Moore, [192])
simulated annealing (Wilhelm & Ward, [205]) : 1987	
	1990 : simulated annealing (Connolly, [55]) 1992 : TESSA (Boswell, [31]) 1994 : MULTIPLE (Bozer *et al.*, [32])
Graph theory (Kim & Kim, [109]) and local search methods : 1995 (Hasan & Osman, [90])	1996 : Biconnected spanning planar subgraph method (Goldschmidt *et al.*, [84])
Method for dynamic layouts (Lacksonen, [119]) : 1997	1998 : Mixed integer linear programming (Papageorgiou & Rotstein, [149])
Multi–floor layout methods (Matsuzaki, [136]) : 1999	
	2002 : Multi–floor layout method using mixed integer linear programming (Papageorgiou & Patziatzis, [150])
FACOPT (Balakrishnan *et al.*, [13]) : 2003	

Figure 2.1: *A graphical representation of layout methods as they developed over the past 50 years.*

processors from $\mathcal{P}$ and (possibly) resources from $\mathcal{R}$ to tasks from $\mathcal{T}$, in order to complete all tasks under a set of imposed constraints. There are two general constraint types in classical scheduling theory: Each task is to be processed by at most one processor at a time and each processor is capable of processing at most one task at a time. A *job* is a subset of one or more tasks. That is, a job J_j (also referred to as job j) may be divided into n_j tasks, $T_{1j}, T_{2j}, \ldots, T_{n_j j}$, where two consecutive tasks in the sequence are to be performed on different processors. The set of jobs will be denoted by $\mathcal{J} = \{J_1, J_2, \ldots, J_k\}$, whilst the set of tasks, $\mathcal{T}$, may now be rewritten as $\mathcal{T} = \{T_{11},\ T_{21}, \ldots, T_{n_1 1}, T_{12}, T_{22}, \ldots, T_{n_2 2}, \ldots, T_{1j}, \ldots, T_{n_j j}, \ldots, T_{1k}, \ldots, T_{n_k k}\}$ [27]. Throughout the remainder of this thesis a job will represent an order received from a single customer for a specific product or number of components, whose production comprises a number of tasks. The job is available for processing from the time the order is received from the customer, until it is completed, and the finished product(s) are dispatched to the customer.

A task $T_{ij} \in \mathcal{T}$ of job J_j is characterized by the vector of processing times, $\mathbf{p}_{ij} = [p_{ij}(1), p_{ij}(2), \ldots, p_{ij}(m)]^{\mathrm{T}}$, where $p_{ij}(\ell)$ is the time required by processor P_ℓ to process task T_{ij}.

The *due date* d_j is the limiting time instant by which job J_j should be completed, as determined by a feasible production schedule. Usually penalty functions are put in place to deal with non–adherence to due dates. The so–called *deadline* $\tilde{d_j}$ is a fixed, real time (instance) limit by which job J_j must be completed, according to the promised delivery time presented to the customer. The *lead–time* of a job is defined as the time interval that a job has to wait for resources to become available before its processing commencement may be scheduled. The *arrival time* r_j of a job J_j is the *starting time instant* s_j of the job on the first machine in its processing sequence (assuming a zero lead–time). If the lead–time of a job is not zero, then the arrival time is the starting time of the job on the first machine in its sequence less the lead–time. Hence, the starting time is adjusted according to the lead–time. The *completion time* of a job on the last machine in its processing sequence of tasks is the time instant when the job is available for shipping to a customer. It often happens that a specific job J_j has a completion time after the

Figure 2.2: *Henry Lawrence Gantt (1861–1919), an industrial engineer who enspired a large body of research in scheduling theory.*

due date because the specific schedule in place was not followed correctly. However, it might happen that the completion time is before the due date. The symbol C_j is used to denote the completion time of job J_j, whilst c_{ij} denotes the completion time of task T_{ij}.

In scheduling the term *capacity planning* refers to deciding how much of a machine's production time should be allocated to each job. The relative urgency of job J_j is expressed by its associated *weight priority* w_j [27]. A manager may assign a priority to each job in terms of a quantitative weight $(1, 2, 3, \ldots)$ or perhaps via a qualitative term such as hot, very hot or hottest, which is then converted to a priority weight via predefined rules. These priorities may also change from day to day, based on the present status of jobs in the system [184]. When a machine is idle, it is best to plan for preventative maintenance activities or cleaning of the machine so that no productive time is detracted from that machine.

Production schedules are generated in practice by using scheduling algorithms that attempt to optimize one or more efficiency criterion. The *rule–*, or *knowledge–based approach* to scheduling attempts to find a schedule that is feasible under the factory's operating environment, mainly working according to if . . . then rules [184]. The *makespan* of a schedule is the time it takes to complete all the scheduled jobs.

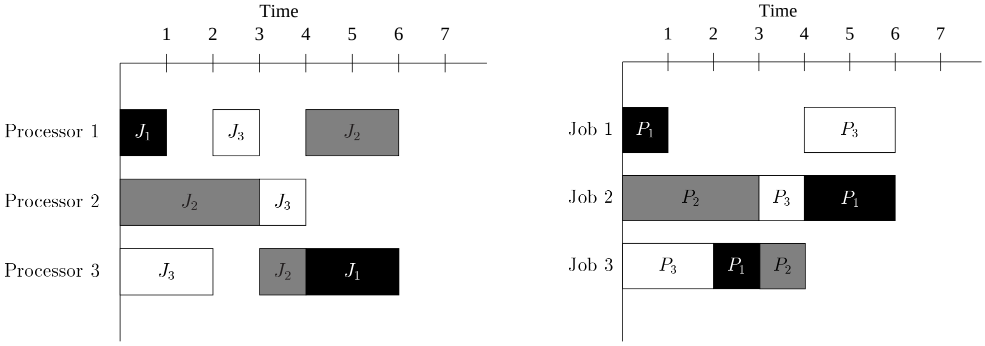
In the set $\mathcal{T}$ *precedence constraints* may be defined by writing $T_{ij} \prec T_{kj}$ if processing of task T_{ij} must be completed before processing of T_{kj} may be started. The tasks in the set $\mathcal{T}$ are called *dependent* if the order of execution of at least two tasks in $\mathcal{T}$ is restricted by a precedence constraint.

The precedence order may be represented by means of a directed graph, where the nodes correspond to the tasks and the arcs to precedence constraints (this is called a *task–on–node graph* in the literature). However, in so–called *activity networks*, precedence constraints are rather represented as a *task–on–arc graph*, where arcs represent tasks and nodes represent time events. A special case of this type of graph is called the *uniconnected activity network* (uan), which is defined as a graph in which any two nodes are connected by a directed path in one direction only [27].

2.3.2 Representations of Schedules

Schedules may be displayed graphically in a variety of forms. The most common way to display a schedule is by means of a so–called *Gantt chart.* A Gantt chart is a line or block chart on which time is represented on the horizontal axis and other quantities (such as job processing, for example) on the vertical axis.

Example 2.4
Figure 2.3(a) shows a Gantt chart with processors on the vertical axis for a problem with 3 jobs, with job sequences as shown in Table 2.1(a) and processing times for the individual tasks shown in Table 2.1(b). Figure 2.3(b) shows a Gantt chart of the same schedule with jobs on the vertical axis. The schedule represented in Figures 2.3(a) and (b) is feasible, because it satisfies the two aforementioned general constraint types, namely that each job may be processed by at most one processor at a time and that each processor may process at most one job at a time. If, for example, the processing of job 2 on processor 1 were to start one time unit earlier, i.e., *at time instant 3 and not at time instant 4, the schedule would be infeasible.* ■



(a) *A Gantt chart representation with processors on the vertical axis.*

(b) *A Gantt chart representation with jobs on the vertical axis.*

Figure 2.3: *A Gantt chart representation of a solution to a scheduling problem with processing sequences as shown in Table 2.1 (a) and processing times in Table 2.1 (b).*

Job	**Processor Sequence**
J_1	$P_1,\ P_3$
J_2	$P_2,\ P_3,\ P_1$
J_3	$P_3,\ P_1,\ P_2$

(a) *The processor sequences of the jobs represented on the Gantt charts in Figures 2.3(a) and (b).*

	P_1	P_2	P_3
J_1	1	0	2
J_2	2	3	1
J_3	1	1	2

(b) *The processing times of the jobs, in Figures 2.3(a) and (b), on the different processors.*

Table 2.1: *The processing times and processor sequences for the different jobs on the Gantt charts in Figures 2.3(a) and (b).*

The *disjunctive graph* representation of a schedule, due to Roy & Sussman [160], is also very popular. Here an *edge–weighted graph* is constructed, consisting of a vertex for each task $T_{ij} \in \mathcal{T}$ and two dummy vertices T_{start} and T_{end}, representing the start and end of a schedule respectively. For every two consecutive tasks of the same job there is a (directed) *conjunctive arc* in the graph. The dummy vertex, T_{start} is the predecessor of the first task T_{1j} of each job J_j, and the dummy vertex T_{end} is the successor of the last task $T_{n_j j}$ of every job J_j. Therefore, between the dummy vertex T_{start} and the first task of each job there exists a conjunctive arc, and between the last task of each job and the dummy vertex T_{end} there is another conjunctive arc. The set of conjunctive arcs is denoted by $\mathcal{A}$. For each pair of tasks $\{T_{im}, T_{j\ell}\}$ that require the same processor, (say) k, there are two arcs $(im, j\ell)$ and $(j\ell, im)$, oppositely directed in the *incomplete* version of the graph. The arcs $(im, j\ell)$ and $(j\ell, im)$ are said to be *disjunctive arc pairs* or *disjunctive edges*. Thus, single arcs between tasks represent the precedence constraints on the tasks of the same job and a pair of oppositely directed arcs between two tasks represent the constraint that each processor can handle at most one task at a time. Each arc $(im, j\ell)$ is labeled by a weight $p_{im}(k)$ corresponding to the processing time of task T_{im}, on the processor k specified for the task. All arcs from vertex T_{start} have weight 0. Let $\mathcal{E}_k$ be the set of pairs of tasks to be processed on processor k. A disjunctive arc pair, $\{(im, j\ell), (j\ell, im)\}$ is called *settled* if exactly one of the two arcs has been added to a set $\mathcal{D}_k \subset \mathcal{E}_k$. By choosing the arc $(im, j\ell)$ say, precedence is assigned to T_{im} over $T_{j\ell}$ on the common processor k. A feasible schedule is defined by a set $\mathcal{D}^* = \cup_{k=1}^{m} \mathcal{D}_k$, where $D^* \subseteq \mathcal{E} = \cup_{k=1}^{m} \mathcal{E}_k$, such that

(i) $(im, j\ell) \in D^*$ if and only if $(j\ell, im) \in \mathcal{E} \setminus \mathcal{D}^*$ and

(ii) the graph $G(\mathcal{D}^*) = (V, \mathcal{A} \cup \mathcal{D}^*)$ is *acyclic*.

A graph in which all the disjunctive arc pairs are settled is called a *complete disjunctive graph*. A complete disjunctive graph corresponds to a feasible schedule if it is acyclic. The makespan, $C_{\max}$, of a feasible schedule is the length of a *longest path*[25] from the start node to the end node in a complete disjunctive graph.

Example 2.5 (Example 2.4 continued)
The disjunctive graph representation of a schedule for the problem with processor sequences for the jobs displayed in Table 2.1(a) and processing times, as displayed in Table 2.1(b), is shown in Figure 2.5. When focusing on a single node (see Figure 2.4), k is the processor number, and i the task number of the particular job J_j. There are two dummy nodes called Start *and* End*. The conjunctive arcs (solid arrows) represent precedence constraints among tasks of the same jobs and the dashed lines with arrows in both directions indicate the disjunctive arc pairs representing the constraints among tasks to be performed on the same processor.* ■

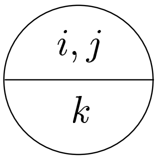


Figure 2.4: *A single node in the disjunctive graph representation of a schedule, where k is the number of the processor on which task i of job j must be performed.*

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[25] A path in a graph is an alternating sequence of *edges* and *adjacent vertices* in a *graph*, both beginning and ending in a *vertex*, in which no *vertex* is repeated.

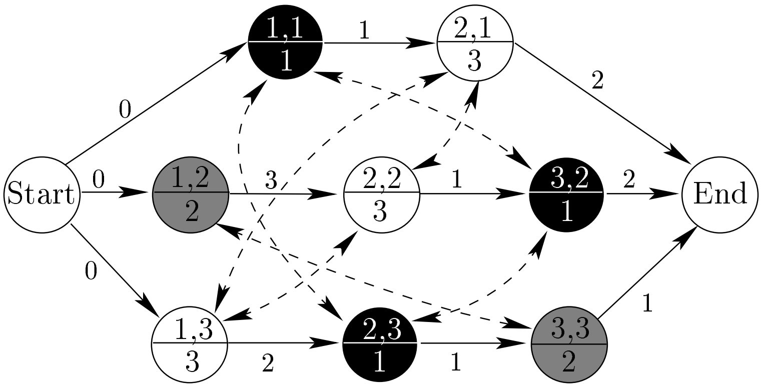

Figure 2.5: *The incomplete disjunctive graph for the processing times and processing sequences displayed in Table 2.1.*

It is important to note that the graph in Figure 2.5 is a representation of the constraints on the tasks and not a representation of a feasible schedule. To construct a feasible schedule each disjunctive arc pair needs to be settled in such a way that the graph $G(\mathcal{D}^*)$ is *acyclic*. The efficiency of a schedule may also be computed by calculating the makespan of the schedule. A smaller makespan implies a better schedule, because it means that all the jobs will be finished earlier. The makespan of a schedule may be computed by finding the length of a longest path from vertex T_{start} to vertex T_{end}. A schedule may have more than one longest path. An algorithm for computing a longest path in a directed graph is presented in Appendix B.

Example 2.6 (Example 2.5 continued)
The graph in Figure 2.6 is an example of a complete disjunctive graph representing a feasible schedule, satisfying the constraints in Figure 2.5. The makespan for the complete disjunctive graph in Figure 2.6 is 8 time units. A longest path from vertex Start *to vertex* End *in this graph is indicated by the sequence of thick solid arcs. The graph in Figure 2.7 is another example of a feasible schedule obtained by fixing the direction of each of the disjunctive arcs in Figure 2.5 (in a manner different to that in Figure 2.6). This schedule has a makespan of 6 time units which is less than the makespan (of 8) of the schedule represented by the complete disjunctive graph in Figure 2.6. The schedule represented by the graph in Figure 2.7 has a Gantt chart representation as shown in Figures 2.3(a) and (b).* ■

2.3.3 Different Types of Schedules

For each set of constraints there are many feasible schedules, but it is desirable that tasks be processed as compactly as possible. A so–called *local left–shift* may be performed on a Gantt chart representation of a schedule by moving a task block to the left and thereby adjusting the starting time of a specific task. The set of feasible schedules in which a local left–shift may be performed in such a manner that the schedule remains feasible is called the set of *semi–active* schedules. A *global left–shift* is performed when a task is moved into a gap earlier on in the schedule. The set of all feasible schedules in which no global left–shift may be made in such a way that the schedule remains feasible (*i.e.*, no task can start earlier without delaying any other task) is called the set of *active* schedules. Several different active schedules may be constructed by performing a series of global left–shifts, starting from a semi–active schedule. A smaller set of schedules is the set of *non–delay* schedules. A schedule is a non–delay schedule if no machine is kept idle at a time when it could begin processing a task. All non–delay

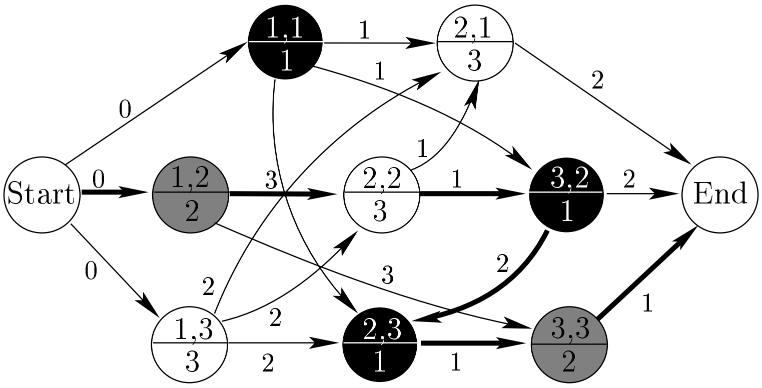

Figure 2.6: *A complete disjunctive graph representing a feasible schedule that satisfies the constraints demonstrated in Figure 2.5. The sequence of thick arcs represents a longest path (of length 8) from vertex* Start *to vertex* End.

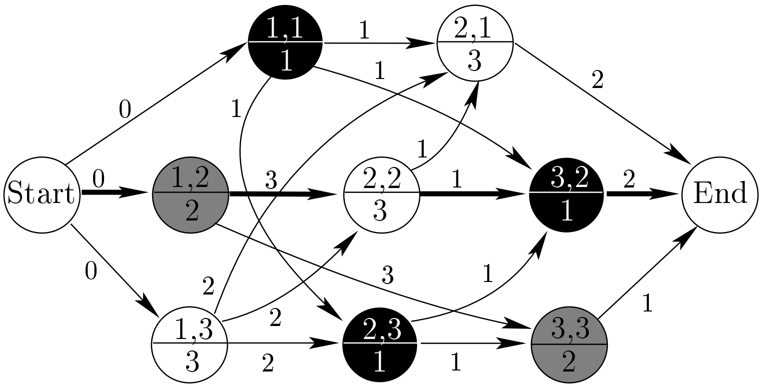

Figure 2.7: *A complete disjunctive graph representing a feasible schedule that satisfies the constraints demonstrated in Figure 2.5. The sequence of thick arcs represents a longest path (of length 6) from vertex* Start *to vertex* End.

schedules are active schedules, but the converse is not necessarily true. There is no guarantee that an *optimal schedule* will be a non–delay schedule, but an optimal schedule (a schedule with minimum makespan) definitely is an active schedule [9]. To decrease the number of schedules that have to be considered, one should only focus on the set of active schedules when faced with scheduling decisions. However, isolating the set of active schedules is, in general, a non–trivial task. The Venn diagram in Figure 2.8 shows a graphical representation of the different schedule types.

2.3.4 Classification Notation for Scheduling Problems

The theory of scheduling is characterized by a virtually unlimited number of problem types. In this section a basic classification of different scheduling problem types is presented. The types of processors in a scheduling problem may be divided into two groups, namely *parallel processors* and *dedicated processors*. Parallel processors all have the same function, whilst dedicated processors are specialized, and are reserved for the execution of specific tasks. Three types of parallel processors may further be distinguished, depending on their speeds. If all parallel processors have equal task processing speeds they are called *identical parallel processors*.

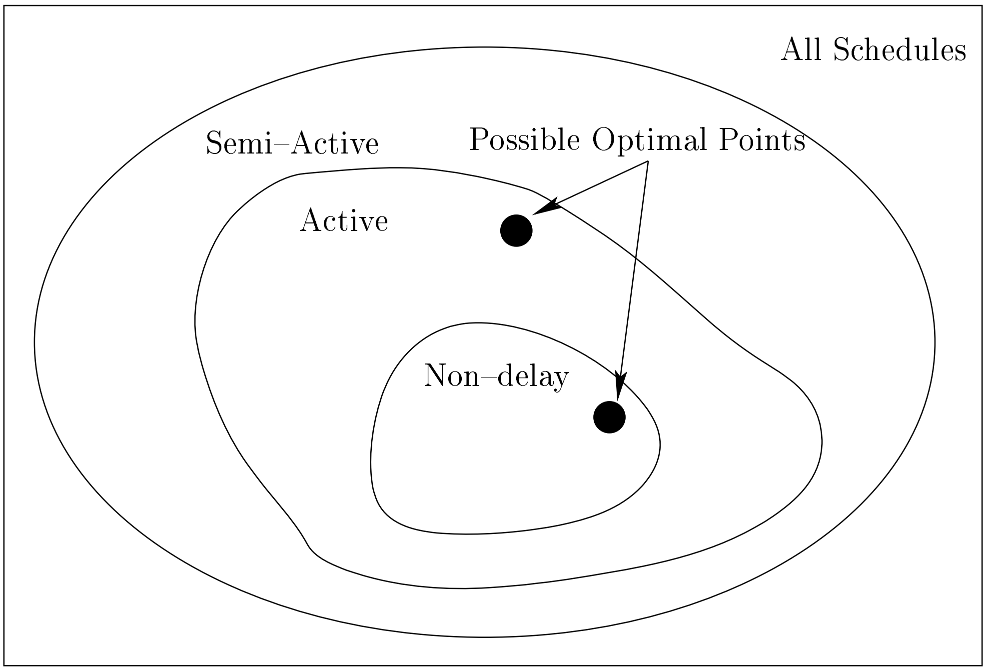

Figure 2.8: *A Venn diagram of the different types of schedules. The black dots indicate possible positions of optimal schedules.*

If parallel processors differ in their processing speeds, but the speed of each processor is constant and does not depend on the task in $\mathcal{T}$ being processed, then the processors are called *uniform parallel processors*. Finally, parallel processors are called *unrelated parallel processors* if the speeds of the processors depend on the tasks processed.

In the case of dedicated processors, there are three models for processing jobs: The *flow–shop*, the *open–shop* and the *job–shop*. In an open–shop the number of tasks in each job is the same and equal to the number of processors, say m. Moreover, task T_{1j} should be processed on processor P_1, task T_{2j} on processor P_2 and so on, but there is no restriction on the order in which tasks are processed. A similar situation is found in a flow–shop, but, in addition, the processing of task $T_{i-1\,j}$ should precede that of task T_{ij} for $i = 2, \ldots, n_j$ and for $j = 1, \ldots, k$. In a flow–shop each job therefore has the same processing order of tasks. In a job–shop the number n_j may be different for all jobs and there may exist a variety of different processing sequences for tasks in different jobs.

The large variety of scheduling problems motivates the introduction of a systematic notation that may serve as a basis for a classification scheme. A notation proposed by Graham, *et al.* [86], and Błażewicz, *et al.* [30] is presented next and used throughout the remainder of this thesis.

The notation consists of three fields, denoted $\boxed{\alpha\,|\,\beta\,|\,\gamma}$. The first field, α, consisting of the ordered pair α_1, α_2, describes the processor environment, where α_1 characterizes the type of processor used:

$$\alpha_1 \in \begin{cases} \varnothing & : \ \text{single processor[26]}, \\ P & : \ \text{identical parallel processors}, \\ Q & : \ \text{uniform parallel processors}, \\ R & : \ \text{unrelated parallel processors}, \\ O & : \ \text{dedicated processors : open}-\text{shop system}, \\ F & : \ \text{dedicated processors : flow}-\text{shop system}, \\ J & : \ \text{dedicated processors : job}-\text{shop system}. \end{cases}$$

The parameter α_2 denotes the number of processors used in the problem:

$$\alpha_2 \in \begin{cases} \varnothing & : \ \text{a variable number of processors}, \\ b & : \ \text{the number of processors is } b \text{ throughout } (b \text{ is a positive integer}). \end{cases}$$

The second field, β consisting of the 8–tuple $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8$, describes task and resource characteristics. The parameter β_1 indicates the possibility of task preemption:

$$\beta_1 \in \begin{cases} \varnothing & : \ \text{no preemption is allowed}, \\ pmtn & : \ \text{preemption is allowed}. \end{cases}$$

The parameter β_2 characterizes additional resources:

$$\beta_2 \in \begin{cases} \varnothing & : \ \text{no additional resources exist}, \\ res & : \ \text{there are specified resource constraints}. \end{cases}$$

The parameter β_3 reflects precedence constraints that may be in place:

$$\beta_3 \in \begin{cases} \varnothing & : \ \text{denotes respectively independent tasks}, \\ prec & : \ \text{general precedence constraints}, \\ uan & : \ \text{uniconnected activity networks}, \\ tree & : \ \text{precedence constraints forming a tree}, \\ chains & : \ \text{a set of chains in the task–on–node graph}. \end{cases}$$

The parameter β_4 describes starting times of tasks:

$$\beta_4 \in \begin{cases} \varnothing & : \ \text{all starting times are zero}, \\ s_j & : \ \text{starting times differ per task}. \end{cases}$$

The parameter β_5 describes task processing times:

$$\beta_5 \in \begin{cases} \varnothing & : \ \text{tasks have arbitrary processing times}, \\ (p_j = p) & : \ \text{all tasks have processing times equal to } p \text{ units}, \\ (\underline{p} \leq p_j \leq \overline{p}) & : \ \text{no processing time } p_j \text{ is less than } \underline{p} \text{ or greater than } \overline{p}. \end{cases}$$

The parameter β_6 describes deadlines:

$$\beta_6 \in \begin{cases} \varnothing & : \ \text{no deadlines are assumed in the system}, \\ \tilde{d} & : \ \text{deadlines are imposed on the performance of a task set}. \end{cases}$$

The parameter β_7 describes the maximal number of tasks constituting a job in the case of a job–shop system:

$$\beta_7 \in \begin{cases} \varnothing & : \ \text{the above number is not limited, or the scheduling problem is not a} \\ & \ \text{job}-\text{shop problem}, \\ (n_j \leq k) & : \ \text{the number of tasks for each job is not greater than } k. \end{cases}$$

The parameter β_8 describes a no–wait property in the case of scheduling on dedicated processors:

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[26] In this notation $\varnothing$ denotes an empty symbol as before, which will be omitted in the remainder of this thesis, in accordance with general practice in the literature.

$$\beta_8 \in \left\{ \begin{array}{lcl} \varnothing & : & \text{buffers of unlimited capacity are assumed,} \\ \text{no}-\text{wait} & : & \text{buffers among processors are of zero capacity and a job, upon} \\ & & \text{completion of processing on one processor, must immediately proceed to} \\ & & \text{the consecutive processor.} \end{array} \right.$$

Buffers usually have unlimited capacity in job–shop systems, *i.e.*, a job may wait after completion on one processor, before its processing starts on the next processor.

The third field, γ, denotes the optimality criterion or performance measure. The most common optimality criterion is the *makespan* $C_{\max} = \max_{1\leq j\leq n}\{C_j\}$, where C_j is the completion time of job J_j, the *total flow time* $\sum_{j=1}^{k} C_j$, and the *weighted flow time* $\sum_{j=1}^{k} w_j C_j$, where w_j is the weight priority associated with the importance of job J_j. In these cases, $\gamma = C_{\max}$ or $\gamma = \sum C_j$ or $\gamma = \sum w_j C_j$ respectively [37].

Other optimality criteria depend on the due date d_j of job J_j, and typically depend on one of the following parameters, which may be computed for each job:

$$\begin{array}{lll} \Gamma_j := & C_j - d_j & \textit{lateness}; \\ E_j := & \max\{0, d_j - C_j\} & \textit{earliness}; \\ \Delta_j := & \max\{0, C_j - d_j\} & \textit{tardiness}; \\ A_j := & \mid C_j - d_j \mid & \textit{absolute deviation}; \\ S_j := & (C_j - d_j)^2 & \textit{squared deviation}; \\ U_j := & \left\{ \begin{array}{ll} 0 & \text{if } C_j \leq d_j \\ 1 & \text{otherwise;} \end{array} \right. & \textit{unit penalty}. \end{array}$$

Let G_j be any of these functions. Then there are four possible objectives, namely $\sum_{j=1}^{n} G_j$, $\max_{1\leq j\leq n}\{w_j G_j\}$, $\min\max_{1\leq j\leq n}\{G_j\}$ or $\sum_{j=1}^{n} w_j G_j$. One of the most important bottleneck optimization criteria, besides $C_{\max}$, is *maximum lateness* $\Gamma_{\max} = \max_{1\leq j\leq n}\{\Gamma_j\}$.

The above scheduling classification scheme is illustrated by means of two simple examples.

Example 2.7

(a) *The scheduling problem* $\boxed{P \mid \mid C_{\max}}$ *is the problem of scheduling non–preemptive and independent tasks with variable processing times and no deadlines, arriving into the system at time 0, on a variable number of identical parallel processors, and no additional resources, in which the optimality criterion is to minimize schedule length, or makespan.*

(b) *The scheduling problem* $\boxed{\ \mid pmtn, s_i \mid \Gamma_{\max}}$ *is the problem of finding a preemptive schedule on one processor for a set of jobs with given arrival times,* $s_j \neq 0$, *and independent tasks having no deadline and arbitrary processing times, and in which the optimality criterion is the minimization of maximum lateness.* ■

2.3.5 Complexity of the Scheduling Problem

Throughout the remainder of this thesis the focus will be on the non–preemptive job–shop scheduling problem with $m = 15$ processors (machines), independent tasks with zero starting times, arbitrary processing times, no more than 25 tasks per job, an unlimited buffer capacity and an optimality criterion of minimizing the makespan (length of the schedule), *i.e.*, a schedule of the form $\boxed{J\,, 15 \mid prec, n_j \leq 25 \mid C_{\max}}$.

The general job–shop scheduling problem, with an optimality criteria to minimize the makespan of the schedule, may be reduced to the following general decision problem:

Decision problem: **Job–shop Scheduling Problem with $m \geq 2$ Processors***:*

INSTANCE: *Processing times p_{ij}, arrival times r_{ij}, number of jobs k, and a positive integer ℓ.*
QUESTION: *Does there exist a feasible schedule with an optimality criterion value less than ℓ for the problem $\boxed{J, m \mid \mid C_{\max}}$ with $m \geq 2$ processors?*

The above problem is a hard problem, from a computational perspective, as the following theorem (for which a proof may be found in [81]) asserts:

Theorem 2.1 (Job–shop Scheduling Problem with $m \geq 2$ Processors)
The decision problem, Job–shop Scheduling Problem with $m \geq 2$ Processors, *is* **NP***–complete.*

The practical implication of Theorem 2.1 is that the time required to resolve scheduling problems optimally typically increases very rapidly as the number of jobs and processors increase. Often this increase is prohibitive in terms of the practical implementability of exact enumerative algorithms, even for a relatively small numbers of jobs and processors (such as the one to be considered in this thesis). In the combinatorial literature a number of simplified scheduling approaches have been designed to circumvent this intractability.

Most notably, it is general practice to relax certain constraints imposed on the original problem and then to solve the relaxed problem as an approximation to the original problem. The solution to the latter may or may not be a good approximation to a solution of the original problem, and such a relaxation approach may consist of [27]:

- allowing preemptions, even if the original problem disallows preemption,
- assuming unit–length tasks, even if variable–length tasks are considered in the original problem,
- assuming certain types of precedence graphs, (such as trees or chains) even when arbitrary graphs result from the original problem.

Another popular approach, when attempting to solve **NP**–complete problems of this nature, is to employ approximate enumerative algorithms which attempt to find an optimal solution, but do not always succeed. The necessary condition for these algorithms to be applicable in practice is that their *worst–case complexity* measure should be asymptotically bounded by a polynomial of low degree in the input length (*i.e.,* the schedule size in the case of a scheduling problem) [27].

The third and last way of dealing with small instances of hard scheduling problems is to use exact enumerative algorithms whose worst–case complexity function is exponential in the input length [27], in the hope that their execution times will nevertheless be reasonable.

2.3.6 Literature on Scheduling Problems

Since 1960 the job–shop scheduling problem has been the subject of a significant number of studies in the literature and is currently most probably the most studied and well developed model in deterministic scheduling [29, 97]. Throughout the years the job–shop scheduling problem has earned the reputation for being particularly difficult to solve [97], and in 1976 Garey, *et al.*[80] proved that the job–shop scheduling problem, with more than one machine, is **NP**–complete.

Traditionally the Gantt chart, as described by Gantt in 1919 [78] and Clark in 1961 [53], was the most popular method of schedule representation, but currently the majority of models use the disjunctive graph representation of schedules instead, as described by Roy & Sussmann [160] in 1964. The Gantt chart is currently mainly used in user interfaces to represent a solution to a problem graphically so that it is easily understood by a layman.

Scheduling algorithms may be divided into two main classes, *optimization algorithms*[27] and *heuristic algorithms*. A brief summary of the different algorithms found in literature within each of these classes is given in Tables 2.2 and 2.3 respectively, and some of these algorithms will be discussed in more detail in the following two subsections.

Method	***Author***
Efficient Methods – Solvable in Polynomial time	Johnson [106] and Williamson, *et al.* [206].
Mathematical Formulations	
(Mixed)(Integer) Linear Programming	Balas [14], Błażewicz, *et al.* [26], Dyer & Wolsey [66], Köppe & Weismantel [115], Serafini [169] and Wagner [200].
Lagrangian Relaxation	Fisher [72].
Cutting Plane	Applegate & Cook [6].
Enumerative Methods	
Branch–and–Bound	Applegate & Cook [6], Ashour & Hiremath [7], Brooks & White [35], Brucker, *et al.* [40], Carlier [45], Carlier & Pinson [46, 47], Charlton & Death [49], Florian, *et al.* [76], Grabowski, *et al.* [85], Greenberg [87], Lageweg, *et al.* [120] and Martin & Shmoys [133].
Dynamic Programming	Kubiak & Van de Velde [117].

Table 2.2: *A summary of the optimization algorithms to solve the scheduling problem, found in literature over the past 50 years.*

2.3.6.1 Exact Optimization Algorithms for Scheduling Problems

The first major work in scheduling theory was done in 1954 by Johnson [106] who developed an efficient (*i.e.*, polynomial–time solvable) algorithm to solve the two machine flow–shop problem, which minimizes the maximum flow time of the schedule. Johnson's work since had a significant impact on scheduling research, because the commonly used objective of minimizing the *makespan* of a schedule originated with him [97]. Another efficient algorithm was developed in

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[27] Optimization algorithms are algorithms that solve an optimization problem to optimality, often at a large computational cost.

[28] An acronym for Greedy Randomized Adaptive Search Process.

Method	***Authors***
Efficient Methods – Solvable in Polynomial Time	Jansen, *et al.* [102, 103] and Sevastianov [171, 172].
Constructive Methods	
Priority Dispatch Rules	Giffler & Thompson [89], Lawrence [122] and Pinedo [152].
Simulation	Baker [11], Chen & Chen [50] and Gere [82].
Bottleneck Heuristics	Adams, *et al.* [2], Applegate & Cook [6], Balas, *et al.* [15], Balas & Vazacopoulos [16], Dausère–Pérès [58], Demirkol, *et al.* [63], Mason [134], Pezzella & Mereli [151], Ramudhin & Marier [158] and Singer [178].
Lagrangian Relaxation	Chen & Luh [51].
Iterative Methods	
Artificial Intelligence	
Neural Networks	Jain & Meeran [99] and Yang & Wang [210].
Local Search	Crawford, *et al.* [57], Pirlot [153], Storer, *et al.* [183], Vaessens [194] and Watson [202].
Genetic Algorithms	Aarts, *et al.* [1], Brizuela & Sannomiya [34], Della Croce, *et al.* [60], Kobayashi, *et al.* [113], Storer, *et al.* [183], Varela, *et al.* [198], Wang & Zheng [201] and Yamanda & Nakano [207, 208].
GRASP[28]	Binato [25].
Tabu search	Al–Turki, *et al.* [5], Chambers & Barnes [48], Jain, *et al.* [100, 101], Nowicki & Smutnicki [148], Pezzella & Mereli [151], Storer, *et al.* [183], Sun, *et al.* [186] and Talliard [189].
Reactive Tabu Search	Battiti [19] and Battiti & Tecchiolli [20].
Simulated annealing	Aarts, *et al.* [1], Mittenthal, *et al.* [140], Storer, *et al.* [183], Steinhöfel, *et al.* [182], Van Laarhoven & Aarts [196], Wang & Zheng [201] and Yamanda & Nakano [209].
Beam Search	Sabuncuoglu & Bayiz [161].
Roling Horizon	Shafaei & Brunn [173] and Singer [178].

Table 2.3: *A summary of the heuristic algorithms for the job–shop scheduling problem found in literature over the past 50 years.*

1997 by Wiliamson [206] for the n job two machine problem. He proved that the existence of a schedule with a makespan of three time units could be determined in a polynomial time given that the total processing time of the tasks on each machine was no more than three.

Although some special cases of the job–shop scheduling problem may be solved to optimality in polynomial time, (as a function of the problem size, usually measured in terms of the number of machines and jobs in the system), the general job–shop problem with n jobs and m machines has $(n!)^m$ possible solutions [184]. Although many of these solutions will not be feasible as a result of precedence and disjunctive constraints, complete enumeration of all the feasible schedules to determine an optimal schedule is nevertheless impractical.

Since the late 1950's researchers have often used mathematical programming techniques to formulate the job–shop scheduling problem mathematically. A survey on different kinds of mathematical programming formulations was conducted by Błażewicz, *et al.* [27] in 1991. They concluded that mathematical programming models have not yet achieved a breakthrough for scheduling problems, because they could only solve very small "toy" instances within a reasonable time. Jain & Meeran [97] noted that until 1998, any success that had been achieved using mathematical formulations, may be attributed to *Lagrangian relaxation approaches*[29] [72] and *decomposition methods*[30] [6]. Another optimization approach, namely that of *dynamic programming*[31] was employed in 1998 by Kubiak & Van de Velde [117] to schedule *deteriorating jobs*[32] in a single machine problem where the processing times of the deteriorating jobs were non–decreasing linear functions of the starting times of the jobs.

The aim in enumerative methods is to eliminate non–optimal solutions, whilst circumventing the need to evaluate all possible solutions. The main enumerative method is the branch–and–bound method. At the start of major research activity on the job–shop scheduling problem, a benchmark problem for 10 jobs and 10 machines was introduced in 1963 by Fisher & Thompson [74]; they called it the *FT10 benchmark problem.* This instance remained unsolved for approximately 25 years, leading to a competition among researchers for a solution procedure that would be able to solve the FT10 benchmark problem [29]. The branch–and–bound approach received substantial attention in the context of scheduling problems during the years 1963–1996. Some branch–and–bound methods developed during this time interval were those of Brooks & White [35] in 1965 and Greenberg [87] in 1968 who based their approach on Manne's integer programing problem [132]. However, none of the above mentioned branch–and–bound approaches were able to resolve the FT10 benchmark problem. Lageweg, *et al.* [120] developed a branch–and–bound approach that was based on the disjunctive graph representation (like all the above mentioned approaches) and they concluded that only small instances of the job–shop scheduling problem could be solved to optimality with the branch–and–bound approach. Charlton & Death [49], Florian, *et al.* [76], Ashour & Hiremath [7] and Fisher [72] obtained lower bounds on the solution of the FT10 benchmark problem by the use of Lagrangian multipliers. Finally, in 1989, Carlier & Pinson [46] developed a branch–and–bound method and proved the optimal value of the FT10 benchmark problem to be 930. Their algorithm was based on bounds obtained for the single machine scheduling problem with precedence constraints, release dates and allowed preemptions [45]. Additionally, they used several priority dispatch rules on subsets of tasks. This problem is polynomial–time solvable and was solved in 14 680 seconds on a PR1ME 2 655 computer [45].

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[29] The Lagrangian relaxation technique is used to compute a lower bound on the optimal scheduling solution. Lagrangian multipliers, which are used as lower bounds, are adjusted iteratively by means of procedures as presented in [72], to obtain strong lower bounds for the branch–and–bound procedure.

[30] Decomposition approaches partition the original problem into a number of smaller, more manageable sub–problems and then solve them to optimality using exact methods.

[31] Dynamic programming is a method devised in 1957 by Bellman [22] according to Błażewicz, *et al.* [27]. In dynamic programming one interprets optimization problems as multistage decision processes, *i.e.*, the problem is divided into a number of stages, and at each stage a decision is required which has an impact on the decisions to be made at later stages.

[32] Deteriorating jobs are jobs whose processing times potentially increase over time, *i.e.*,the processing time of each job is a non–decreasing function of the starting time of the job, which means that the processing time of each job is schedule dependent.

Other branch–and–bound type algorithms developed during the period in which solutions to the FT10 benchmark problem were attempted, were the single machine scheduling problem developed in 1986 by Grabowski, *et al.* [85], and the branch–and–bound procedure developed in 1996 by Martin & Shmoys [133] that was not based on the disjunctive graph representation of a schedule, but on a time orientated branching scheme.

2.3.6.2 Heuristic Methods for Scheduling Problems

As early as the 1960's, researchers noticed that they should be concerned not only with obtaining optimal solutions to scheduling problems, but that they should also consider the suitability of solution techniques in terms of practical and economical applicability [44]. This led to the development of a large number of approximation or heuristic approaches to the scheduling problem (see Table 2.3), because optimization methods carry with them a high computational cost of execution and typically do not solve practically sized problems within a reasonable time. Heuristic methods may be divided into three classes: *efficient methods*, which are executable in polynomial time; *constructive methods*, where a solution is constructed directly from problem data; and *iterative methods*, where a good schedule is constructed by continually reordering machine sequences, according to certain fixed rules. See Table 2.3 for a summary of seminal constructive and iterative methods found in literature.

(i) **Efficient Methods**
In 1999 Jansen, *et al.* [102] developed a polynomial time heuristic scheme for job–shops with a fixed number of machines and with a fixed number of tasks per job. They divided the sets of jobs into two subsets, small jobs and a constant number of large jobs (jobs with a long processing time). A relative ordering for the large jobs is determined and then linear programming techniques are used to construct a schedule (probably infeasible) containing the small jobs, by using an algorithm developed in 1986 by Sevastianov [170]. The small jobs which could be preempted at this stage are removed and placed at the end of the schedule. Sevastianov [171, 172] also constructed heuristic algorithms which solve job–shop scheduling problems in a polynomial time by using *non–strict vector summation methods*[33]. In 1999, Schuurman [165] outlined 10 open problems for scheduling in the area of polynomial–time heuristics.

(ii) **Constructive Methods**
Some of the earliest constructive heuristic algorithms were so–called *priority dispatch rules*[34]. In 1960, Griffler & Thompson [89] produced an algorithm, using priority dispatch rules, that generates active schedules. Priority dispatch rules, such as those defined by Lawrence & Pinedo [122, 152] in 1984, are usually implemented using computerized simulation programs [9, 50, 82]. Studies of the effectiveness of dispatching rules in a job–shop situation were conducted by Conway, *et al.* [56] in 1967. They found that in a multi−machine environment the shortest processing time rule (SPT) retained the advantage of throughput maximization. Elvers [68] studied the performance of 10 dispatching rules over 5 variations of the SPT rule within job–shop scheduling problems which use due date

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[33] The *non–strict vector summation method* consists of assigning an $(m-1)$–dimensional vector to each job and then finding an order in which the vector should be summed so that all partial sums would lie within a given family of half–spaces (specified for a given scheduling problem). The partial sums are sometimes allowed to go out of this family of half–spaces, which explains the non–strictness.

[34] Priority dispatch rules assign priorities to all the tasks available to be sequenced according to a predefined set of rules, and then schedule the tasks in order of decreasing priority values [98]. They are very fast to implement (carry a low computational burden).

assignment criteria. He showed that when the due dates were set to approximately 6 times the total processing time or less, the SPT rule performs best. He also found that due date based rules do not perform well in general and that the popular first–in–first–out rule (FIFO) performs worse than rules based on processing time. According to Jain & Meeran [97], Lawrence [122] compared the performance of ten individual priority dispatch rules with a randomized combination of these rules and showed that combined methods provided far better results than individual priority dispatch rules, but required substantially more computing time. Priority dispatch rule methods typically choose only one task at a time to add to a current partial sequence of tasks on machines, while exact branch–and–bound methods evaluate all possible tasks simultaneously. The so–called *beam search*[35] technique [145, 161] provides a balance between these two extreme approaches, by evaluating a specifiable number of best solutions at any given decision point.

For many years the only viable heuristic methods were priority dispatch rules, but with the advent of more powerful computers so–called *bottleneck heuristics* emerged to bridge the gap between exact algorithms and priority dispatch methods [97]. The *shifting bottleneck procedure*[36] of Adams, *et al.* [2] was the first heuristic technique to solve the FT10 benchmark problem of Fisher & Thompson [74] to optimality. Adams, *et al.* used a single machine scheduling problem proposed by Carlier [45] in 1982. This single machine scheduling problem approach had some draw–backs [58] in the sense that only partial knowledge of the whole problem was utilized so that in some cases an optimal solution would not be found. In the algorithm, only problems with independent jobs were considered, whereas dependence between jobs of a machine typically exists in the job–shop scheduling problem. Therefore, in some cases, the real bottleneck machine was not selected to be *sequenced*[37] next. A monotonic decrease in the makespan was not guaranteed in the re–optimization step, and the procedure was shown to be sensitive to the number of *local optimization cycles*[38]. Dauzere–Peres & Lasserre [58] modified the shifting bottleneck procedure of Adams, *et al.* [2] produced in 1988, by eliminating the draw–backs in Carlier's [45] single machine sequencing algorithm and in 1996 Ramudhin & Marier [158] generalized the shifting bottleneck procedure of Adams, *et al.* [2] for job–shops to solve various types of scheduling problems, including open–shops and shops where only partial ordering on tasks pertaining to each job or machine is specified. Applegate & Cook [6] and Demirkol, *et al.* [63] examined the performance of shifting bottleneck procedures by means of computational studies. They found that the shifting bottleneck procedure with optimal sub–problems and full re–optimization at each iteration, consistently outperformed priority dispatch rules, but required high computational times for large problems. All of the above mentioned shifting bottleneck procedures had the minimization of the makespan as performance measure. However, Mason, *et al.* [134] developed a shifting bottleneck procedure in 2002 for minimizing the total weighted tardiness in a schedule.

Another constructive heuristic approach that has recently emerged as a practical approach

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[35] Beam search is an adaption of the branch–and–bound method in which only some nodes are evaluated. At root level a set of β promising descending nodes is selected, after which only one promising descending node is selected for each node to continue the search in each branch. The value β is called the beam width of the search.

[36] In the shifting bottleneck procedure the machines are sequenced one by one (successively), each time taking the machine identified as a bottleneck, according to a specified criterion, among the machines not yet sequenced. Every time a new machine is sequenced, all previously established sequences are locally re–optimized [2], and the procedure is repeated.

[37] A machine is said to be sequenced if the sequence of the tasks that have to be processed by that machine is fixed.

[38] See [58] for an explanation of the local optimization procedure.

for complex scheduling problems is the *Lagrangian relaxation*[39] method heuristic, as applied by Chen & Luh [51] in 2003. This approach uses dynamic programming to solve relaxed versions of the problem, where the number of Lagrangian multipliers (used to relax the machine capacity constraints) is proportional to the time horizon. This method may become time and computationally expensive for problems with long time horizons.

(iii) **Iterative Methods**

All the methods discussed under the previous heading are from the class of so–called *constructive* methods, because they all build solutions directly from the problem data. The methods discussed under the current heading are from the class of so–called *iterative* methods, because they modify a solution by continually reordering the sequence of scheduling tasks.

The class of iterative methods may be divided further into two subclasses, namely, *artificial intelligence* and *local search* methods.

Artificial intelligence is a subfield of computer science concerned with integrating biological and computer intelligence. A well–known class of artificial intelligence methods is the class of *neural network models*[40], as applied to scheduling problems by Jain & Meeran [99] and Yang & Wang [210].

Local search strategies fall somewhat between *general*[41] and *problem specific*[42] search methods. *Genetic algorithms* tend to be more general in terms of their implementation, whereas *tabu search*[43] and *simulated annealing* are more problem specific. In 1996, Pirlot [153] presented in a tutorial a pragmatic comparison of the three methods and a precise description of each. A local search consists of searching for a good solution by moving from one solution to another in its immediate neighborhood in solution space, according to certain well–defined rules [153]. A survey on different deterministic and random local search methods was conducted by Vaessens, *et al.* [194] in 1994. They also discuss some suggested local search neighborhoods that may be employed in scheduling problems. Watson, *et al.* [203] conducted a study in 2001 on a descriptive cost model used by local search methods in job–shop schedules, while in 2002, Jain, *et al.* [100] evaluated neighborhoods and moves of local search procedures. They measured the effectiveness of a search based on the fact that the time complexity of a move depends on the size of the neighborhood from which it is drawn and the complexity of determining the cost of the move. They

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[39] The heuristic Lagrangian relaxation approach is based on machine decomposition, and is carried out by relaxing the task precedence constraints, rather than machine capacity constraints. The relaxed problem is decomposed into single or parallel machine scheduling sub–problems. The sub–problems are then solved using a dynamic programming approach.

[40] Neural networks are organized in a framework based on the brain structure of simple living entities. In these techniques information processing is carried out through a massively interconnected, weighted network of parallel processing units called neurons. Neural networks are simple to implement and have an ability to learn and generalize by using a so–called training set of data with which to compare generated solutions and then by modifying the generating rules (by means of adjusting weights) according to discrepancies found between the generated solutions and the data in the training set [99].

[41] General search methods have a wide range of applicability, but are often weak when applied to specific problem instances, because they typically do not exploit structure which is unique to the problem instance [27].

[42] Problem specific search methods are designed to exploit any structure and properties unique to the problem instance for which they are intended. These methods are typically highly efficient, but have little use in other domains of application and are usually expensive to implement [27].

[43] The tabu search method was initially proposed by Glover in 1993 [83]. It may be described as a local search technique guided by the use of adaptive or flexible memory structures. A specific new solution is only selected if the move that was performed to obtain that solution was not reversed within the previous ℓ moves. Here ℓ is called the *tabu list* length or tabu tenure of the procedure. For more detail see §3.1.2.2.

found that the tabu search method of Nowicki & Smutnicki [148] developed in 1996 was the most efficient local search method.

The tabu search method of Nowicki & Smutnicki [148] is a fast heuristic algorithm based on the tabu search method with a specific neighborhood definition, employing a *critical path* and blocks of tasks, as defined in 1986 by Grabowski, *et al.* [85]. Their aim was to reduce the neighborhood size at each iteration of the search. In a study on tabu search methods conducted by Jain, *et al.* [101] in 2000, their neighborhood is described as the "most restrictive neighborhood in literature." Another tabu search technique implemented was the parallel tabu search approach developed by Taillard in 1994 [189], which proved to be better than the shifting bottleneck method employed by Pezzella & Merelli [151] to generate an initial solution for their tabu search procedure. In 1995 Sun, *et al.* [186] also proposed a practical, yet effective, tabu search method to manipulate the *active chain*[44] of a schedule, whereas Al–Turki, *et al.* [5] developed a tabu search method for the single machine scheduling problem with non–regular performance measures and *V–shaped*[45] properties. Finally, a tabu search method for the flexible job–shop was developed by Chambers & Barnes [48] in 1996 . One of the draw–backs of tabu search methods used for scheduling is the difficulty to determine the best tabu list length and therefore Battiti, *et al.* [19, 20] introduced the reactive tabu search method, where the appropriate size of the tabu list is learned in an automated way by reacting to the occurance of cycles in the search process.

A computational study on a number of local search procedures for job–shop scheduling problems was conducted by Aarts, *et al.* [1] in 1994. Some of the algorithms under investigation were simulated annealing and genetic algorithms. They showed that simulated annealing performed the best, assuming the same amount of running time for all the methods. When the simulated annealing method was compared to more tailored algorithms (such as the tabu search method) it still performed the best when the running time was of no concern, but the tabu search method outperformed simulated annealing when running time was a factor. In 1992, Van Laarhoven & Aarts [196] proposed an algorithm based on a generalization of simulated annealing. The generalization involves the acceptance of cost–increasing transitions with a non–zero probability to avoid being trapped at a local optimum. Another method that employed the simulated annealing local search approach was the hybrid heuristic method of Mittenthal, *et al.* [140] which is a combination of a greedy algorithm and a simulated annealing algorithm for problems where the optimal schedule is V–shaped. A new simulated annealing algorithm combined with the traditional shifting bottleneck method was proposed in 1996 by Yamanda & Nakano [209], where a variant of Giffler & Thompson's [89] active scheduler method was used to generate new schedules. A new schedule was then probabilistically accepted or rejected at each iteration. If the schedule was rejected, the shifting bottleneck procedure was applied to repair the rejected schedule, and the new schedule was then accepted if the objective function improved. Steinhöfel, *et al.* [182] developed a parallelized version of simulated annealing in 2002 based on algorithms for the job–shop scheduling problem. These algorithms use a neighborhood, as introduced by Van Laarhoven, *et al.* [197] in 1992. A parallel algorithm for computing a longest path in a directed graph is employed in these algorithms, and both homogeneous and inhomogeneous *Markov chains*[46] are used

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[44] An *active chain* of tasks constitutes those tasks on a longest path in a disjunctive graph representation of an active schedule.

[45] A schedule is *V–shaped* in terms of processing times when jobs are sequenced such that jobs preceding the shortest job are in decreasing order and jobs following the shortest job are sequenced in increasing order.

[46] A *Markov chain* or Markov process is a stochastic process with the property that the conditional probability

for *cooling schedules*[47]. In 2002, Wang & Zheng [201] introduced a hybrid strategy combining simulated annealing and a genetic algorithm, which produced results competitive with the best literature results available at that time.

Genetic algorithms appeared for the first time near the end of the 1960s and were intended to solve a number of problems in industry that were difficult to solve with the methods available at that time [198]. Yamanda & Nakano [207] developed a genetic algorithm that represented a schedule directly with task completion times instead of a bit string representation, as was done previously. The crossover strategy of Giffler & Thompson [89] for generating active schedules was used. In 1997, Yamanda & Nakano [208] found it necessary to combine their genetic algorithm with other heuristics, such as the shifting bottleneck procedure or other local search methods, in order to solve larger problems. They also proposed a multi–step crossover method which outperformed other genetic algorithms on the benchmark problems proposed by Fisher & Thompson [74]. Kobayashi, *et al.* [113] developed a genetic algorithm in 1995 that solved the FT10 benchmark problem to optimality and also employed the crossover strategy of Giffler & Thompson [89]. The genetic algorithm developed by Della Croce, *et al.* [60] used an encoding based on preference rules and always produced feasible populations. Their procedure produced comparable results to those obtained by the shifting bottleneck procedure, tabu search and simulated annealing, but at a cost of longer computational times. Brizuela & Sannomiya, [34] designed a genetic algorithm in 2000 that incorporated problem specific knowledge. The aim of their study was to emphasize the gap between classical job–shop scheduling problems, for which many procedures had been developed, and real manufacturing problems that relax the restrictions in the definition of a job–shop.

Researchers also studied the dynamic aspects of scheduling problems, because the computational complexity of the job–shop scheduling problem increases exponentially as the size of the problem increases. Shafaei & Brunn [173] and Singer [178] implemented *rolling horizon*[48] methods using priority dispatch rules and the shifting bottleneck methodology respectively on the sub–problems created.

Another method sometimes used to solve job–shop scheduling problems is the *greedy randomized adaptive search*[49] (GRASP) method, as proposed in 2000 by Binato, *et al.* [25]. A GRASP is a *metaheuristic*[50] for combinatorial optimization problems which, according to Binato, *et al.* has been applied successfully to numerous combinatorial optimization problems.

A graphical representation of scheduling methods developed over time is shown in Figure 2.9.

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of a transition to any state depends only on the current state, and not on previous states.

[47] When using a simulated annealing approach the probability of accepting a move that worsens the objective function value is decreased according to a so–called cooling schedule.

[48] The *rolling horizon* method divides a given scheduling problem into a number of sub–problems, each corresponding to a time window of the overall schedule. Each sub–problem is solved individually and finally all the results obtained from the sub–problems are combined to obtain a solution for the overall schedule.

[49] A GRASP consists of two phases, a construction heuristic, followed by a local search procedure. The construction phase builds a feasible solution whose neighborhood is explored by a local search procedure. The local search iteratively replaces the current solution with the best one in its neighborhood. The search terminates when there is no better solution in the current solution's neighborhood.

[50] A *metaheuristic* is a top–level general strategy which guides other heuristics to search for feasible solutions in domains where the task is hard. It is generally used in **NP**–hard or **NP**–complete problems.

1918: Gantt chart (Gantt, [78])

1954: Polynomial solvable optimization algorithm (Johnson, [106]).

Benchmark problems (Fisher & Thompson, [74]) :1963

1964: Disjunctive Graph technique (Roy & Sussmann, [160])

Branch–and–bound method (Brooks & White, [35]) :1965

1966: Simulation (Gere, [82]) and Branch–and–bound method (Greenberg, [87])

1970: Heuristic methods (Campbell, *et.al.*, [44]) and
branch–and–bound method (Charlton & Death, [49]).

Lagrangian relaxation (Fisher, [72]) and :1971
branch–and–bound method (Florian *et al.*, [76])

Branch–and–bound method (Ashour & Hiremath, [7]) :1973

1976: Job–shop scheduling **NP**–complete (Garey *et al.*, [80]).

Branch–and–bound method (Lageweg *et al.*, [120]) :1977

1982: Branch–and–bound method - single–machine (Carlier, [45]).

Preemptive scheduling - single–machine (Baker *et al.*, [10]) :1983
and Complexity (Błażewicz, *et al.*, [30])

1984: Simulation (Baker, [11]).

1986: Branch–and–bound method - single–machine (Grabowski *et al.*, [85]).

1988: Shifting bottleneck (Adams *et al.*, [2]).

Branch–and–bound method (Carlier & Pinson, [46]) :1989

Cutting plane (Applegate & Cook, [6]) and :1991
mathematical programming (Błażewicz, *et al.*, [26])

1992: Tabu search (Storer, *et al.*[183]) and simulated annealing (Van Laarhoven & Aarts, [196]).

Shifting bottleneck (Dauzere–Peres & Lasserre, [58]), :1993
simulated annealing (Mittenthal, *et al.*, [140]) and tabu search (Taillard, [188])

1994: Simulated annealing (Aarts, *et al.*, [1]), Branch–and–bound (Brucker, *et al.* and
Carlier & Pinson, [40, 47]),
Tabu search (Chambers & Barnes and Taillard, [48, 189]), Reactive tabu search
(Battiti & Tecchiolli, [20]), survey of local search (Vaessens, *et al.*, [194]) and
polynomial algorithms (Williamson, *et al.*, [206]).

Shifting bottleneck (Balas, *et al.*, [15]), genetic algorithm (Della Croce, *et al.* :1995
and Kobayashi, *et al.*, [60, 113]) and tabu search (Sun, *et al.*, [186])

1996: Survey (Błażewicz, *et al.* and Pirlot, [29, 153]), Reactive tabu search (Battiti, [19]),
branch–and–bound method (Martin & Shmoys, [133]), tabu search
(Nowicki & Smutnicki, [148]), shifting bottleneck (Ramudhin & Marier, [158]) and
simulated annealing (Yamanda & Nakano, [208])

Shifting bottleneck (Demirkol, *et al.*, [63]) and :1997
genetic algorithm (Yamanda & Nakano, [208])

1998: shifting bottleneck (Balas & Vazacopoulos, [16]), survey (Crawford, *et al.*, [57] and
Jain & Meeran, [97, 98]), neural networks (Jain & Meeran, [99]), tabu search
(Jain, *et al.*, [101]) and non–strict vector summation (Sevastianov, [171])

Polynomial algorithms (Jansen, *et al.*, [102, 103]) and (Schuurman & Woeginger, [165]), :1999
beam search (Sabuncuoglu & Bayiz, [161]) and rolling horizon (Shafaei & Brun, [173])

2000: Local search (Binato, *et al.*, [25]), disjunctive graph (Błażewicz, *et al.*, [28]),
complexity (Greenberg, [88]) and tabu search & simulated annealing
(Pezzella & Mereli, [151]).

Tabu search (Al–Turki, *et al.*, [5]), genetic algorithm (Brizuela & Sannomiya, [34]),:2001
artificial intelligence (Lee, [123]), rolling horizon (Singer, [178]),Hybrid heuristic
(Wang & Zheng, [201]), survey (Watson, *et al.*, [203]) and neural networks
(Yang & Wang, [210]), Simulation (Chen & Chen, [50]), Lagrangian relaxation
(Chen & Luh, [51]), integer programming (Köppe & R. Weismantel, [115]),

2002: Artificial intelligence (Kim, *et al.*, [110]), shifting bottleneck (Mason, *et al.*, [134]),
simulated annealing (Steinhöfel, *et al.*, [182]) and a genetic algorithm (Varela, *et al.*, [198]).

Disjunctive graph (Mason & Oey, [135]) and linear programming (Serafini, [169]) :2003

Figure 2.9: *A graphical representation of scheduling methods as they developed over the past 80 years.*

Chapter 3

Methodological Background

The aim of this chapter is to provide the reader with a more detailed impression than that given in Chapter 2 of specifically those methods that were implemented in this thesis to solve (i) the layout problem and (ii) the job–shop scheduling problem experienced at LWC — the factory upon which the case study in later chapters is based.

3.1 The Layout Problem

Layout planning involves decisions about the physical arrangement of equipment within a factory. A *centre* in a factory is a specific workstation where one machine is located, or where a number of machines performing the same task are located. A *task* is therefore performed at a centre. A *job* is a set of tasks that has to be performed in a specific sequence, to fill a particular order or create a particular product. The notion of *physical arrangement* of centres in a factory raises four questions [116]:

1. Which centres should be included in the layout?
2. How much space does each centre require and what is the capacity of each centre?
3. How should each centre's space be configured?
4. Where should each centre be located?

The last question has two dimensions: *relative location* and *absolute location.* The relative location is the location of a centre relative to the other centres, whilst the absolute location is its actual placement position inside the factory walls, for example near a door.

3.1.1 Conventional Approach to the Layout Problem

A factory exhibiting the characteristics of a job–shop normally has a process layout (as discussed in §2.2.1.1), because small quantities of a large variety of different products are typically manufactured at a time. Throughout the remainder of this thesis the focus will fall on the process layout, because this is the layout at LWC as will be explained later.

In developing a process layout a so–called conventional approach toward solving the layout problem generally follows the steps indicated below [185].

1. **Determination of Space Requirements.**
   The space required for each centre is determined. This includes working area, aisles and space for in–process inventory.

   Example 3.1
   Suppose there are 6 centres in a factory, with the space required for each centre as shown in Table 3.1. The required space includes the working area, aisles and space for in–process inventory.

Centre	Area Required [m^2]
A	72
B	63
C	49
D	42
E	30
F	20

Table 3.1: *The space in* m^2 *required by each centre in Example 3.1.*

Suppose the factory has a length of 28m *and a width of* 20m. *The total amount of available space is therefore* $560\mathrm{m}^2$. *The objective in this example (to be continued as a series of further examples) will be to minimize the total material–handling cost for the factory.* ■

2. **Computation of Closeness Ratings.**
   It is important to decide which centres to position close to each other. The so–called *from–to matrix* and *rel–chart* (short for relationship chart) provide closeness ratings for centre pairs. The rel–chart describes qualitatively the degree of closeness that should exist between any two centres [203]. There are standard codes used in describing this closeness, as shown in Table 3.2. They are listed in descending order of priority in the table: A, E, I, O, U and X.

Code	Priority	Value
A	Absolutely necessary	4
E	Especially important	3
I	Important	2
O	Ordinary	1
U	Unimportant	0
X	Undesirable	–1

Table 3.2: *The standard codes used for closeness ratings of centres in rel–charts.*

The codes in Table 3.2 are assigned to each centre pair by the management of the factory or by the workers in the factory. The from–to matrix describes the estimated number of trips or transportations of unit loads of production material between all centre pairs in the factory. A so–called *flow–chart* may be constructed from a from–to matrix by building a triangular matrix in which entries represent the compounded flow between the corresponding centres. The flow–chart thus only has one entry for the flow from (say) centre A to (say) centre B and *vice versa*, which constitutes the two flows added together. This forms a quantitative measure of desired closeness between centres, which may be transformed into the qualitative measure, shown in Table 3.2, by denoting the degree of closeness by an A, E or I if the number of trips fall within desired intervals corresponding to these codes, as determined by the factory management. If there is almost no flow between two centres the flow is marked by an O or an U, whereas when management does not want any flow between two specified machines, the flow is marked with an X denoting an undesirable flow.

Example 3.2 (Example 3.1 continued)
Suppose the flows [number of trips per time unit] *between the centres in Example 3.1 are given by the from–to matrix in Table 3.3. The corresponding flow–chart for the from–to matrix in Table 3.3 is shown in Table 3.4.*

From–to Matrix

	To					
From	A	B	C	D	E	F
A			1500			300
B	1000		300			
C	300			1500		
D						1500
E		300				
F						

Table 3.3: *The from–to matrix for a factory with 6 centres, as described in Examples 3.1 and 3.2. Each centre pair entry represents the flow* [number of trips per time unit] *from the centre in the row to the centre in the column.*

Flow–chart

	Centres					
	A	B	C	D	E	F
A		1000	1800			300
B			300		300	
C				1500		
D						1500
E						
F						

Table 3.4: *The flow–chart corresponding to the from–to matrix in Table 3.3 for Example 3.2. Each entry of the flow–chart represents the compounded (two–directional) flow* [number of trips per time unit] *between the centre pair corresponding to the entry.*

The flow–chart may be converted to a rel–chart (see Table 3.5) using the codes in Table 3.2. The rel–chart is typically used in the next step of the procedure, when constructing a graphical representation of the layout.

It is important to notice the triangular characteristic of the flow–chart (Table 3.4) and the rel–chart (Table 3.5) constructed from the from–to matrix. ■

3. **Construction of a Graphical Representation.**
During this step the conversion from the flow–chart to a rel–chart is utilized. The centres are represented by nodes of a so–called *closeness graph*, and the number of edges between two nodes represent the closeness between the nodes. The decoding scheme is as follows.

Rel–chart

	Centres					
	A	B	C	D	E	F
A		*E*	*A*	*U*	*U*	*O*
B			*O*	*U*	*O*	*U*
C				*A*	*U*	*U*
D					*U*	*A*
E						*U*
F						

Table 3.5: *The rel–chart for Example 3.2 with the corresponding flow–chart in Table 3.4.*

Code A is represented by 4 edges, E by 3 edges, I by 2 edges, O by 1 edge and U is represented by the absence of an edge. A wiggly edge represents the code X. The objective is to arrange the nodes so that a minimum number of edges are crossed when proceeding from one centre to another (so as to minimize expected materials transportation congestion on the factory floor) with the frequencies indicated by the decoded rel–chart. It might take a number of trials before one obtains a desirable arrangement. The procedure starts with the conversion or decoding of the rel–chart to what is called a *value chart*, using the values shown in Table 3.2 associated with the codes: A, E, I, O, U and X.

The *measure of importance* of each centre, which ascertains the degree of closeness one centre (say centre i) has with respect to all other centres, is obtained by adding the row and column values in the value chart for centre i together. A centre(s) with the highest total is repeatedly selected and then placed in the middle of the nodal diagram (the closeness graph). Any centres that are joined to this centre by means of four edges are located around this centre point of the graph (These joined centres are still unselected as are all the others not yet selected). Next, from the remaining unselected centres in the diagram, one with the next highest importance measure is selected and the centres with four–edges are located around this centre. This procedure is continued with each appropriate centre in the diagram. After all four–relationship centres have been exhausted, and if some of the centres are still absent from the diagram, all the centres are made unselected and the procedure is continued with three–relationship centres, following the same sequence of steps as were used with four–relationships, and so on.

Example 3.3 (Example 3.2 continued)

Value Chart

	Centres						**Measure of Importance**
	A	B	C	D	E	F	
A		3	4	0	0	1	8
B			1	0	1	0	5
C				4	0	0	**9**
D					0	4	8
E						0	1
F							5

Table 3.6: *The value chart for Example 3.3 with corresponding rel–chart in Table 3.5.*

The rel–chart in Table 3.5 may be converted to the value chart shown in Table 3.6. The *next step is to construct a closeness graph from the value chart in Table 3.6. Centre* C *has the highest value in the value chart and is therefore selected to be in the middle of the closeness graph. The centres corresponding to the value* 4 *in centre* C*'s row or column are inserted into the graph together with the corresponding number of edges (see Figure 3.1). The graph now contains centres* C, D *and* A.

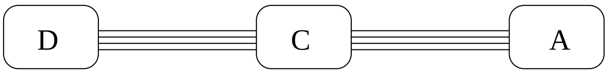

Figure 3.1: *The resulting closeness graph after the first step of construction from the value chart in Table 3.6.*

The next step is to determine the centre in the graph that has the second largest measure of importance in the value chart. Centres D *and* A *have the same measure of importance* (8) *in the value chart. Therefore any one of these two centres is selected randomly, and centres joined to the selected centre by means of* 4 *edges are inserted into the graph. Suppose centre* D *is selected. Then centre* F *is inserted (see Figure 3.2).*

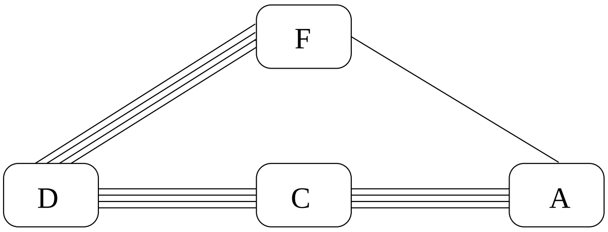

Figure 3.2: *The resulting closeness graph after two steps of construction from the value chart in Table 3.6.*

The next centre selected for insertion is centre A *and note that there is no centre at this point that is not yet in the graph and has a four–relationship with centre* A. *Also none of the remaining centres have four–relationships with any of the other centres that is absent from the graph. We continue by exploring the three–relationships in exactly the same way. Starting with centres* C *and* D *respectively, no centre is found that has a three–relationship with them. Centre* A *has a three–relationship with centre* B, *and therefore centre* B *is inserted next. The procedure continues, by looking for other three–relationships, then for two–relationships and finally for one–relationships. A one–relationship between centres* B *and* E *is found and the procedure is concluded by inserting centre* E. *Figure 3.3 shows the completed closeness graph. Note that none of the edges cross each other.* ■

4. **Construction of an Effectiveness Evaluation Chart.**
An *effectiveness evaluation chart* provides a measure of effectiveness of the nodal arrangement developed in step 3. Different arrangements may be evaluated by developing a chart for each, and the one with the lowest value may then be selected as the best arrangement to be used in the next step. The effectiveness evaluation chart is achieved by first converting the nodal representation of the layout into a semi–scaled grid representation. For each centre the necessary area is equated to the *approximate* number of grid–blocks required, using a convenient scale. For example, 4 square metres could equal one grid–block.

In the overall grid arrangement, one should ensure that the numbered blocks in one direction (e.g. width) are such that the resultant dimension is an integer multiple of the

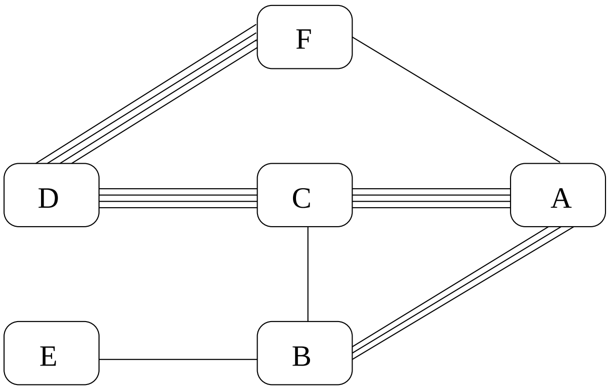

Figure 3.3: *A closeness graph for the value chart in Table 3.6.*

column span. Recall from §2.2.4 that the *rectilinear distance* between two points with Cartesian coordinates (a, b) and (x, y) is defined as

$$d = |x - a| + |y - b|,$$

while the *Euclidean distance* between two points (a, b) and (x, y) is defined as

$$d = \sqrt{(x - a)^2 + (y - b)^2}.$$

See Figures 3.4(a) and (b) for graphical representations of these two distance measures.

(a) *Rectilinear distance:* $d = |x - a| + |y - b|$ (b) *Euclidean distance:* $d = \sqrt{(x - a)^2 + (y - b)^2}$

Figure 3.4: *Two different methods to measure distance between two points in the plane.*

The closeness measure is defined in terms of the distance traveled between centres. Since these distances are usually traversed along grid–like aisles that run between centres, the rectilinear distance between the centroids of the centres seems an appropriate measure of distance. An effectiveness evaluation chart, similar to a value chart (the rel–chart transformed to a flow–chart), may be useful in developing this measure for all centres. The closeness measure may therefore be taken as the shortest rectilinear distance between two centres, multiplied by the number of edges between those two centres. The grand total of all pairwise closeness measures gives the measure of effectiveness of the nodal diagram; the grid chart with minimum grand total is selected for the next step.

Example 3.4 (Example 3.3 continued)
The first step in constructing an arrangement of centres is to partition the floor into

equally sized blocks, say 20m^2 *blocks. The next step is to approximate the number of blocks required for each centre (see Table 3.7). Recall that the objective is to minimize the material–handling cost. The material–handling cost between a pair of centres may be measured by multiplying the flow of production material* [number of trips per time unit] *between the centres by the distance between the centres. The values in the value chart represent a measure of the magnitude of the flow between the centres and therefore it is sufficient to multiply the distance between the centres by the values in the value chart. A feasible layout emanating from the closeness graph in Figure 3.3, with an effectiveness measure of* 45*, is shown in Figure 3.5. The corresponding effectiveness evaluation chart is shown in Table 3.8. The individual entries in the effectiveness evaluation chart were computed by multiplying the rectilinear distance (in blocks between the centre in the row and the centre in the column) with the value in that specific entry in the value chart in Table 3.6.* ■

Centre	**Number of Blocks**
A	4
B	3
C	3
D	2
E	2
F	1

Table 3.7: *The approximated number of grid blocks occupied by each centre on the factory floor.*

	D	F	A	A		
	D	C	A	A		
		C	C	B		
	E	E	B	B		

Figure 3.5: *A feasible layout for the closeness graph in Figure 3.3.*

Effectiveness Evaluation Chart

	Centres						
	A	B	C	D	E	F	*Total*
A		3.0 × 3	3.0 × 4	2.5 × 0	4.5 × 0	2.0 × 1	23
B			3.0 × 1	5.5 × 0	2.5 × 1	5.0 × 0	5.5
C				2.5 × 4	1.5 × 0	2.0 × 0	10
D					3.0 × 0	1.5 × 4	6
E						3.5 × 0	0
							45

Table 3.8: *The effectiveness evaluation chart for the layout in Figure 3.5.*

5. **Development of Templates.**
After the best layout has been chosen from step 4, a good visual representation of the layout is produced in order to explain it to the management of the factory. Most often layout problems are better grasped by laymen when considering a visual representation of the layout.

There are three basic ways of representing a layout: simple sketches, related two–dimensional templates, or three–dimensional models may be used. Sketching the layout is easily and quickly achieved and is usually done on grid paper. The most obvious disadvantage of this approach is that a change in the layout requires a redraw of the whole factory floor. Using two–dimensional templates is very popular and relatively inexpensive. Templates are made of metal, wood, plastic or paper and cut to the shapes of the various centres. The centres are then arranged and rearranged on grid paper until a satisfactory layout is achieved. Three–dimensional models are popular if the height of the centres are important, but are considerably more expensive.

Example 3.5 (Example 3.4 continued)
A sketch of the layout found in the previous example (see Figure 3.5) is shown in Figure 3.6. The purpose of the sketch is to create an attractive visualization of the factory layout. Figure 3.6 has more detail than Figure 3.5 and the correct dimensions of the centres have been used in Figure 3.6. ■

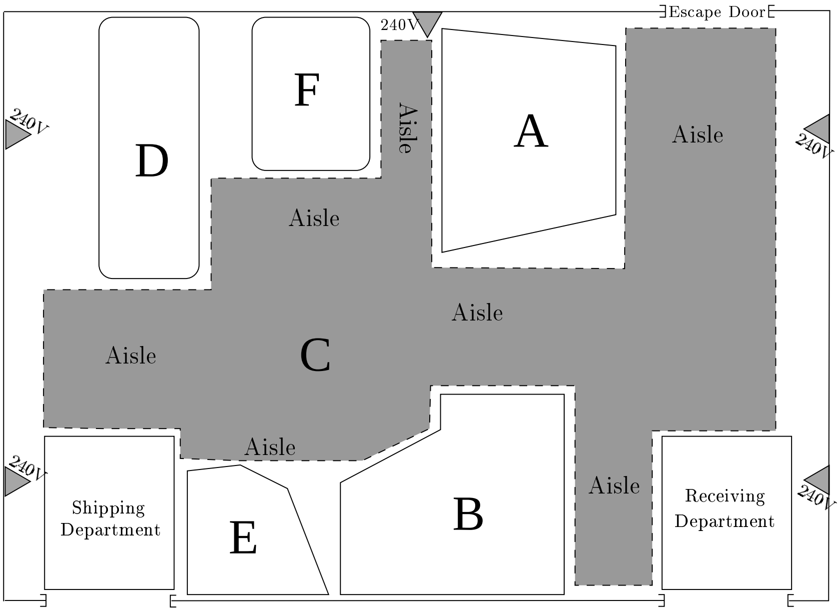

Figure 3.6: *A sketch drawn for Example 3.5 of the layout shown in Figure 3.5.*

The final desired layout of the facility should take into account the sizes of centres and aisles. It is important to determine and show the positions of the aisles, walls, windows, spaces between centres, in–process inventory storage space and personnel working. The flow of material is usually also indicated, using arrows. To avoid clutter, the material–flow, overhead pipes and ducts are usually indicated by means of an overlay. Outlets for 240V and 120V (depending on the regional voltage supplied to the factory) electrical services, water supply, drains, compressed air supply, natural gas, bench lights and other utilities should all be shown and labeled [185].

Generally one begins by selecting a scale for the visual representation. The most common scale used is one centimeter for one metre (1:100)[1]. A plan of the outside walls and other permanent structures is drawn. The receiving and shipping departments are fixed by selecting the material–flow pattern. The positions of aisles (also accommodating quick

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[1] This is the standard scale used by architects in South Africa.

evacuation routes in case of emergency) are defined. All parts of the facility should be easily accessible, but the minimum number of aisles should be placed by which to cover maximum space, in order to reduce required floorspace. Aisles are characterized by length, width and location. The width of an aisle should be determined by the kind of traffic that will be using that aisle (for example, forklifts, people or trolleys). Main aisles fit for two way traffic should have a minimum width of 5 m to 6 m. For one way traffic 4m width aisles are usually sufficient and aisles only used by personnel are usually only 1m wide [185].

6. **Making manual changes.**
   The sizes and shapes of the centres may be changed to fit to their real size and shape, *i.e.,* the sizes now do not include the aisle and workspaces as previously. Certain performance criteria, like safety and ergonomic criteria (*e.g.,* if a centre is noisy the management of the facility would like to place it far from the reception area), depend on the absolute location of a centre. Neither the rel–chart nor the from–to matrix are able to reflect these criteria, and hence final manual changes are usually required.

3.1.2 Computer–Aided Approach to the Layout Problem

Managers or designers of a factory have traditionally solved layout problems manually. With the emergence of the discipline operations research and the use of digital computers during the second half of the 20th century, new analytical methods were designed to solve layout problems. Recently computer programs have also been used to solve layout problems. This is useful especially for process layouts, because product layouts are generally not very complicated to solve by hand.

Any one or more of the following approaches may be used to solve factory layout problems in a computer aided fashion:

- Exact (mixed–integer programming) approaches, mainly branch–and–bound approaches.
- Heuristic procedures.
- Probabilistic approaches.
- The application of graph theoretic procedures.

The objectives of these procedures depend on the manner in which centre relationships are expressed. When qualitative relationships are used, the objective is usually to maximize the adjacencies between centres. When centre relationships are quantitative, the objective is usually to minimize the material–handling cost. The rest of this section is devoted to a more detailed discussion of the two most popular computer aided methods amongst those listed above.

3.1.2.1 Exact Approaches

Mathematical programming models of production floor layouts may be divided into two categories, based on the nature of centre locations. If centres may be located only at a discrete number of points on the factory floor it is called a *discrete layout problem/model*, while if they may be located at any point on the factory floor it is called a *continuous layout problem/model.* In this subsection discrete layout problems/models will be considered first, followed by a discussion of continuous layout problems/models. Throughout this subsection rectangular shapes are assumed for centres and rectilinear distances between the centres are used in an attempt at a realistic representation of closeness.

(i) *Mathematical Programming Model with a Discrete Layout*
Suppose there are n locations at which to place m centres, with $m \leq n$. The mathematical programming problem is then to

$$\text{minimize } Z = \sum_{i=1}^{m} \sum_{k=1}^{n} \sum_{j=1}^{m} \sum_{h=1}^{n} C_{ik,jh} X_{ik} X_{jh} \qquad (3.1)$$

subject to

$$\sum_{i=1}^{m} X_{ik} \leq 1, \qquad k = 1, \ldots, n \qquad (3.2)$$

$$\sum_{k=1}^{n} X_{ik} = 1, \qquad i = 1, \ldots, m \qquad (3.3)$$

$$X_{ik} \in \{0, 1\}, \qquad \forall\, i, k$$

where

$$f_{ij} = \text{material flow from centre } i \text{ to centre } j,$$

$$d_{kh} = \text{rectilinear distance from location } k \text{ to location } h,$$

$$F_{ik} = \text{cost of placing centre } i \text{ at location } k,$$

$$C_{ik,jh} = \begin{cases} f_{ij} d_{kh}, & \text{if } i \neq j \text{ and } k \neq h, \\ F_{ik}, & \text{if } i = j \text{ and } k = h, \\ 0, & \text{otherwise,} \end{cases}$$

$$X_{ik} = \begin{cases} 1, & \text{if centre } i \text{ is placed at location } k, \\ 0, & \text{otherwise.} \end{cases}$$

Constraints (3.2) guarantee that a solution has at most one centre at any specific location $k \in \{1, \ldots, n\}$, while constraints (3.3) guarantee that each centre $i \in \{1, \ldots, m\}$ should be allocated to exactly one location. $C_{ik,jh}$ is the material–handling flow between centres i and j expressed as a product of the flow and the travel distance, whereas $C_{ik,ik} = F_{ik}$ represents the installation cost of centre i at a specific location k. This model may solve a problem with a constructive or improvement objective in mind. If the modelling objective is to improve the current layout, the fixed input values $C_{ik,ik}$ should be adjusted ensuring that there is no cost involved in installing a centre at a location at which it is currently positioned. Implementing this model with a constructive objective in mind, it is assumed that the factory is empty at first and no matter what layout is chosen, all centres must be installed fully. The objective function (3.1) of this typical QAP is to minimize the material–handling cost expressed as the product of flow, typically measured in m^3/second, and travel distance, usually measured in metre as well as the cost incurred by installing centres. The branch–and–bound procedure is usually employed to solve this quadratic integer programming problem. The model does not incorporate the fact that centres may have different sizes. This is a typical limitation of the QAP.

In order to remedy this situation, Bazaraa [21] suggested a quadratic *set–covering* approach, in which several candidate locations are made available for the location of each centre. This prevents each location from being available to every centre and is also capable of accommodating different centre sizes. Furthermore, the number of combinations to be evaluated is smaller. The resulting model may also be solved by the branch–and–bound procedure. This procedure is capable of producing rectangular shapes for the centres as well as for the layout outline. Bazaraa simplified the model by partitioning the available floorspace into blocks of equal size. The grid–points that are thus formed, serve as the available locations for the centres. This model has two draw–backs: Firstly, the candidate locations for each centre have to be established in advance and secondly, the specification of centre shapes might not be practical in the sense that some centres have L–shapes or U–shapes but the model assigns rectangular shapes to them.

The objective of this alternative approach by Bazaraa is to minimize the material–handling cost as well as the relocation cost of centres. Let

d_{kh} = rectilinear distance between the $k-$th and the $h-$th locations (grid$-$points),
f_{ij} = flow volume per time unit between centres i and j,
F_{ik} = fixed cost of placing centre i at location k,
$I(i)$ = set of candidate locations for centre i,
$\mathcal{S}_i(k)$ = set of squares occupied by centre i if it is placed at location k,

$$a_{ikt} = \begin{cases} 1, & \text{if block } t \in \mathcal{S}_i(k) \\ 0, & \text{otherwise,} \end{cases}$$

$$X_{ik} = \begin{cases} 1, & \text{if centre } i \text{ is placed at location } k \\ 0, & \text{otherwise.} \end{cases}$$

Then the objective is to

$$\text{minimize } Z = \sum_{i=1}^{m}\sum_{j=1}^{m}\sum_{k=1}^{I(i)}\sum_{h=1}^{I(j)} f_{ij}X_{ik}X_{jh}d_{kh} + \sum_{i=1}^{m}\sum_{k=1}^{I(i)} F_{ik}X_{ik}, \tag{3.4}$$

subject to

$$\sum_{i=1}^{m} X_{ik} \leq 1, \qquad k = 1, 2, \ldots, n, \tag{3.5}$$

$$\sum_{k=1}^{I(i)} X_{ik} = 1, \qquad i = 1, 2, \ldots, m, \tag{3.6}$$

$$\sum_{i=1}^{m}\sum_{k=1}^{I(i)} a_{ikt}X_{ik} \leq 1, \qquad \text{for each block } t, \tag{3.7}$$

$$X_{ik} \in \{0, 1\}, \qquad k = 1, 2, \ldots, I(i) \text{ and } i = 1, 2, \ldots, m.$$

Let us focus on the objective function (3.4) first. It is important to notice that the two terms do not have the same units. The first term represents flow with a typical unit of m^3/second multiplied by the distance in metres between two centres, which results in a term with a unit of m^4/second. The second term is a financial term and thus has a monetary unit. There typically exists no known conversion rule between these units. Hence it is desirable to incorporate a real–valued scaling parameter ($0 \leq \theta \leq 1$) which compensates for this discrepancy. This parameter may then be varied manually during a sensitivity analysis in an attempt to test different conversion rules[2]. The objective is then

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[2] Bazaraa [21] did not incorporate this scaling factor. It was a contribution of the author in order to compensate for different units.

to rather

$$\text{minimize } Z = \theta\left(\sum_{i=1}^{m}\sum_{j=1}^{m}\sum_{k=1}^{I(i)}\sum_{h=1}^{I(j)} f_{ij}X_{ik}X_{jh}d_{kh}\right) + (1-\theta)\left(\sum_{i=1}^{m}\sum_{k=1}^{I(i)} F_{ik}X_{ik}\right). \tag{3.8}$$

Constraints (3.5) and (3.6) have exactly the same meaning as constraints (3.2) and (3.3) in the previous mathematical programming model, while constraints (3.7) ensure that there is only one centre or part thereof occupying each block.

Example 3.6 (The set–covering approach applied to Examples 3.1–3.4)
The first step in applying the set–covering approach to a factory layout problem is to discretize the floor of the factory into equally sized blocks. The 20m × 28m *factory floorspace of Example 3.1 is partitioned into* 5m × 4m *blocks, as shown in Figure 3.7. The grid–points are numbered horizontally and in a top-down manner (see Figure 3.7).*

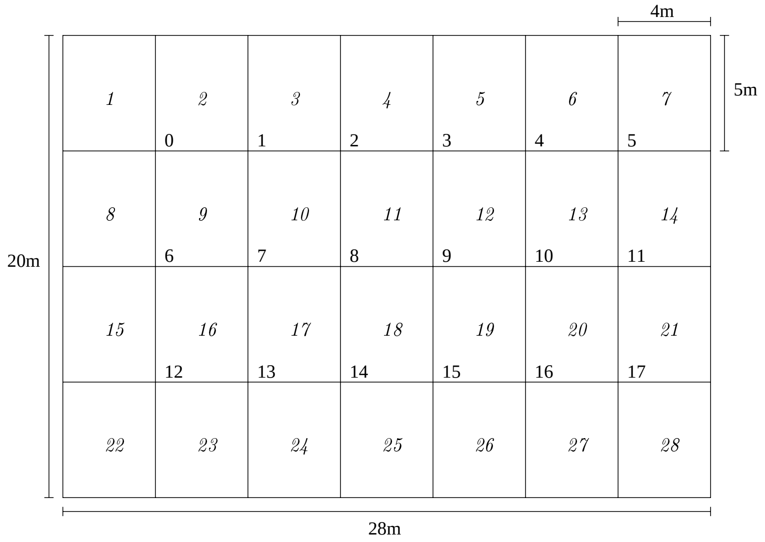

Figure 3.7: *The 20m × 28m floorspace of the hypothetical factory in Example 3.6 partitioned into 5m × 4m grid blocks. The blocks are numbered in italics and the numbers in normal font represent grid–points.*

Next, the candidate grid–points for the individual centres are determined, with dimensions as shown in Table 3.9. With this specific discretization of the factory floor all centres have all grid–points as candidate points.

Name	Length [m]	Width [m]
A	8	9
B	7	9
C	7	7
D	6	7
E	5	6
F	4	5

Table 3.9: *The dimensions of the centres in Examples 3.1 and 3.6.*

The flows between the centres are shown in Table 3.3, and are reprinted in Table 3.10 for reference purposes. The distances between grid–points are shown in Table 3.11 and are

From–to Matrix

	To					
From	A	B	C	D	E	F
A			1500			300
B	1000		300			
C	300			1500		
D						1500
E		300				
F						

Table 3.10: *The flow [number of trips] between the centres in Example 3.6.*

Location	*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*
0		4	8	12	16	20	5	9	13	17	21	25	10	14	18	22	26	30
1			4	8	12	16	9	5	9	13	17	21	14	10	14	18	22	26
2				4	8	12	13	9	5	9	13	17	18	14	10	14	18	22
3					4	8	17	13	9	5	9	13	22	18	14	10	14	18
4						4	21	17	13	9	5	9	26	22	18	14	10	14
5							25	21	17	13	9	5	30	26	22	18	14	10
6								4	8	12	16	20	5	9	13	17	21	25
7									4	8	12	16	9	5	9	13	17	21
8										4	8	12	13	9	5	9	13	17
9											4	8	17	13	9	5	9	13
10												4	21	17	13	9	5	9
11													25	21	17	13	9	5
12														4	8	12	16	20
13															4	8	12	16
14																4	8	12
15																	4	8
16																		4
17																		

Table 3.11: *Rectilinear distances [m] between the grid–points on the discretized factory floor in Figure 3.7.*

required for minimization of material–handling cost in the factory.

Before the model is solved, the binary parameters a_{ikt} *have to be determined. However, it is clear that the parameters are the same for all centres, because all centres have the same list of candidate locations and no centre occupies more than* 4 *blocks at any orientation (see Table 3.7). Therefore we ignore the first subscript of the parameter* a_{ikt} *in this example and only determine* a_{kt} *where* $a_{kt} = 1$ *if* t *is one of the* 4 *blocks surrounding grid–point* k*. The values of* a_{kt} *are shown in Table 3.12.*

Let the cost of placing a centre at a specific grid location be a pseudo–random number between 0 *and* 10 000*, as shown in Table 3.13.*

The resulting QAP was solved via a **Lingo 8.0** *program (see Appendix A.1) on a* 2.66 *GHz Pentium* 4 *machine with* 512 *Mb of memory. An objective function value of* 35 080 *was found within* 27 *seconds for* $\theta = 0.5$*, and for* $\theta = 1$ *the program terminated within* 33 *seconds with an objective function value of* 54 500*. A visual representation of the optimal layout found, when* $\theta = 0.5$ *(*i.e.*, when floor costs and installation costs are weighted equally), is shown in Figure 3.8 and for* $\theta = 1$ *(*i.e.*, when only flow costs are considered and installation costs are ignored), in Figure 3.9.* ■

(ii) *Mathematical Programming with a Continuous Layout*
Patsiatzis & Papageorgiou [150] used a mixed integer linear programming problem (MILP) to model the continuous layout problem. In this formulation centres are allowed to rotate 90° and two centres are connected at their geometrical centroids for the purpose of flow measurement.

	Blocks																											
Location	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*
0	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1

Table 3.12: *The blocks occupied by each centre if it were to be located at a specific grid–point, with the blocks and locations numbered as in Figure 3.7.*

	Grid–points																	
Centres	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
A	3 878	2 235	2 857	4 565	2 084	9 815	5 077	6 237	6 237	2 176	2 234	4 663	9 470	6 897	347	2 205	6 139	7 961
B	9 162	7 265	2 227	5 907	7 316	1 305	8 908	5 761	9 550	3 836	7 112	495	2 592	691	4 628	6 713	1 567	8 419
C	8 761	8 415	9 865	2 685	44	6 894	9 085	176	2 486	4 111	1 597	787	4 764	4 809	6 996	125	2 924	9 694
D	2 749	1 893	7 705	9 403	9 951	1 801	5 378	9 579	1 136	7 755	267	3 087	2 603	1 682	8 624	5 149	4 687	2 437
E	3 169	8 305	3 606	8 978	6 570	5 598	827	2 180	1 961	2 547	1 721	7 206	5 973	3 645	7 852	1 234	5 029	991
F	4 367	1 069	7 715	1 946	222	9 682	7 535	597	6 439	8 386	3 195	6 279	3 881	1 670	7 526	4 441	685	5 409

Table 3.13: *The (random) cost of placing a centre at a specific location in the grid in Figure 3.7.*

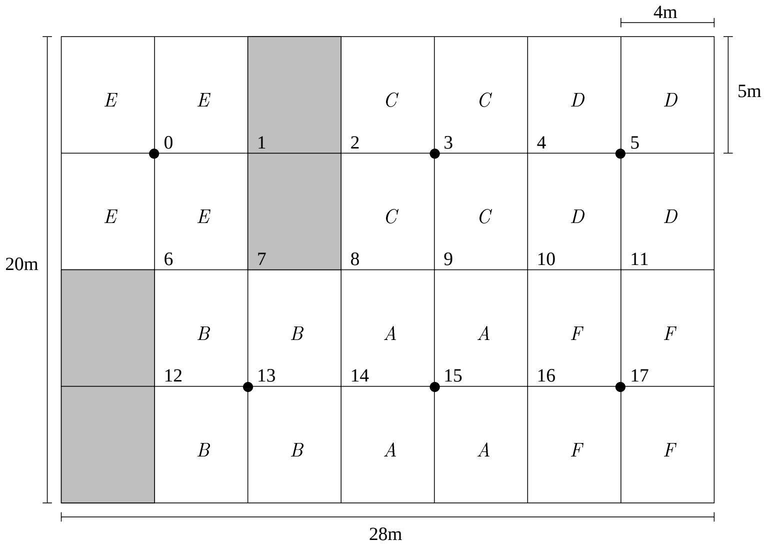

Figure 3.8: *An optimal layout of centres in Example 3.6, when* $\theta = 0.5$ (i.e., *when flow and fixed cost are considered equally important, measured as the number of trips per time unit and rands respectively). The objective function value of this layout is* 35 080 *monetary units.*

The formulation also incorporates a multi–floor representation. For more detail about a single floor MILP the reader is referred to Papageorgiou & Rotstein's [149] work of 1998.

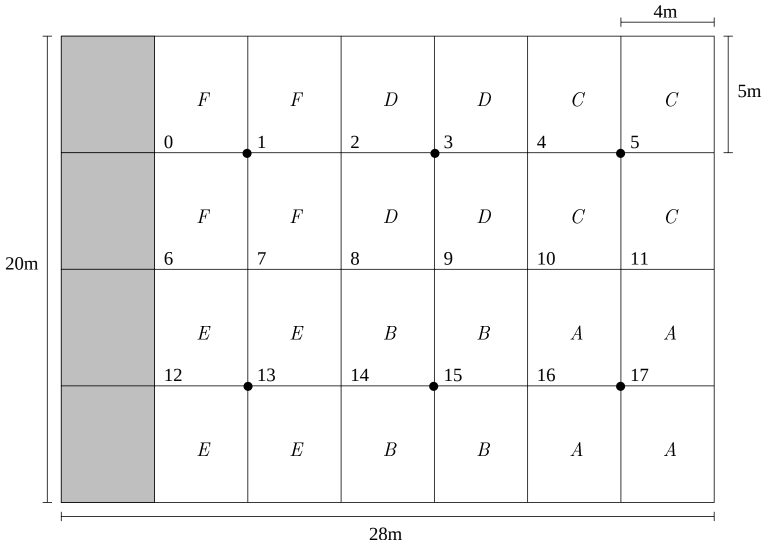

Figure 3.9: *An optimal layout of centres in Example 3.6, when* $\theta = 1$ (i.e., *when only flow costs are considered). The objective function value of this layout is* 54 500 *monetary units.*

In these approaches the following data are assumed to be known:

- A set of m centres and their dimensions,
- A set of K potential factory floors,
- A connectivity network representing materials flow possibilities,
- Costs of installing centres,
- Floor height,
- Space and centre allocation limitations.

A centre i is said to be connected to a centre j if there is positive flow from centre i to centre j. A detailed layout for each floor is determined so as to minimize the total factory layout cost. This cost involves the cost of handling material between centres as well as the installation cost of centres. The following indices, parameters, binary variables and continuous variables are used in the mathematical model formulation.

Indices:

i, j	for centres,
k	for floors.

Parameters:

α_i, β_i	dimensions of centre i (length and width),
H	floor height of all floors,
C^c_{ij}	connection cost for centres i and j (for example, the cost of flow),
C^v_{ij}	vertical movement cost between centre i and j,
G	the cost per metre of the electrical cables required for the installation of centres,
I_i	cost of installing centre i,
$X^{\max}, Y^{\max}$	dimensions of the available floorspace.

$$f_{ij} = \begin{cases} 1, & \text{if flow from centre } i \text{ to centre } j \text{ is positive,} \\ 0, & \text{otherwise.} \end{cases}$$

Binary variables:

$$
\begin{array}{rcl}
V_{ik} & = & \begin{cases} 1, & \text{if centre } i \text{ is assigned to floor } k, \\ 0, & \text{otherwise,} \end{cases} \\
Z_{ij} & = & \begin{cases} 1, & \text{if centres } i \text{ and } j \text{ are allocated to the same floor,} \\ 0, & \text{otherwise,} \end{cases} \\
O_i & = & \begin{cases} 1, & \text{if } \alpha_i, \text{ the length of centre } i, \text{ is parallel to the horizontal axis,} \\ 0, & \text{otherwise,} \end{cases} \\
E1_{ij}, E2_{ij} & & \text{non–overlapping binary variables.}
\end{array}
$$

Continuous variables:

ℓ_i	the dimension of centre i, parallel to the x–axis (not necessarily the same as α_i),
w_i	the dimension of centre i, parallel to the y–axis (not necessarily the same as β_i),
x_i, y_i	coordinates of the geometrical centroid of centre i,
R_{ij}	relative distance in the x–direction between centres i and j if centre i is to the right of centre j on a specific floor,
L_{ij}	relative distance in the x–direction between centres i and j if centre i is to the left of centre j on a specific floor,
A_{ij}	relative distance in the y–direction between centres i and j if centre i is above centre j on a specific floor,
B_{ij}	relative distance in the y–direction between centres i and j if centre i is below centre j on a specific floor,
U_{ij}	relative distance in the z–direction between centres i and j if centre i is higher than centre j (*i.e.*, on different floors),
D_{ij}	relative distance in the z–direction between centres i and j if centre i is lower than centre j (*i.e.*, on different floors),
T_{ij}	total 3D–rectilinear distance between centres i and j,
F_i	the cost of relocating and installing centre i at specific coordinates.

The variables ℓ_i and w_i are not necessarily the same as α_i and β_i, in the sense that α_i and β_i are respectively the physical length and width of centre i, whilst ℓ_i and w_i depend on the orientation of centre i.

There are a number of different types of constraints that are incorporated in the model of Patsiatzis & Papageorgiou [150]. These constraints include the following:

(a) *Floor constraints*

Each centre should be assigned to exactly one floor:

$$\sum_{k=1}^{K} V_{ik} = 1, \qquad i = 1, \ldots, m. \tag{3.9}$$

The values of the Z_{ij} variables may be obtained by incorporating the following constraints.

$$Z_{ij} \geq V_{ik} + V_{jk} - 1, \quad i = 1, \ldots, m-1, \; j = i+1, \ldots, m, \; k = 1, \ldots, K, \tag{3.10}$$

$$Z_{ij} \leq 1 - V_{ik} + V_{jk}, \quad i = 1, \ldots, m-1, \; j = i+1, \ldots, m, \; k = 1, \ldots, K, \tag{3.11}$$

$$Z_{ij} \leq 1 + V_{ik} - V_{jk}, \quad i = 1, \ldots, m-1, \; j = i+1, \ldots, m, \; k = 1, \ldots, K. \tag{3.12}$$

Note that constraints (3.10) force Z_{ij} to be 1 when centres i and j are on the same floor; in this case constraints (3.11) and (3.12) are inactive. Constraints (3.11) and (3.12) are active and force Z_{ij} to be zero when centres i and j are not on the same floor.

(b) *Centre orientation*
The length and width of a centre may be written in terms of the orientation of that centre:

$$\begin{aligned} \ell_i &= \alpha_i O_i + \beta_i(1 - O_i), \quad i = 1, \ldots, m, & (3.13)\\ w_i &= \alpha_i + \beta_i - \ell_i, \quad i = 1, \ldots, m. & (3.14) \end{aligned}$$

(c) *Centre overlapping constraints*
If two centres, i and j (say), are on the same floor, they will not overlap if at least one of the following inequalities is active:

$$\begin{aligned} x_i - x_j &\geq \frac{\ell_i + \ell_j}{2}, \quad i = 1, \ldots, m-1,\ j = i+1, \ldots, m, & (3.15)\\ x_j - x_i &\geq \frac{\ell_i + \ell_j}{2}, \quad i = 1, \ldots, m-1,\ j = i+1, \ldots, m, & (3.16)\\ y_i - y_j &\geq \frac{w_i + w_j}{2}, \quad i = 1, \ldots, m-1,\ j = i+1, \ldots, m, & (3.17)\\ y_j - y_i &\geq \frac{w_i + w_j}{2}, \quad i = 1, \ldots, m-1,\ j = i+1, \ldots, m. & (3.18) \end{aligned}$$

This may be modelled more efficiently by including constraints which include a very large constant M, introducing two additional sets of binary variables $E1_{ij}$ and $E2_{ij}$. Each pair of values (0 or 1) of these variables determine which constraints from the set (3.15)–(3.18) are active. For every i, j such that $j > i$ and $Z_{ij} = 1$ (*i.e.*, the centres are on the same floor) it is required that:

- if constraint (3.15) is active, then: $E1_{ij} = 0$ and $E2_{ij} = 0$,
- if constraint (3.16) is active, then: $E1_{ij} = 1$ and $E2_{ij} = 0$,
- if constraint (3.17) is active, then: $E1_{ij} = 0$ and $E2_{ij} = 1$ and
- if constraint (3.18) is active, then: $E1_{ij} = 1$ and $E2_{ij} = 1$.

The constraints included in the model are therefore:

$$\begin{aligned} x_i - x_j + M(1 - Z_{ij} + E1_{ij} + E2_{ij}) &\geq \frac{\ell_i + \ell_j}{2}, & (3.19)\\ &\forall\ i = 1, \ldots, m-1,\ j = i+1, \ldots, m,\\ x_j - x_i + M(2 - Z_{ij} - E1_{ij} + E2_{ij}) &\geq \frac{\ell_i + \ell_j}{2}, & (3.20)\\ &\forall\ i = 1, \ldots, m-1,\ j = i+1, \ldots, m,\\ y_i - y_j + M(2 - Z_{ij} + E1_{ij} - E2_{ij}) &\geq \frac{w_i + w_j}{2}, & (3.21)\\ &\forall\ i = 1, \ldots, m-1,\ j = i+1, \ldots, m,\\ y_j - y_i + M(3 - Z_{ij} - E1_{ij} - E2_{ij}) &\geq \frac{w_i + w_j}{2}, & (3.22)\\ &\forall\ i = 1, \ldots, m-1,\ j = i+1, \ldots, m. \end{aligned}$$

(d) *Distance constraints*
The distance constraints for a multi-floor problem may be represented as follows:

$$\begin{aligned} R_{ij} - L_{ij} &= x_i - x_j, \quad \forall\ (i,j) : f_{ij} = 1, & (3.23)\\ A_{ij} - B_{ij} &= y_i - y_j, \quad \forall\ (i,j) : f_{ij} = 1, & (3.24)\\ U_{ij} - D_{ij} &= H \sum_{k=1}^{K} k(V_{ik} - V_{jk}), \quad \forall\ (i,j) : f_{ij} = 1. & (3.25) \end{aligned}$$

The total rectilinear distance between centres i and j is given by:

$$T_{ij} \quad = \quad R_{ij} + L_{ij} + A_{ij} + B_{ij} + U_{ij} + D_{ij} \quad \forall\ (i,j) : f_{ij} = 1. \tag{3.26}$$

(e) *Additional layout design constraints*
Additional lower bound constraints have to be added to avoid centres crossing the outer walls of the factory:

$$x_i \quad \geq \quad \frac{\ell_i}{2}, \quad i = 1, \ldots, m, \tag{3.27}$$

$$y_i \quad \geq \quad \frac{w_i}{2}, \quad i = 1, \ldots, m, \tag{3.28}$$

$$x_i + \frac{\ell_i}{2} \quad \leq \quad X^{\max}, \quad i = 1, \ldots, m, \tag{3.29}$$

$$y_i + \frac{w_i}{2} \quad \leq \quad Y^{\max}, \quad i = 1, \ldots, m. \tag{3.30}$$

The cost of installing a specific centre i may be calculated as:

$$F_i \quad = \quad I_i + Gx_i, \quad i = 1, \ldots, m. \tag{3.31}$$

(f) *Objective function*
The objective function in this model, is then to

$$\text{minimize} \sum_{i=1}^{m} \sum_{\substack{j=1 \\ j \neq i \\ f_{ij}=1}}^{m} (C^c_{ij} T_{ij} + C^v_{ij} D_{ij}) + \sum_{i=1}^{m} F_i,$$

subject to constraints (3.9)–(3.14) and (3.19)–(3.31). The first term of the objective function represents the cost of product flow through the factory, including the handling cost of material. The second term represents the installation costs of the centres.

Example 3.7 (The MILP applied to Examples 3.1–3.4)
The problem described in Example 3.1 has only 1 *floor and therefore the parameters* H, C^v_{ij} *and* K *in the above model may be omitted in this case. The variables* V_{ik}, Z_{ij}, U_{ij} *and* D_{ij} *are only applicable if there are multiple floors and are therefore also omitted in this example. The connection cost (flow) between two centres* i *and* j *may be found in Table 3.10, whereas the values for* α_i *and* β_i *are given in Table 3.9. The appropriate mixed integer linear programming problem may therefore be stated as:*

$$\text{minimize} \ \ Z = \sum_{i=1}^{6} \sum_{\substack{j=1 \\ j \neq i \\ f_{ij}=1}}^{6} C^c_{ij} T_{ij} + \sum_{i=1}^{6} F_i$$

subject to

$$\ell_i = \alpha_i O_i + \beta_i (1 - O_i), \qquad i = 1, \ldots, 6,$$

$$w_i = \alpha_i + \beta_i - \ell_i, \qquad i = 1, \ldots, 6,$$

$$x_i - x_j + M(E1_{ij} + E2_{ij}) \geq \frac{\ell_i + \ell_j}{2}, \qquad i = 1, \ldots, 5, \quad j = i+1, \ldots, 6,$$

$$\begin{aligned}
x_j - x_i + M(1 - E1_{ij} + E2_{ij}) &\geq \frac{\ell_i + \ell_j}{2}, && i = 1, \ldots, 5, \quad j = i+1, \ldots, 6,\\
y_i - y_j + M(1 + E1_{ij} - E2_{ij}) &\geq \frac{w_i + w_j}{2}, && i = 1, \ldots, 5, \quad j = i+1, \ldots, 6,\\
y_j - y_i + M(2 - E1_{ij} - E2_{ij}) &\geq \frac{w_i + w_j}{2}, && i = 1, \ldots, 5, \quad j = i+1, \ldots, 6,\\
R_{ij} - L_{ij} &= x_i - x_j, && \forall\ (i,j) : f_{ij} = 1,\\
A_{ij} - B_{ij} &= y_i - y_j, && \forall\ (i,j) : f_{ij} = 1,\\
T_{ij} &= R_{ij} + L_{ij} + A_{ij} + B_{ij}, && \forall\ (i,j) : f_{ij} = 1,\\
x_i &\geq \frac{\ell_i}{2}, && i = 1, \ldots, 6,\\
y_i &\geq \frac{w_i}{2}, && i = 1, \ldots, 6,\\
x_i + \frac{\ell_i}{2} &\leq 28, && i = 1, \ldots, 6,\\
y_i + \frac{w_i}{2} &\leq 20, && i = 1, \ldots, 6,\\
F_i &= I_i, && i = 1, \ldots, 6.
\end{aligned}$$

The installation cost ($F_i = I_i$) for the different centres were taken to be the same random numbers between 0 *and* 10 000 *as in Example 3.6, shown in Table 3.13. Solving this problem via a* **Lingo 8.0** *program (see Appendix A.2) an objective function value of* 82 632 *monetary units was found within* 3 *minutes and* 38 *seconds on a* 2.66 *GHz Pentium* 4 *machine with* 512 *Mb of memory. The resulting physical layout of the factory is shown in Figure 3.10.* ■

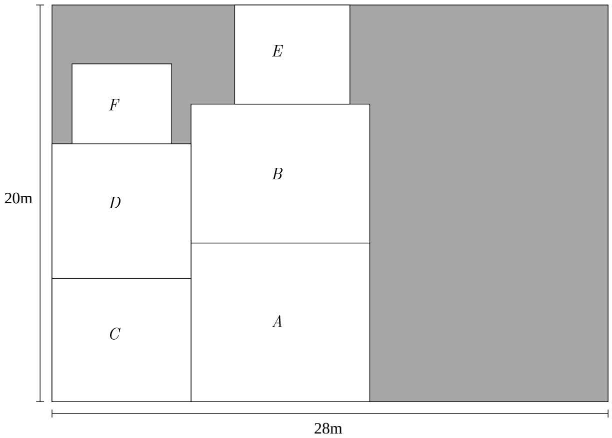

Figure 3.10: *The optimal layout for the problem in Example 3.7, shown to scale. This layout has an objective function value of* 82 632 *monetary units.*

3.1.2.2 Heuristic Approaches

There is a large number of heuristic procedures suitable for solving layout problems. One of the most popular and widely used procedures is discussed here, namely the tabu search.

The tabu search approach is a heuristic method that applies certain restrictions to guide a local search procedure for a good solution to a multi–dimensional optimization problem, typically with a large solution space. A *memory* component forces the tabu search to explore new areas of the search space. Certain solutions that have been considered in the recent history of the search are memorized, and these become tabu (forbidden) points in the sense that a forbidden attribute is assigned to such points [83]. The tabu points are avoided when making decisions about selecting the next candidate solution during the search procedure.

The tabu search procedure is a greedy heuristic, because when deciding which solution or point to visit next, a local decision is made and future problems that may arise as a result of this local decision are ignored.

The rationale of the memory component is to force the search procedure to explore *new* areas in solution space instead of repeatedly visiting the same points in solution space, perhaps becoming trapped in cycles or at local optima. There are three widely used methods of memory implementation in tabu searches: *attribute–based* memory, *recency–based* memory and *frequency–based* memory. Attribute–based memory is a memory structure which activates a certain attribute to be tabu for the duration of a certain time interval. An example of attribute–based memory in the context of the layout problem is when all the moves that change the position of centre i are declared tabu for a number of moves. Recency–based memory depends on two variables, denoted $tabu\_start(e)$ and $tabu\_end(e)$, which bracket the time period during which attribute e is to be considered tabu. It is easy to test whether an attribute e is tabu by verifying whether $tabu\_end(e) \geq current\_iteration$. An attribute is called *tabu–active* at a certain iteration if it is tabu at that iteration. When recency–based memory is used, the attribute e is therefore tabu–active within the iteration interval $[tabu\_start(e), tabu\_end(e)]$. An example of a recency–based memory use is when the reversal of all executed moves are considered tabu for the next (say) 10 moves. Frequency–based memory uses frequency measures consisting of ratios whose numerators represent counts of the number of occurrences of a particular event (*e.g.,* the number of times that a specific move is made) and whose denominators represent, for example, the sum of numerators (*e.g.,* the total number of moves). Frequency–based memory is usually combined with an incentive assignment method in which certain attributes may be assigned an incentive, whilst others incur a penalty. An example of frequency–based memory use is when the reversal of all moves that occur more than (say) 10% of the elapsed search time are designated tabu–active.

There are special cases in which a tabu restriction may be overridden. When a tabu move would result in a better solution than any one visited up to that point during the search, its tabu classification may be overridden. A condition that allows such an override to occur is called an *aspiration criterion*.

Different kinds of strategies are typically used when a tabu search is performed. Two very common strategies are *intensification* and *diversification* strategies. By following an intensification strategy, it is more important to choose a move with the greatest improvement in the objective function than to choose a move that results in a slightly smaller improvement, but which occurs for the first time. Diversification strategies instead seek to generate solutions that embody attributes significantly different from those encountered previously during the search. This approach is usually employed to perturb the search away from local optima. A combination of these two strategies typically yields good results.

Isolating a suitable candidate solution subset of possible moves from a large neighborhood at each iteration of the search procedure is a very important aspect of tabu search implementations. This avoids the computational expense of evaluating moves from the entire neighborhood set.

There are different stopping mechanisms used for the tabu search method. The most common method is to terminate the search after a fixed number of iterations. Another method is to terminate the search if there is no substantial improvement in the objective function value for a certain number of iterations, or if the objective function value does not change for a fixed number of iterations.

Example 3.8 (The tabu search heuristic applied to Example 3.1–3.4)
Suppose we focus on the discrete layout problem discussed in §3.1.2.1(i). The layout of the hypothetical factory in Example 3.1 may be represented by an array with 6 indices, each representing the position of a specific centre. The aim of this model is to minimize the total material–handling cost. The initial layout is chosen randomly and shown in Figure 3.11, with a value of 122 000 *for the objective function in (3.1). The layout is represented in a similar manner to that shown in Figure 3.7, and the array representation*[3] *of the initial layout is* $[A, B, C, D, E, F] = [2, 15, 12, 0, 5, 17]$.

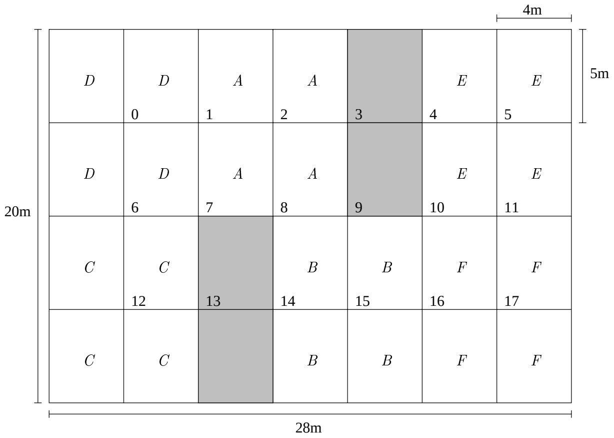

Figure 3.11: *An initial random layout with an objective function value of* 122 000 *for Example 3.8.*

The neighborhood of a candidate solution is defined to be all layouts created by moving one randomly chosen centre to a different position using the particular candidate solution as starting point. An intensification strategy is followed in the sense that the move that improves the objective function the most, or degrades it the least, is selected rather than a move that is explored for the first time. All feasible moves are inserted into a candidate list and the move that improves the objective function (minimizing material–handling cost) the most is executed, thus forming the next candidate solution. The neighborhood of the initial (random) candidate solution is shown in Table 3.14. The move from this candidate list with the minimum objective function value (moving centre B to position 14*) is chosen and executed, resulting in the layout shown in Figure 3.12. The tabu list now contains one entry which is the reversal of the move*

Centre	New Position	Objective Function
A	3	124 000
B	14	118 000
C	13	119 600
E	4	120 800

Table 3.14: *The neighborhood candidate list during the first tabu search iteration in Example 3.8.*

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[3] In an *array representation* of a layout the grid–points on which the centres of an ordered list of machines are positioned, are displayed in a vector format.

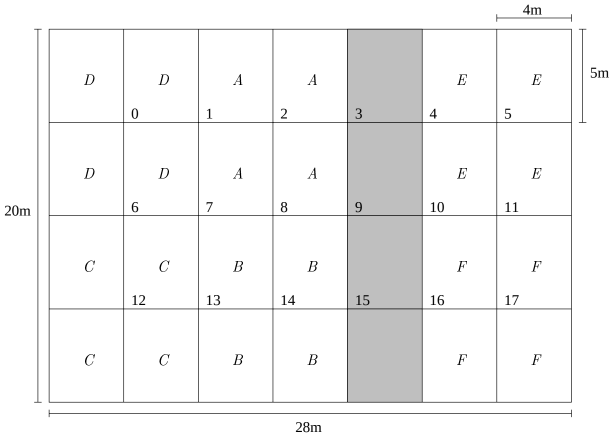


Figure 3.12: *The facility layout after one tabu search move has been performed for Example 3.8.*

Centre	New Position	Objective Function	Tabu Status
A	3	128 000	
B	15	122 000	Tabu
E	4	116 800	
F	16	110 800	

Table 3.15: *The neighborhood candidate list during the second tabu search iteration in Example 3.8.*

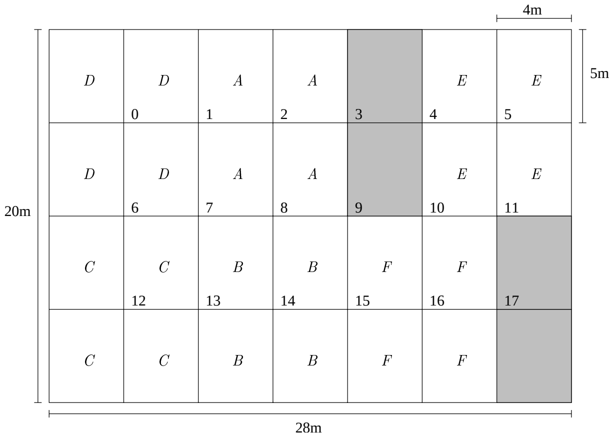


Figure 3.13: *The facility layout after two tabu search moves has been performed for Example 3.8.*

Centre	New Position	Objective Function	Tabu Status
A	3	128 000	
E	4	109 600	
F	17	118 000	Tabu

Table 3.16: *The neighborhood candidate list during the third tabu search iteration in Example 3.8.*

of centre B from grid–point 15 *to grid–point* 14*. The neighborhood of this new layout is given in Table 3.15. The move from this candidate list resulting in the smallest objective function* *value (moving centre F to position* 16*) is chosen and executed, resulting in the layout shown in Figure 3.13. Another move, moving centre F from grid–point* 16 *to grid–point* 17*, is now added to the tabu list. The neighborhood of this new layout is given in Table 3.16. The move from this candidate list resulting in the smallest objective function value (moving centre E to position* 4*) is chosen and executed, resulting in the layout shown in Figure 3.14. Another move, moving centre E from grid–point* 4 *to grid–point* 5*, is now added to the tabu list. The neighborhood of this new layout is given in Table 3.17 and considering the tabu list presented in Table 3.18, both moves are tabu and therefore the final solution to this tabu search is the layout shown in Figure 3.14. A graph of the change in the objective function as a function of the number of tabu search moves executed is shown in Figure 3.15. The final layout has an objective function value of* 109 600*.* ■

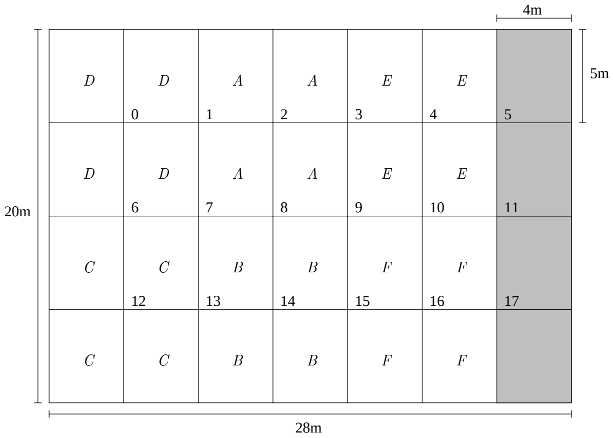


Figure 3.14: *The final facility layout after three tabu search moves have been performed for Example 3.8. This layout results in an objective function value of* 109 600*.*

Centre	New Position	Objective Function	Tabu Status
E	5	110 800	Tabu
F	17	116 800	Tabu

Table 3.17: *The neighborhood candidate list during the fourth tabu search iteration in Example 3.8.*

Nr.	Centre	From Position	To Position
1	B	14	15
2	F	16	17
3	E	4	5

Table 3.18: *The tabu list for the tabu search presented in Example 3.8.*

3.2 The Scheduling Problem

A large variety of different models have traditionally been used to schedule job–shops. The model presented by Adam, *et al.* [2] in 1988, which minimizes the makespan of a schedule, is discussed in this section. The notation introduced in §2.3.1 and §2.3.2 is again employed here,

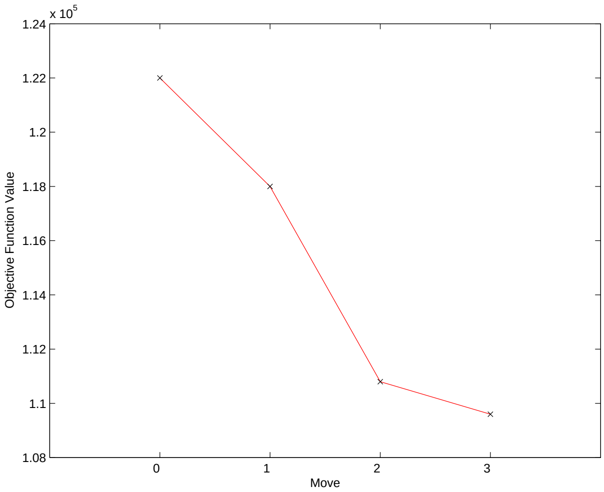


Figure 3.15: *The changes in the objective function value as the moves progressed in Example 3.8.*

where p_{ij} is the time required to process the i–th task of job j on a specific processor (machine) assigned to task T_{ij}. Let s_{ij} be the earliest possible starting time of task T_{ij} on a specific processor (machine) P_k assigned to it. The objective in the model of Adams, *et al.* is to

$$\text{minimize} \qquad s_{\text{end}} \tag{3.32}$$

subject to

$$\begin{aligned} s_{jk} - s_{ik} \geq p_{ik} \qquad & \forall \quad (T_{ik}, T_{jk}) \in \mathcal{A}, & (3.33)\\ s_{j\ell} - s_{im} \geq p_{im} \text{ or } s_{im} - s_{j\ell} \geq p_{j\ell} \qquad & \forall \quad \{T_{im}, T_{j\ell}\} \in \mathcal{E}_k \text{ and } \forall\ P_k \in \mathcal{P}, & (3.34)\\ s_{ij} > 0 \qquad & \forall \quad T_{ij} \in \mathcal{T}. & (3.35) \end{aligned}$$

Here $\mathcal{A}$ is defined as in §2.3.2, as the set of all conjunctive arcs, $\mathcal{T}$ is the set of tasks for all the jobs, and $\mathcal{P}$ is the set of processors (machines). The objective of this model is to minimize the makespan, s_{end}, of the schedule; this is achieved by minimizing the earliest possible starting time of the dummy task T_{end}, because T_{end} is the successor of the last task of each job. Constraints (3.33) ensure that the processing sequence of tasks in each job correspond to the predetermined order. Constraints (3.34) ensure that there is at most one task at any time processed by each machine, and constraints (3.35) ensure completion of all jobs.

This disjunctive graph model is used to solve job–shop scheduling problems, by applying exact or heuristic methods.

3.2.1 Exact Scheduling Methods

The disjunctive graph model may be used to solve the job–shop scheduling method optimally by using one of the following two methods: a mixed integer linear programming approach or the so–called direct branch–and–bound approach, where branching occurs on the "or" in constraint (3.34).

3.2.1.1 Mixed Integer Linear Programming

The "or" in the constraints presented in (3.34) of the disjunctive graph model may be removed by including an additional set of constraints of the form

$$\begin{aligned} s_{j\ell} - s_{im} + M(1 - y_{j\ell,im}) &\geq p_{im} \quad \forall\ \{T_{im}, T_{j\ell}\} \in \mathcal{E}_k,\ \forall\ P_k \in \mathcal{P}, \qquad (3.36)\\ s_{im} - s_{j\ell} + My_{j\ell,im} &\geq p_{j\ell} \quad \forall\ \{T_{im}, T_{j\ell}\} \in \mathcal{E}_k,\ \forall\ P_k \in \mathcal{P}, \qquad (3.37)\end{aligned}$$

and an additional set of binary variables

$$y_{j\ell,im} \in \{0,1\} \quad \forall\ \{T_{j\ell}, T_{im}\} \in \mathcal{E}_k,\ k = 1, \ldots, m, \qquad (3.38)$$

where M is a large number. According to Jain & Meeran [97], Van Hulle [195] showed that, in order for the feasible region to be defined properly, M has to be greater than the sum of all but the smallest processing time of the tasks, *i.e.*,

$$M > \sum_{i=1}^{n} \sum_{j=1}^{n_i} \sum_{k=1}^{m} p_{jk} - \min\,(p_{jk}).$$

The disjunctive graph model may now be formulated as a mixed integer linear programming problem in which the objective is to

$$\text{minimize} \qquad s_{\text{end}}$$

subject to

$$\begin{aligned} s_{jk} - s_{ik} &\geq p_{ik} \quad \forall\ (T_{ik}, T_{jk}) \in \mathcal{A}, &(3.39)\\ s_{j\ell} - s_{im} + M(1 - y_{j\ell,im}) &\geq p_{im} \quad \forall\ \{T_{im}, T_{j\ell}\} \in \mathcal{E}_k\ \forall\ P_k \in \mathcal{P}, &(3.40)\\ s_{im} - s_{j\ell} + My_{j\ell,im} &\geq p_{j\ell} \quad \forall\ \{T_{im}, T_{j\ell}\} \in \mathcal{E}_k\ \forall\ P_k \in \mathcal{P}, &(3.41)\\ s_{ij} &> 0 \quad \forall\ T_{ij} \in \mathcal{T} &(3.42)\\ y_{j\ell,im} &\in \{0,1\} \quad \forall\ \{T_{j\ell}, T_{im}\} \in \mathcal{E}_k\ k = 1, \ldots, m. &(3.43)\end{aligned}$$

This model may now be solved by means of a standard branch–and–bound approach, branching on non–integral values of the binary variables (3.38) in relaxations of (3.39)–(3.43).

Example 3.9 (Example 2.6 continued)
Consider the incomplete disjunctive graph shown in Figure 3.16 (which is the same graph as in Figure 2.5, reproduced here for ease of reference). The processing sequences as well as the processing times for the different tasks are presented in Tables 3.19(a) and (b) respectively.

Furthermore, according to the rule of Van Hulle [195], it is necessary that $M > 12$ for the feasible region to be well defined. Say $M = 50 > 12$, then the mixed integer linear programming problem is to

$$\text{minimize} \qquad s_{\text{end}} \qquad (3.44)$$

subject to

$$\left.\begin{aligned} s_{\text{end}} - s_{21} &\geq 2\\ s_{21} - s_{11} &\geq 1 \end{aligned}\right\} \quad \text{Job 1}, \qquad (3.45)$$

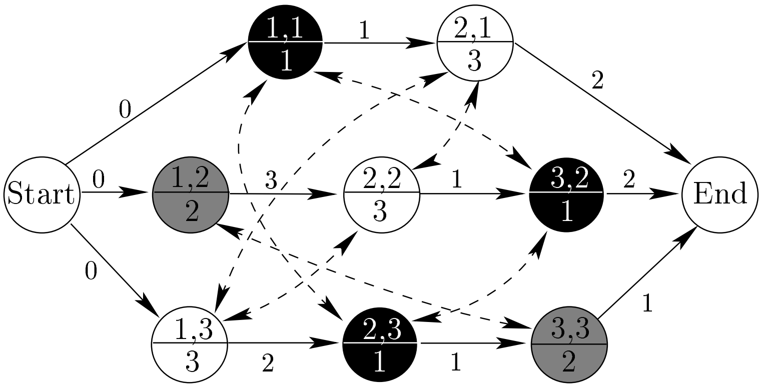


Figure 3.16: *The incomplete disjunctive graph for the processing times and processing sequences displayed in Table 3.19.*

Job	**Processor Sequence**
J_1	$P_1,\ P_3$
J_2	$P_2,\ P_3,\ P_1$
J_3	$P_3,\ P_1,\ P_2$

(a) *Processor sequences of the jobs represented in the incomplete disjunctive graph in Figure 3.16.*

	P_1	P_2	P_3
J_1	1	0	2
J_2	2	3	1
J_3	1	1	2

(b) *Processing times of the jobs, in Figure 3.16, on the different processors.*

Table 3.19: *The processor sequences and processing times for the different jobs in the incomplete disjunctive graph in Figure 3.16.*

$$\left.\begin{aligned} s_{\text{end}} - s_{32} &\geq 2 \\ s_{32} - s_{22} &\geq 1 \\ s_{22} - s_{12} &\geq 3 \end{aligned}\right\} \quad \text{Job 2,} \tag{3.46}$$

$$\left.\begin{aligned} s_{\text{end}} - s_{33} &\geq 1 \\ s_{33} - s_{23} &\geq 1 \\ s_{23} - s_{13} &\geq 2 \end{aligned}\right\} \quad \text{Job 3,} \tag{3.47}$$

$$\left.\begin{aligned} s_{32} - s_{11} + 50(1 - y_{32,11}) &\geq 1 \\ s_{11} - s_{32} + 50\, y_{32,11} &\geq 2 \\ s_{32} - s_{23} + 50(1 - y_{32,23}) &\geq 1 \\ s_{23} - s_{32} + 50\, y_{32,23} &\geq 2 \\ s_{23} - s_{11} + 50(1 - y_{23,11}) &\geq 1 \\ s_{11} - s_{23} + 50\, y_{23,11} &\geq 1 \end{aligned}\right\} \quad \text{Processor 1,} \tag{3.48}$$

$$\left.\begin{aligned} s_{12} - s_{33} + 50(1 - y_{12,33}) &\geq 1 \\ s_{33} - s_{12} + 50\, y_{12,33} &\geq 3 \end{aligned}\right\} \quad \text{Processor 2,} \tag{3.49}$$

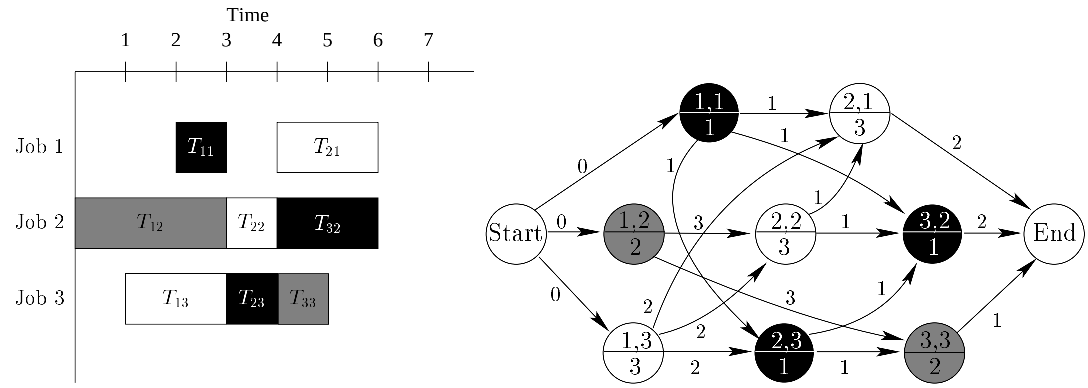
$$\left.\begin{aligned} s_{21} - s_{22} + 50(1 - y_{21,22}) &\geq 1 \\ s_{22} - s_{21} + 50\, y_{21,22} &\geq 2 \\ s_{22} - s_{13} + 50(1 - y_{22,13}) &\geq 2 \\ s_{13} - s_{22} + 50\, y_{22,13} &\geq 1 \\ s_{13} - s_{21} + 50(1 - y_{13,21}) &\geq 2 \\ s_{21} - s_{13} + 50\, y_{13,21} &\geq 2 \end{aligned}\right\} \quad \text{Processor 3,} \tag{3.50}$$

$$s_{i1} \geq 0 \qquad i = 1, 2, \tag{3.51}$$

$$s_{ij} \geq 0 \qquad i = 1,2,3 \;\;\&\;\; j = 2,3, \tag{3.52}$$

$$y_{j\ell,im} = 0 \text{ or } 1 \qquad \{T_{j\ell}, T_{im}\} \in \mathcal{E}_k, \text{ for } k = 1,\ldots,m. \tag{3.53}$$

This problem consists of 7 *binary variables and* 27 *non–trivial constraints and may be solved via a branch–and–bound approach, branching on the* 7 *binary variables. The problem was solved via a* **Lindo 6.0** *program (see Appendix A.3) and an optimal objective function value of* 6 *time units was obtained within* 1 *second on a* 2.66 *GHz Pentium* 4 *machine with* 512 *Mb of memory. The optimal feasible schedule thus obtained is shown in the Gantt chart in Figure 3.17(a) and the disjunctive graph associated with the Gantt chart follows in Figure 3.17(b). The optimal variable values obtained are shown in Table 3.20.* ■



(a) *Gantt chart* (b) *Complete Disjunctive graph*

Figure 3.17: *A Gantt chart and complete disjunctive graph representing an optimal schedule for the job–shop scheduling problem in Example 3.9.*

Variable	**Value**
s_{11}	2
s_{21}	4
s_{12}	0
s_{22}	3
s_{32}	4
s_{13}	1
s_{23}	3
s_{33}	4
$y_{32,11}$	1
$y_{32,23}$	1
$y_{23,11}$	1
$y_{12,33}$	1
$y_{21,22}$	1
$y_{22,13}$	1
$y_{13,21}$	1

Table 3.20: *A list of the variable values corresponding to the optimal solution depicted in Figure 3.17 of the job–shop scheduling problem in Example 3.9.*

The method employed in Example 3.9 may only be used to solve small problems, because the worst–case complexity of the branch–and–bound method is typically exponential in the number of binary variables and constraints.

3.2.1.2 The Direct Branch–and–Bound Approach

Branching and bounding is a general methodology for solving many types of combinatorial optimization problems. The basic idea of *branching* is to conceptualize the optimization problem as a decision tree. A number of new branches is grown at each node of the tree, one for each possible decision. These, in turn, become new nodes for branching again, and so on. Leaf nodes, which cannot be branched any further represent candidate solutions or dead ends. An optimal solution to the problem is a candidate solution (leaf) with the best objective function value. The worst–case time complexity of the branch–and–bound method is typically exponential in the number of decisions to be resolved.

The function of the so–called *bounding* process is to provide a means for dramatically reducing the number of computations in this procedure. Suppose that, at an intermediate stage, a candidate solution has been obtained with an associated objective function value of Z. Suppose also that a sub–problem encountered in the branching process has an associated *lower bound* $b > Z$. The sub–problem and the branches sprouting from that sub–problem will not yield the optimum solution (in a minimization problem) because the lower bound of the sub–problem is greater than Z. When such a sub–problem is found, its node is said to be *fathomed*. When a node is fathomed, no further branching takes place at that node. In this way the complexity of the enumeration process is reduced by pruning the branch–and–bound decision tree appropriately.

The candidate solution used in comparisons that allow branches to be fathomed is called a *trial solution*. A trail solution may be obtained by first running a heuristic or it may be obtained and improved in the course of a tree search procedure. A branch–and–bound algorithm must maintain knowledge of the remaining unsolved sub–problems. This can be done by maintaining a list of the unsolved problems. An *active* sub–problem is a sub–problem that is not fathomed and whose own sub–problems have not yet been generated [145].

The branch–and–bound method may be applied directly to the original disjunctive graph model (3.32)–(3.35) by branching on the "or." This is achieved by first solving a relaxed version of the problem, which is the problem without the set of disjunctive constraints (3.34). If the starting times of the tasks satisfy the disjunctive constraints the problem is solved. Conversely, if there are disjunctive constraints not satisfied, branching occurs on the "or" of the disjunctive constraints.

Example 3.10 (Example 3.9 continued)
Consider the incomplete disjunctive graph in Figure 3.16. A relaxed version of the disjunctive graph model (3.54)–(3.59) *is constructed by removing the disjunctive constraints from the original disjunctive graph model* (3.32)–(3.35). *The objective in this relaxation is to*

$$\text{minimize} \quad s_{\text{end}} \tag{3.54}$$

subject to

$$\left.\begin{array}{rcl} s_{\text{end}} - s_{21} & \geq & 2 \\ s_{21} - s_{11} & \geq & 1 \\ s_{22} - s_{12} & \geq & 3 \end{array}\right\} \quad \text{Job 1,} \tag{3.55}$$

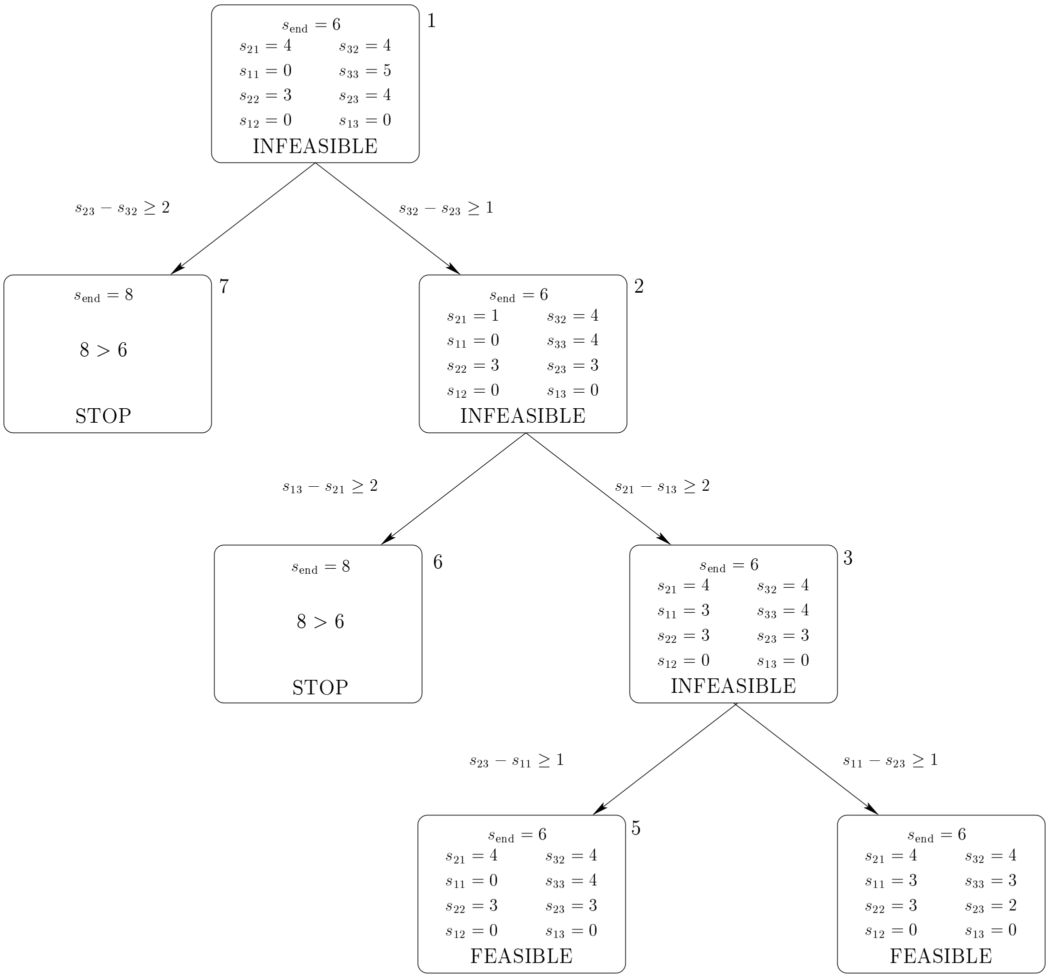


Figure 3.18: *The branch–and–bound decision tree created by branching on the "or" in constraints (3.34) of the disjunctive graph model in Example 3.10.*

$$\left.\begin{array}{rcl} s_{end} - s_{32} & \geq & 2 \\ s_{32} - s_{22} & \geq & 1 \end{array}\right\} \quad \text{Job 2,} \tag{3.56}$$

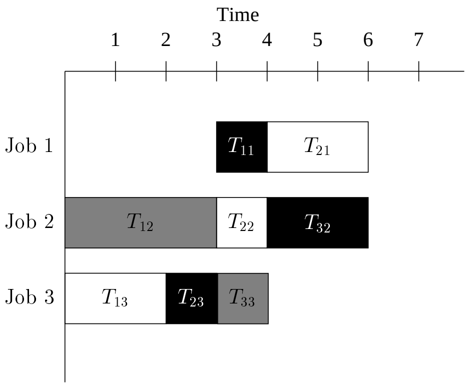
$$\left.\begin{array}{rcl} s_{end} - s_{23} & \geq & 1 \\ s_{23} - s_{13} & \geq & 2 \\ s_{33} - s_{23} & \geq & 1 \end{array}\right\} \quad \text{Job 3,} \tag{3.57}$$

$$s_{i1} \geq 0 \qquad i = 1, 2, \tag{3.58}$$

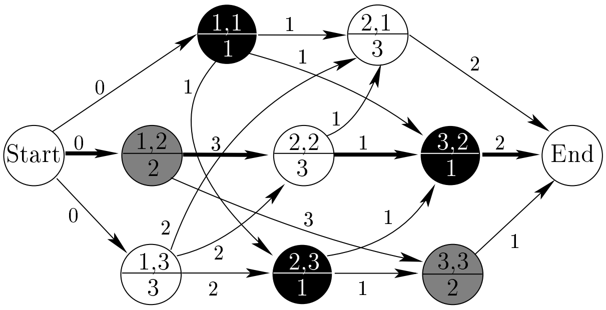
$$s_{ij} \geq 0 \qquad i = 1, 2, 3, \qquad j = 2, 3. \tag{3.59}$$

An infeasible schedule with an objective function value of 6 *time units was obtained by using* **Lindo 6.0** *to solve the relaxed disjunctive graph model* (3.54)–(3.59)*. The variable values found after solving this relaxed version of the original scheduling problem are presented in node 1 in the branch–and–bound decision tree shown in Figure 3.18. Tasks* T_{32} *and* T_{23} *both have to be processed by the same processor and according to the variables they overlap,* i.e., *the processor processing them has to process two tasks at the same time. This is a violation of the constraints set on the job–shop scheduling problem. The first branching therefore occurs on the* $s_{32} - s_{23} \geq 1$ or $s_{23} - s_{32} \geq 2$ *constraint. As shown in the branch–and–bound decision tree (node* 2*) an infeasible solution with an objective function value of* 6 *time units was obtained when the constraint* $s_{32} - s_{23} \geq 1$ *was added to the relaxed problem presented in node* 1*. Tasks*

T_{21} and T_{13} overlap on their common processor and therefore the branching in this case occurs on the $s_{13} - s_{21} \geq 2$ or *$s_{21} - s_{13} \geq 2$ constraint. As indicated at node 3 in the branch–and–bound decision tree an infeasible solution with an objective function value of 6 time units was obtained. Tasks T_{11} and T_{23} overlap on their common processor and therefore the branching in this case occur on $s_{23} - s_{11} \geq 1$ and $s_{11} - s_{23} \geq 1$ that is added to the relaxed problem in nodes 3 and node 5 respectively. As indicated in the branch–and–bound decision tree a feasible solution was found in node 4 with an objective function value of 6 time units. The value of 6 time units now forms a lower bound in the sense that if a feasible schedule was to be found with an objective function value of more than 6 time units the schedule will be fathomed, because a better solution had already been found. The relaxed problem at node 3 with an added constraint of $s_{23} - s_{11} \geq 1$ as presented by node 5 also has an objective function value of 6 time units, which equals the lower bound obtained at node 4. As shown in the branch–and–bound decision tree both nodes 6 and 7 represent feasible solutions with an objective function value of 8 time units, which is worse than 6 time units and therefore the solutions found at nodes 6 and 7 are fathomed. The optimal objective function value of 6 time units is therefore obtained at node 4. This problem admits two optimal solutions and therefore the optimal starting times of the different tasks could be either those displayed in node 4 or node 5. The Gantt chart and complete disjunctive graph representation of the optimal solution represented by node 4 is shown in Figure 3.19.* ■



(a) *Gantt chart*



(b) *Complete Disjunctive graph. The bold arcs represent the critical path.*

Figure 3.19: *The Gantt chart and disjunctive graph for the optimal solution obtained at node 4 of the branch–and–bound decision tree in Figure 3.18.*

3.2.2 Heuristic Scheduling Methods

There is a large variety of heuristic methods that may be used to solve the job–shop scheduling problem. In this section the tabu search method is presented.

3.2.2.1 Tabu Search

Throughout the literature found on job–shop scheduling problems the tabu search method developed by Nowicki & Smutnicki [148] was categorized as one of the fastest and best tabu search heuristic applications [85]. In this section the tabu search method is discussed in detail. This section opens by establishing some additional notation, and this is followed by a presentation of necessary application information. The section concludes with an outline of the algorithm presented by Nowicki & Smutnicki.

Define the set $\mathcal{M}_k = \{T_{ij} \in \mathcal{T} \mid \; p_{ij}(k) > 0 \text{ and } p_{ij}(\ell) = 0 \text{ for } \ell \neq k\}$ to be the set of tasks processed by machine $P_k \in \mathcal{P}$, and let $m_k = |\mathcal{M}_k|$ be the number of elements in $\mathcal{M}_k$. Here $\mathcal{P}$ represents the set of processors, as before. The processing order of the tasks on machine P_k may be represented as $\pi_k = \{\pi_k(1), \ldots, \pi_k(m_k)\}$ where $P_k \in \mathcal{P}$ and $\pi_k(i)$ denotes the task to be processed i–th by machine P_k. The set of all permutations of π_k is represented by Π_k. The processing order of tasks on machines may be represented by an m–tuple $\pi = (\pi_1, \ldots, \pi_m)$ where $\pi \in \Pi = \Pi_1 \times \Pi_2 \times \cdots \times \Pi_m$ and $|\mathcal{P}| = m$.

Nowicki & Smutnicki use a graph, similar to the disjunctive graph, to represent a processing order π graphically. The graph $G(\pi) = (\mathcal{T}, \mathcal{A} \cup \mathcal{E}(\pi))$ consists of n nodes representing the tasks. $\mathcal{A}$ is the set of conjunctive arcs, as defined in §2.3.2, and

$$\mathcal{E}(\pi) = \cup_{k=1}^{m} \cup_{i=1}^{m_k - 1} \{(\pi_k(i), \pi_k(i+1))\}$$

represents the processing sequence of tasks on machines. The graph $G(\pi)$ represents a feasible schedule if it contains no cycle.

A critical path in $G(\pi)$ is denoted by $u = (u_1, \ldots, u_w)$ where $u_i \in \mathcal{T}, 1 \leq i \leq w$ and w is the number of nodes in the critical path. This critical path is naturally decomposed into r different blocks as suggested by Grabowski [85]. Each *block* $B_i = (u_{a_i}, \ldots, u_{b_i})$ is a maximum subsequence (subset of consecutive tasks) of the critical path u, where all tasks in block B_i are processed on the same machine. Two consecutive blocks contain tasks processed on different machines. Let us consider an example.

Example 3.11
Due to the small size of the previous scheduling example problem and the fact that it will not illustrate the working of the heuristic methods satisfactorily, it was decided to base the examples in the remainder of this chapter on the (larger) Fisher & Thompson benchmark problem [74]. This problem consists of 6 *processors and* 6 *jobs with* 6 *tasks for each job. The order of the processors for each job is given in Table 3.21(a), and the processing times on the respective processors by job are presented in Table 3.21(b). The disjunctive graph of this problem is given in Figure 3.20.*

In this example $M_1 = \{T_{21}, T_{52}, T_{43}, T_{24}, T_{55}, T_{46}\}$, $M_2 = \{T_{31}, T_{12}, T_{53}, T_{14}, T_{25}, T_{16}\}$, $M_3 = \{T_{11}, T_{22}, T_{13}, T_{34}, T_{15}, T_{66}\}$, $M_4 = \{T_{41}, T_{62}, T_{23}, T_{44}, T_{65}, T_{26}\}$, $M_5 = \{T_{61}, T_{32}, T_{63}, T_{54}, T_{35}, T_{56}\}$ *and* $M_6 = \{T_{51}, T_{42}, T_{33}, T_{64}, T_{45}, T_{36}\}$.

Consider the feasible processing order $\pi = (\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6)$ *where* $\pi_1 = \{T_{24}, T_{21}, T_{43}, T_{46}, T_{52}, T_{55}\}$, $\pi_2 = \{T_{12}, T_{14}, T_{16}, T_{31}, T_{25}, T_{53}\}$, $\pi_3 = \{T_{22}, T_{13}, T_{11}, T_{34}, T_{15}, T_{66}\}$, $\pi_4 = \{T_{23}, T_{26}, T_{44},$

Job	**Processor Sequence**
J_1	$P_3,\ P_1,\ P_2,\ P_4,\ P_6,\ P_5$
J_2	$P_2,\ P_3,\ P_5,\ P_6,\ P_1,\ P_4$
J_3	$P_3,\ P_4,\ P_6,\ P_1,\ P_2,\ P_5$
J_4	$P_2,\ P_1,\ P_3,\ P_4,\ P_5,\ P_6$
J_5	$P_3,\ P_2,\ P_5,\ P_6,\ P_1,\ P_4$
J_6	$P_2,\ P_4,\ P_6,\ P_1,\ P_5,\ P_3$

(a) *Processor sequences of the jobs represented in the incomplete disjunctive graph in Figure 3.20.*

	P_1	P_2	P_3	P_4	P_5	P_6
J_1	3	6	1	7	6	3
J_2	10	8	5	4	10	10
J_3	9	1	5	4	7	8
J_4	5	5	5	3	8	9
J_5	3	3	9	1	5	4
J_6	10	3	1	3	4	9

(b) *Processing times of the jobs, in Figure 3.20, on the different machines.*

Table 3.21: *The processor sequences and processing times for the different jobs in the incomplete disjunctive graph in Figure 3.20.*

$T_{41}, T_{62}, T_{65}\}$, $\pi_5 = \{T_{32}, T_{54}, T_{35}, T_{63}, T_{61}, T_{56}\}$ and $\pi_6 = \{T_{33}, T_{42}, T_{36}, T_{51}, T_{64}, T_{45}\}$. The graph $G(\pi)$ is shown in Figure 3.21 and the corresponding Gantt chart in Figure 3.22. The critical path in Figure 3.21 is $u = (T_{12}, T_{22}, T_{13}, T_{23}, T_{33}, T_{42}, T_{36}, T_{46}, T_{52}, T_{62}, T_{65})$ shown as bold faced dashed arcs, with $w = 11$ and the blocks are $B_1 = \{T_{12}\}$, $B_2 = \{T_{22}, T_{13}\}$, $B_3 = \{T_{23}\}$, $B_4 = \{T_{33}, T_{42}, T_{36}\}$, $B_5 = \{T_{46}, T_{52}\}$ and $B_6 = \{T_{62}, T_{65}\}$. The objective function value (minimize makespan) for the schedule is 74 units. ■

Nowicki & Smutnicki applied a tabu search method similar to the one discussed in §3.1.2.2, but first adapted to the job–shop scheduling problem. The tabu search method makes use of a short–term and long–term recency–based memory structure. The inverted move ($\overline{v}$) of each move (v) performed is inserted into a tabu list $\mathcal{F}$, with a maximum length of $f_{\max}$, which keeps track of the $f_{\max}$ most recently performed moves. Two different stopping criteria are typically used

(a) to stop when a maximum number of moves have been performed, or

(b) to stop when a certain time limit was reached.

The aim of the particular method proposed by Nowicki & Smutnicki was to reduce the computational complexity of a single neighborhood search, which is directly proportional to the size of a single move's neighborhood. Several different tabu search moves for job–shop scheduling problems have been documented in the literature, but one of the most common moves discussed is the interchange of adjacent or non–adjacent tasks processed on the same machine [196]. The neighborhood associated with this move type is quite large and was reduced by removing moves that would not immediately improve the makespan of the schedule. Since the makespan of a

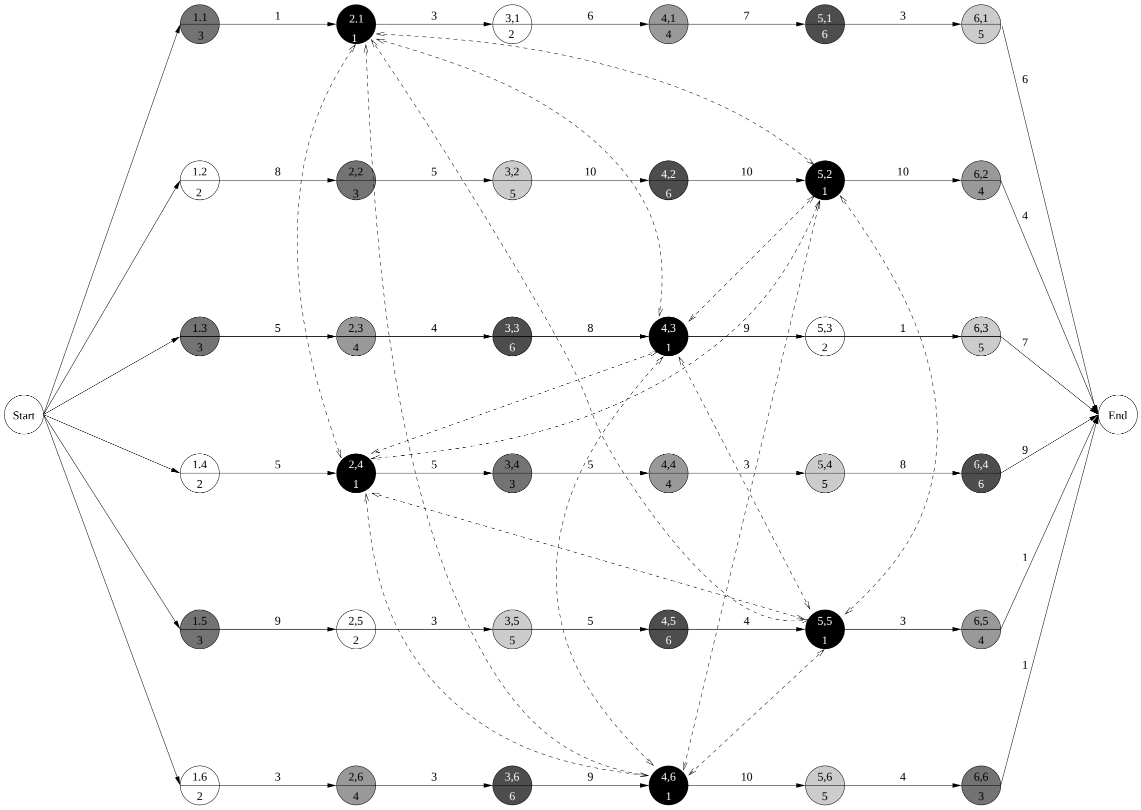


Figure 3.20: *The incomplete disjunctive graph representation of the benchmark problem presented by Fisher & Thompson [74], where only the disjunctive arcs for processor 1 are shown.*

schedule is determined by computing the length of a critical path through the graph $G(\pi)$, it makes sense to consider only adjacent tasks on a critical path that are processed on the same machine, (*i.e.*, tasks in the same block) for the neighborhood.

A set of moves called the "interchanges near the borderline of blocks on a single critical path" is employed in this tabu search algorithm. To reduce the neighborhood size, it was decided to consider only a single (arbitrarily selected) critical path. The fixed set of moves consists of a swap of the first two and last two tasks in blocks $B_2, \ldots, B_{r-1}$ along with the swap of the last two tasks of the first block B_1 and a swap of the first two tasks of the last block B_r. Therefore we may define the set of moves $V(\pi) = \cup_{i=1}^{r} V_i(\pi)$, where

$$V_1(\pi) = \begin{cases} \{(u_{b_1-1}, u_{b_1})\} & \text{if } a_1 < b_1 \text{ and } r > 1, \\ \varnothing & \text{otherwise,} \end{cases}$$

$$V_j(\pi) = \begin{cases} \{(u_{a_j}, u_{a_j+1}), (u_{b_j-1}, u_{b_j})\} & \text{if } a_j < b_j, \text{ for } j = 2, \ldots, r-1 \text{ and } r > 2, \text{ and} \\ \varnothing & \text{otherwise,} \end{cases}$$

$$V_r(\pi) = \begin{cases} \{(u_{a_r}, u_{a_r+1})\} & \text{if } a_r < b_r \text{ and } r > 1, \\ \varnothing & \text{otherwise,} \end{cases}$$

where u_{a_i} is the first task in block B_i and u_{b_i} is the last task in block B_i.

The set of moves is not empty while $r > 1$ and there exists at least one block containing more than one task. Let $Q(\pi, v)$ be the new processing order after move $v \in V(\pi)$ has been applied to processing order π. The set $\mathcal{H}(\pi)$ is the set of processing orders obtained by applying all the moves in $V(\pi)$ to π, *i.e.*,$\mathcal{H}(\pi) = \{Q(\pi, v) : v \in V(\pi)\}$.

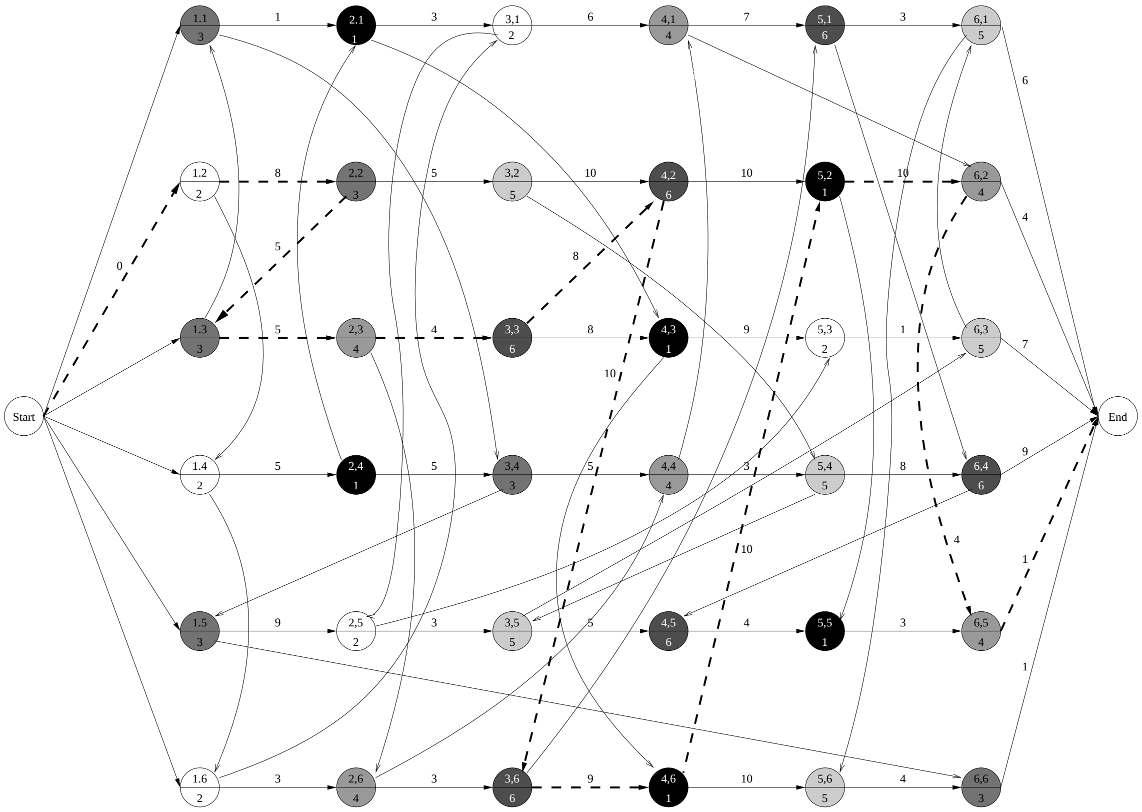


Figure 3.21: *A representation of the graph $G(\pi)$ representing a feasible schedule of Example 3.11.*

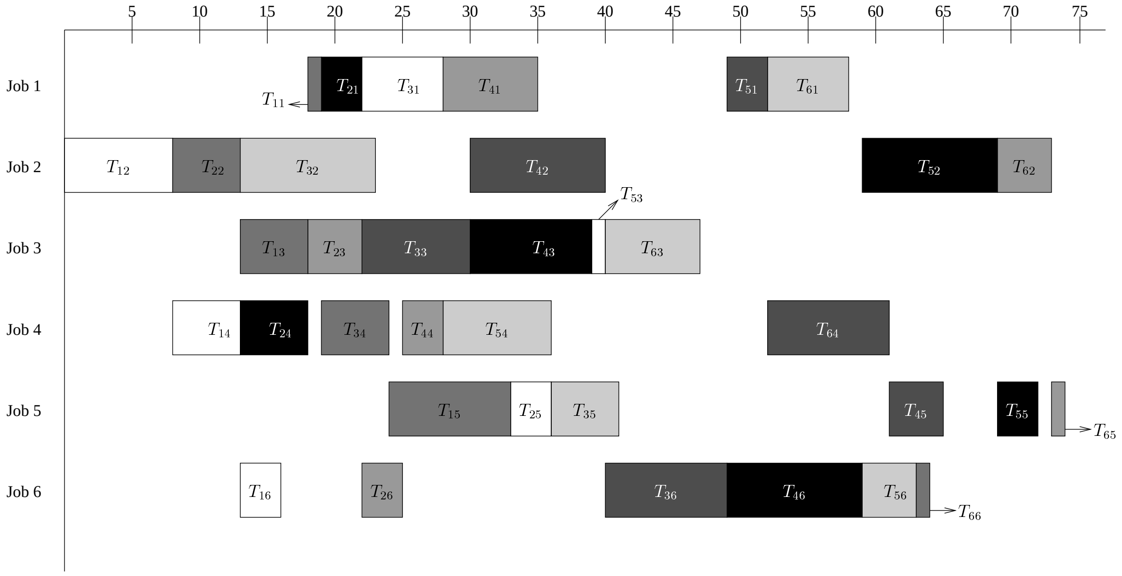


Figure 3.22: *A representation of the Gantt chart representing a feasible schedule of Example 3.11.*

Example 3.12 (Example 3.11 continued)
The set of moves obtained from the blocks defined in the previous example is $V(\pi) = \{V_2(\pi), V_4(\pi), V_5(\pi), V_6(\pi)\}$ *with the values of* $V_i(\pi)$ *presented in Table 3.22. The new objective function*

values obtained when executing each move separately on the schedule in Figures 3.21 and 3.22 are given in Table 3.23. Moves v_1*,* v_3 *and* v_4 *in Table 3.23 will improve the objective function value of the problem in Example 3.11. The best improvement is achieved on execution of move* v_1 *in Table 3.23, the new processing order, after performing the move, being*

$$Q(\pi, v_1) = (\pi_1, \pi_2, \{T_{13}, T_{22}, T_{11}, T_{34}, T_{15}, T_{66}\}, \pi_4, \pi_5, \pi_6),$$

where $\pi_1, \pi_2, \pi_4, \pi_5$ *and* π_6 *are defined as in Example 3.11.* ■

i	$V_i(\pi)$
2	$\{(T_{22}, T_{13})\}$
4	$\{(T_{33}, T_{42}), (T_{42}, T_{36})\}$
5	$\{(T_{46}, T_{52})\}$
6	$\{(T_{62}, T_{65})\}$

Table 3.22: *The different moves obtained from the blocks identified in Example 3.11.*

	Move	**New Objective Function**
v_1	(T_{22}, T_{13})	67
v_2	(T_{33}, T_{42})	75
v_3	(T_{42}, T_{36})	69
v_4	(T_{46}, T_{52})	69
v_5	(T_{62}, T_{65})	77

Table 3.23: *The new objective function values after each move was executed on the schedule in Example 3.11.*

Nowicki & Smutnicki proved that $\mathcal{H}(\pi)$ contains only feasible schedules. The set of moves $V(\pi)$ may be divided into three subsets, namely non–tabu moves (N), profitable tabu moves (TP) and non–profitable tabu moves (TN). Due to the small neighborhood size of $V(\pi)$, most moves in $V(\pi)$ will be TN–moves. If all the moves are TN–moves the youngest move ($\mathcal{F}_{f_{\max}}$) is repeatedly inserted into the tabu list $\mathcal{F}$, until $V(\pi) \setminus \mathcal{F} \neq \varnothing$.

The classical tabu search method is an iterative improvement method which starts with an initial feasible solution. This initial solution has a weak influence on the final best makespan obtained [148]. Glover & Laguna [83] mention that the results obtained by the tabu search algorithm typically only improves when a longterm memory element is implemented and therefore Nowicki & Smutnicki introduced the tabu seach algorithm with backtracking. This algorithm "resumes the search from unvisited neighbors of solutions previously generated." The last $\ell_{\max}$ best processing orders obtained are stored in a list ($\mathcal{L}$) during execution of the tabu search method. Each processing order is stored along with the current tabu list and available moves not yet explored. In other words $\mathcal{L} = (L_1, \ldots, L_{\ell_{\max}})$ where $L_i = (\pi, V(\pi) \setminus \{v'\}, \mathcal{F})$, with v' the move previously performed from π. The triplet is only stored if $V(\pi) \setminus \{v'\} \neq \varnothing$. After the normal tabu search algorithm has terminated, it is started again with the processing order, set of moves and tabu list located in the last position ℓ in $\mathcal{L}$. Such a tabu search method, that makes use of the list $\mathcal{L}$, is called the *tabu search method with backtracking.*

The tabu search method with backtracking has no long–term memory to prevent repeated cycles in a search and therefore Nowicki & Smutnicki introduced a cycle tracker to detect cycles of a maximum length of $\delta_{\max}$. The search is terminated when a cycle is detected and the successive triplet in the list $\mathcal{L}$ is explored next. The pseudo code for the tabu search procedure with backtracking proposed by Nowicki & Smutnicki is given in Algorithm 2.

Algorithm 2 The tabu search method proposed by Nowicki & Smutnicki [148].

Input: An initial processing order $\pi^* = \pi$ obtained by any heuristic algorithm, the makespan of the processing order $C^* = C_{\max}(\pi^*)$, the tabu list $\mathcal{F} = \varnothing$ and $\mathcal{L} = \varnothing$. The number of iterations, *iter*, and the flag *save*. The flag *save* controls the process of storing triplets in $\mathcal{L}$. A move v is added to a tabu list $\mathcal{F}$ and denoted by $\mathcal{F} \oplus v$.

Output: The best processing order π^* and the makespan $C_{\max}(\pi^*)$.

```
 1: $iter \leftarrow iter + 1$, determine $V(\pi)$.
 2: if $V(\pi) = \varnothing$ then
 3:     STOP, ($\pi^*$ is optimal).
 4: end if
 5: Get all TP–moves i.e., $\mathcal{A} = \{v \in V(\pi) \cap \mathcal{F} : C_{\max}(Q(\pi, v)) < C^*\}$.
 6: if $V(\pi) \setminus \mathcal{F} \cup \mathcal{A} \neq \varnothing$ then
 7:     select $v'$ so that $C_{\max}(Q(\pi, v)) = \min\{C_{\max}(Q(\pi, v')) : v \in (V(\pi) \backslash \mathcal{F}) \cup A\}$.
 8:     go to step 16.
 9: end if
10: if $|V(\pi)| = 1$ then
11:     select $v' \in V(\pi)$
12: else
13:     repeat $\mathcal{F} \leftarrow \mathcal{F} \oplus \mathcal{F}_{f_{\max}}$
14:         until $V(\pi) \setminus \mathcal{F} \neq \varnothing$.
15:     select $v' \in V(\pi) \setminus \mathcal{F}$.
16: end if
17: $\pi' \leftarrow Q(\pi, v')$, $\mathcal{F}' \leftarrow \mathcal{F} \oplus \bar{v}'$.
18: if $save$ = true and $V(\pi) \setminus \{v'\} \neq \varnothing$ then
19:     $\mathcal{L} \leftarrow \mathcal{L} \uplus (\pi, V(\pi) \setminus \{v'\}, \mathcal{F})$.
20:     $\pi \leftarrow \pi'$, $\mathcal{F} \leftarrow \mathcal{F}'$, $save \leftarrow$ false.
21: end if
22: if $C_{\max}(\pi) < C^*$ then
23:     $\pi^* \leftarrow \pi$, $C^* \leftarrow C_{\max}(\pi)$, $iter \leftarrow 0$, $save \leftarrow$ true and go to step 1.
24: end if
25: if $iter < maxiter$ and no cycle of size $1 \leq \delta \leq \delta_{\max}$ is detected for the past $c_{\max} \times \delta_{\max}$
    iterations then
26:     go to step 1.
27: end if
28: if $\ell \neq 0$ then
29:     $(\pi, V(\pi), \mathcal{F}) \leftarrow L_\ell$, $\ell \leftarrow \ell - 1$, $iter \leftarrow 1$, $save \leftarrow$ true and go to step 2.
30: else
31:     STOP.
32: end if
```

Example 3.13 (Example 3.12 continued)

Assume that the schedule presented in Figures 3.21 and 3.22 is the initial schedule of a tabu search with backtracking to obtain the best schedule for the benchmark problem of Fisher & Thompson presented in Example 3.11. Let the maximum length of the tabu list be $f_{\max} = 8$. *When the tabu search method with backtracking is applied, the improvement of the objective function value as in Example 3.12, calls for an insertion into the list* $\mathcal{L}$. *Currently the list* $\mathcal{L}$ *is empty and therefore* $L_1 = \{\pi, V(\pi) \setminus \{v_1\}, \mathcal{F}\}$ *with* $\pi = \{\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6\}$, *(with the* π_i *as presented in Example 3.11) and* $\mathcal{F} = \varnothing$. *Assume the maximum length of list* $\mathcal{L}$ *is* $\ell_{\max} = 5$.

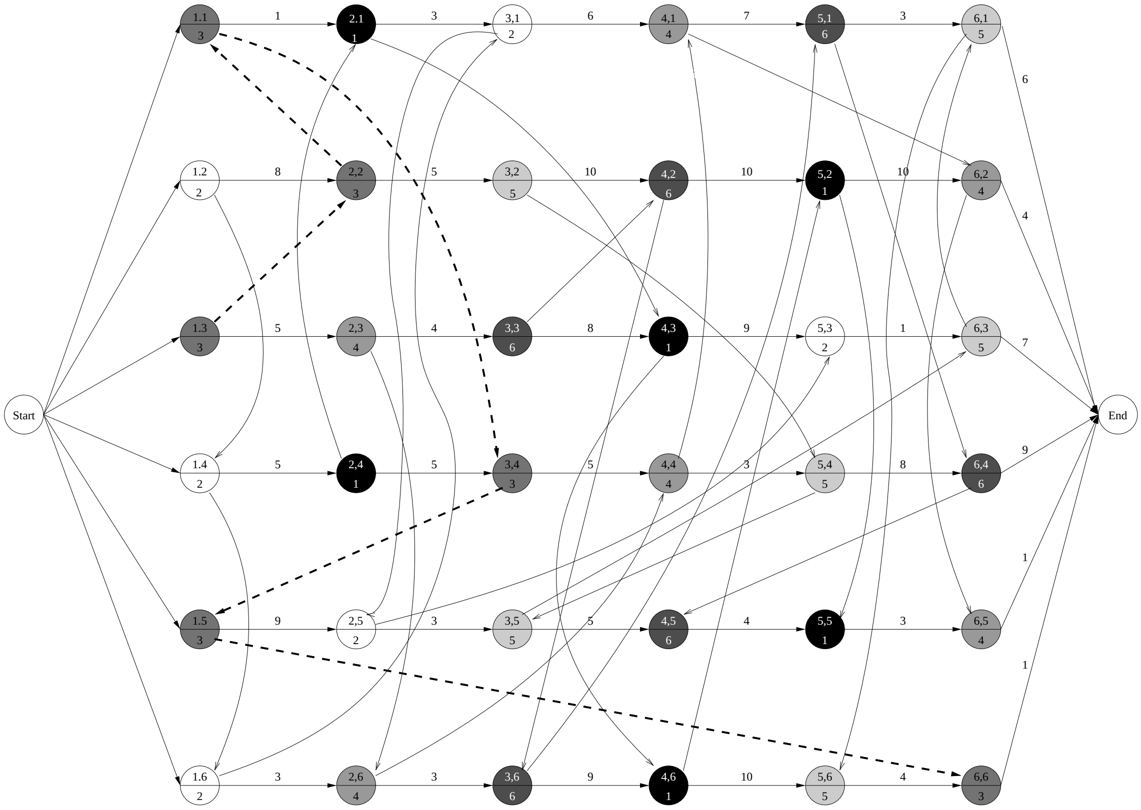


Figure 3.23: *The graph $G(\pi)$ representing a feasible schedule after one iteration of the tabu search method with backtracking of Example 3.13. The processing order of the third machine is shown as the bold faced dashed arcs.*

After the insertion of L_1 into $\mathcal{L}$, the reverse of move $v_1 = (T_{22}, T_{13})$ is inserted into the tabu list and therefore $\mathcal{F} = \{(T_{13}, T_{22})\}$. The graph for the new schedule is presented in Figure 3.23, whereas the Gantt chart for this schedule is given in Figure 3.24. This completes the first iteration of the tabu search method with backtracking.

The critical path for the new schedule is $u = (T_{12}, T_{22}, T_{32}, T_{42}, T_{36}, T_{46}, T_{52}, T_{62}, T_{65})$, with $w = 9$ and the new blocks are $B_1 = \{T_{12}\}$, $B_2 = \{T_{22}\}$, $B_3 = \{T_{32}\}$, $B_4 = \{T_{42}, T_{36}\}$, $B_5 = \{T_{46}, T_{52}\}$ and $B_6 = \{T_{62}, T_{65}\}$. The moves obtained from the blocks is $V(\pi) = \{V_4(\pi), V_5(\pi), V_6(\pi)\}$ with $\pi = (\pi_1, \pi_2, \{T_{13}, T_{22}, T_{11}, T_{34}, T_{15}, T_{66}\}, \pi_4, \pi_5, \pi_6)$ and the corresponding changes to the objective function value, when the moves are executed on the schedule displayed in Figure 3.24, are presented in Table 3.24. Move v_1 presents the most significant improvement to the schedule. Therefore $L_2 = \{\pi, V(\pi) \setminus \{v_1\}, \mathcal{F}\}$ with $\pi = (\pi_1, \pi_2, \{T_{13}, T_{22}, T_{11}, T_{34}, T_{15}, T_{66}\}, \pi_4, \pi_5, \pi_6)$, $V(\pi) = \{(T_{42}, T_{36}), (T_{46}, T_{52}), (T_{62}, T_{65})\}$ and $\mathcal{F} = \{(T_{13}, T_{22})\}$. After execution of move v_1 the new schedule has an objective function value of 58 and its graph is given in Figure 3.25, whereas its Gantt chart is presented in Figure 3.26. This concludes the second iteration of the tabu search with backtracking for the Fisher & Thompson benchmark problem.

The third iteration of the tabu search commences with a critical path $u = (T_{12}, T_{14}, T_{16}, T_{26}, T_{36}, T_{42}, T_{51}, T_{64}, T_{45}, T_{55}, T_{65})$, and $w = 11$, with the new blocks $B_1 = \{T_{12}, T_{14}, T_{16}\}$, $B_2 = \{T_{26}\}$, $B_3 = \{T_{36}, T_{42}, T_{51}, T_{64}, T_{45}\}$, $B_4 = \{T_{55}\}$ and $B_5 = \{T_{65}\}$. The set of moves obtained from the blocks is $V(\pi) = \{V_1(\pi), V_3(\pi)\}$ with $\pi = (\pi_1, \pi_2, \{T_{13}, T_{22}, T_{11}, T_{34}, T_{15}, T_{66}\}, \pi_4, \pi_5, \{T_{33}, T_{36}, T_{42}, T_{51}, T_{64}, T_{45}\})$, $V_1(\pi) = \{(T_{14}, T_{16})\}$ and $V_3(\pi) = \{(T_{36}, T_{42}), (T_{64}, T_{45})\}$. Move (T_{36}, T_{42}) is tabu, whereas the objective function values obtained after the other moves were executed individ-

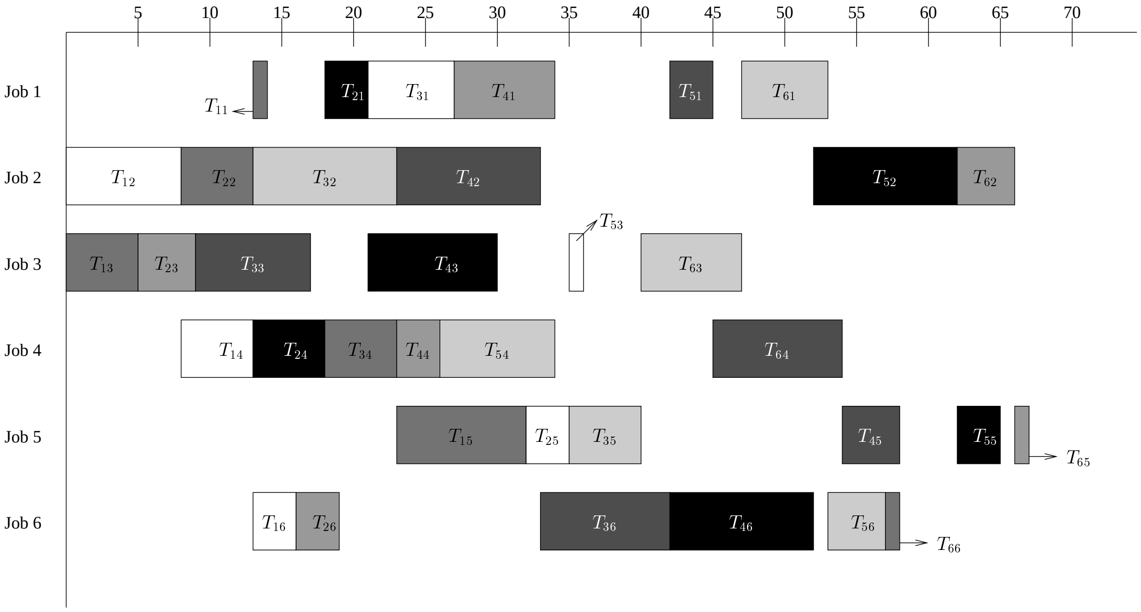


Figure 3.24: *The Gantt chart representing the feasible schedule in Figure 3.25 of Example 3.12.*

i	**Move**	$V_i(\pi)$	**New Objective Function Value**
4	v_1	(T_{42}, T_{36})	58
5	v_2	(T_{46}, T_{52})	62
6	v_3	(T_{62}, T_{65})	70

Table 3.24: *The new objective function values after each move is executed on the schedule in Figure 3.24.*

ually on the schedule, are presented in Table 3.25. None of the moves give an improvement on the current objective function value, but the move v_2 *that will result in the smallest increase in the objective function value is still executed. The graph of the new schedule, after move* v_2 *was executed, is shown in Figure 3.27, whereas the corresponding Gantt chart is shown in Figure 3.28.*

	Move	**New Objective Function Value**
v_1	(T_{14}, T_{16})	61
v_2	(T_{64}, T_{45})	58

Table 3.25: *The new objective function values after each move is executed on the schedule in Figure 3.26.*

Similar iterations may be carried out while incrementing the iteration counter, until a move is reached that improves the best objective function value obtained thus far, at which stage the iteration counter is set back to 1. *If the iteration counter reaches a maximum value (in this case* 2 500*), the current schedule, neighborhood and tabu list are replaced with the values in the last entry in the list* $\mathcal{L}$. *This process was carried out until the list* $\mathcal{L}$ *was empty and the iteration counter reached* 2 500. *The final schedule had an objective function value of* 55 *and its graph* $G(\pi)$ *and Gantt chart are shown in Figures 3.29 and 3.30 respectively.*

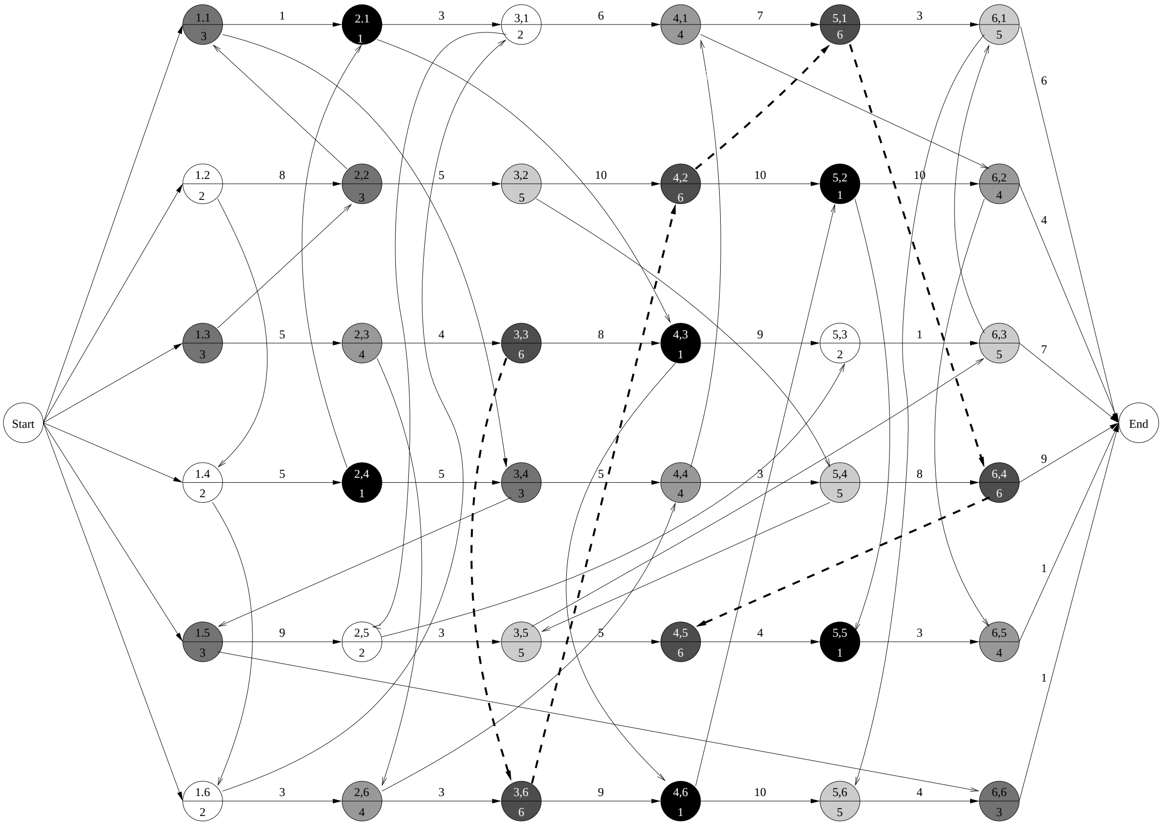


Figure 3.25: *A representation of the graph $G(\pi)$ representing a feasible schedule after the second iteration of the tabu search method with backtracking. The processing order of the sixth machine is shown as bold faced dashed arcs.*

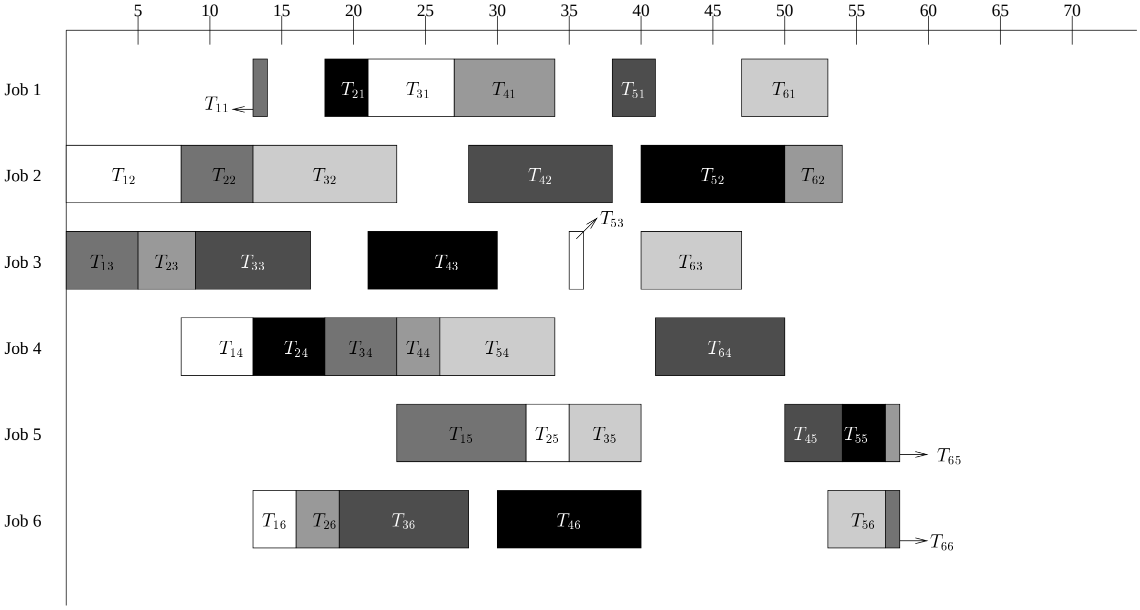


Figure 3.26: *A representation of the Gantt chart representing the feasible schedule in Figure 3.25 after the second iteration in the tabu search method with backtracking.*

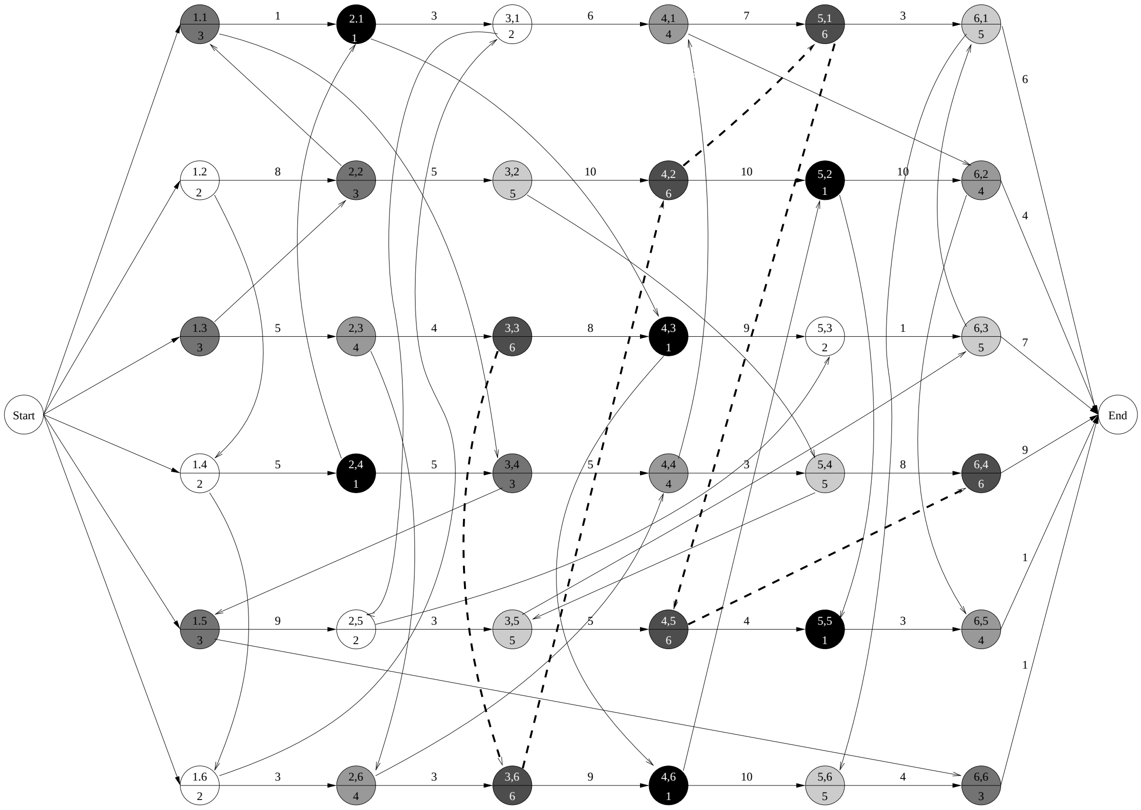


Figure 3.27: *The graph $G(\pi)$ representing a feasible schedule after the third iteration of the tabu search method with backtracking in Example 3.13. The processing order of the sixth machine is shown as bold faced dashed arcs.*

Figure 3.31 shows the change in the objective function over the first 600 *moves. The optimal objective function value was obtained at move* 31 *(the reader may very the optimal value in [74]). The peaks in the graph appear in cases where all the available moves increase the objective function value. In these cases the move that increase the objective function value the least is executed.*

In the case where the tabu list length was increased to respectively 15 *and* 30 *moves, the changes in the objective function values are presented in Figures 3.32 and 3.33. In both these cases the optimum objective function value took longer to realize. This is partly due to the small neighborhood of each move as well as the tabu list length, while some of the peaks are due to the backtracking move.* ∎

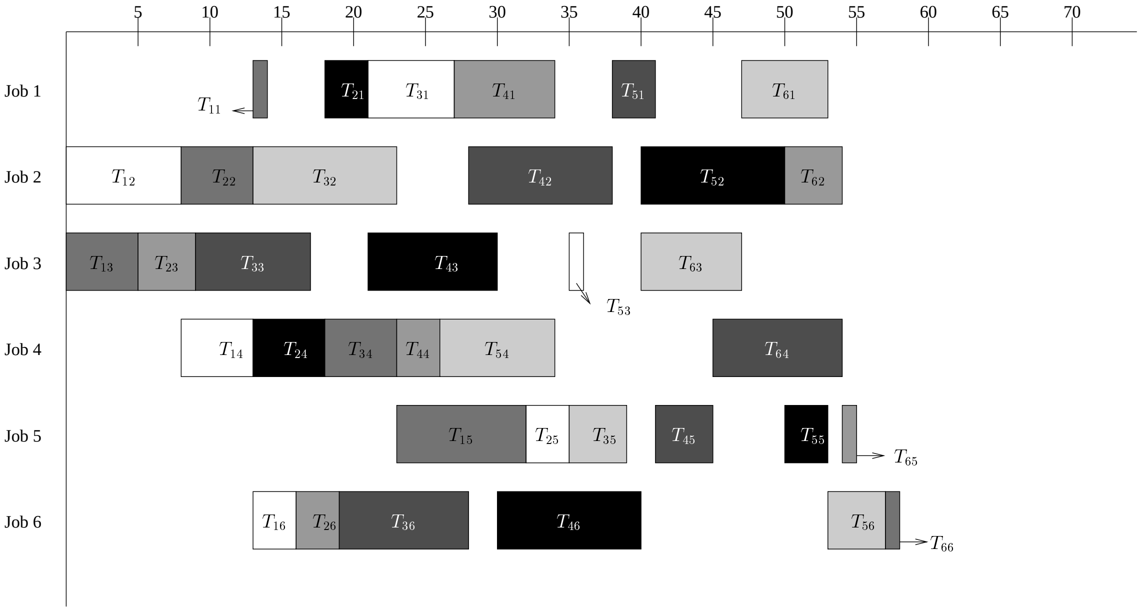


Figure 3.28: *The Gantt chart representing the feasible schedule in Figure 3.27 after the third iteration in the tabu search method with backtracking in Example 3.13.*

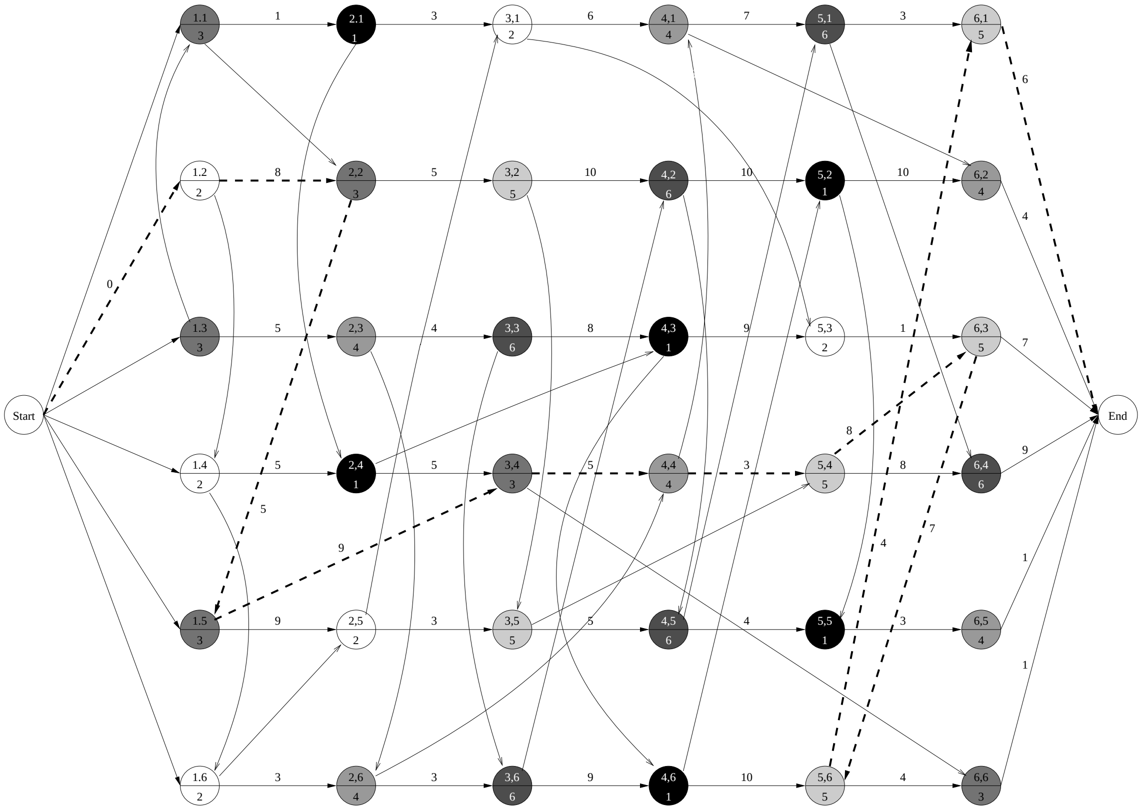


Figure 3.29: *The graph $G(\pi)$ of an optimal schedule obtained by the tabu search method with backtracking for the Fisher & Thompson benchmark problem with 6 machines and 6 jobs with 6 tasks each in Example 3.13. The bold faced dashed arcs indicate a critical path.*

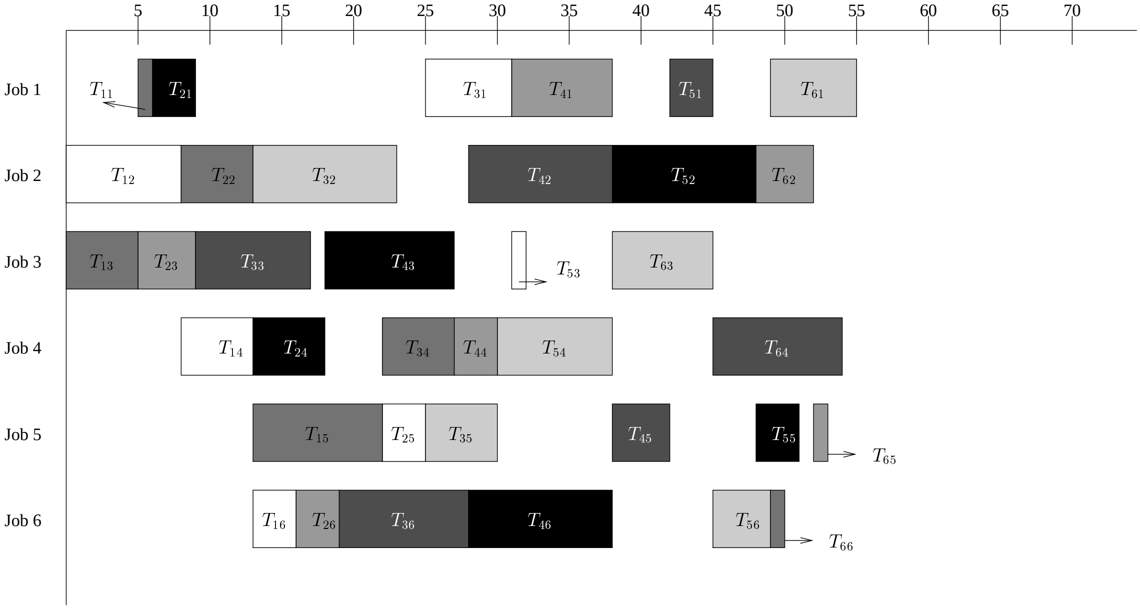


Figure 3.30: *The Gantt chart of an optimal schedule obtained by the tabu search method with backtracking for the Fisher & Thompson benchmark problem with* 6 *machines and* 6 *jobs with* 6 *tasks each in Example 3.13.*

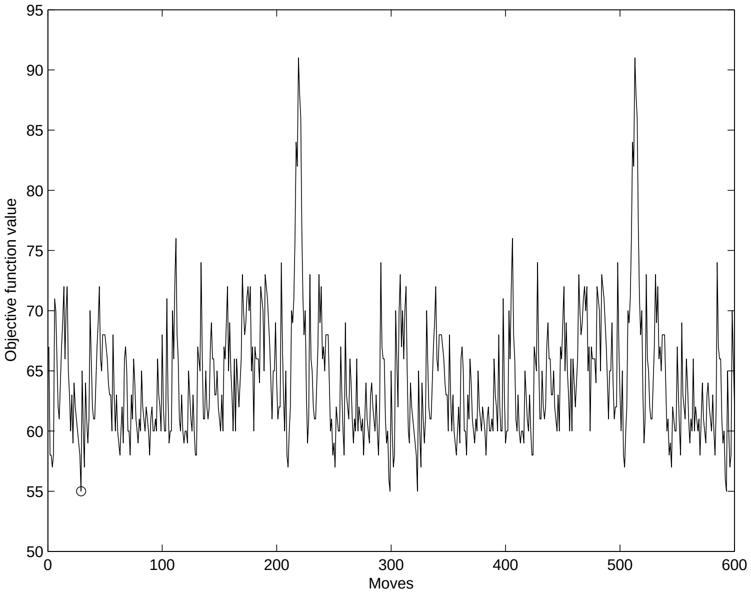


Figure 3.31: *The change in the objective function value over the first* 600 *moves of the tabu search method with backtracking with tabu list length* $f_{\max} = 8$. *The circle indicates where an optimal schedule was first obtained as discussed in Example 3.13.*

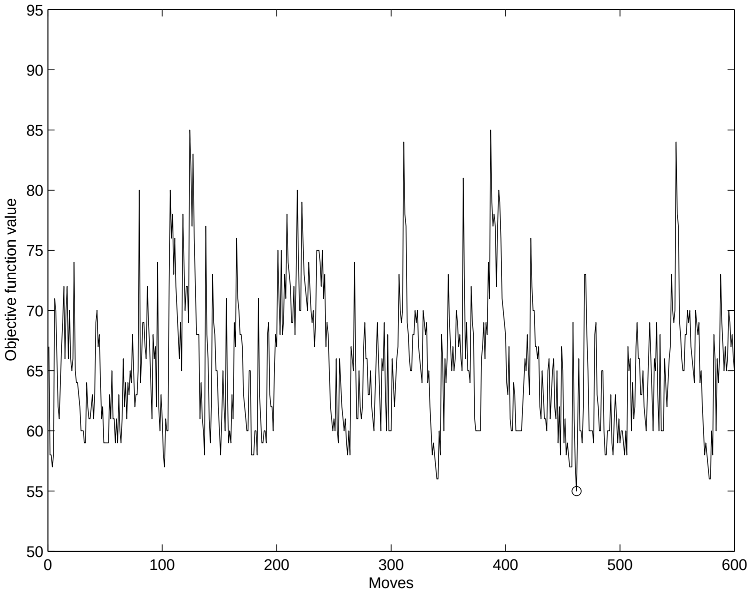


Figure 3.32: *The change in the objective function value over the first* 600 *moves of the tabu search method with backtracking with a tabu list length of* $f_{\max} = 15$ *moves. The circle indicates where an optimal schedule was obtained.*

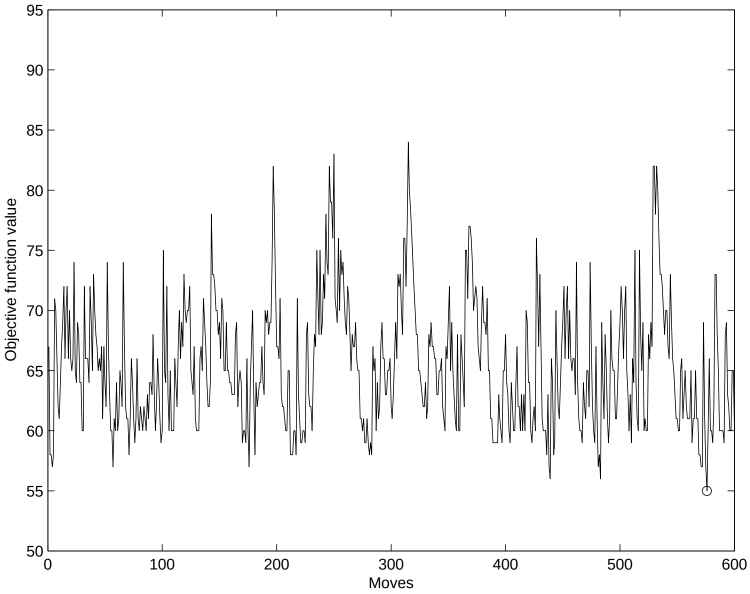


Figure 3.33: *The change in the objective function value over the first* 600 *moves of the tabu search method with backtracking with a tabu list length of* $f_{\max} = 30$ *moves. The circle indicates where an optimal schedule was obtained.*

Chapter 4

Formal Problem Statement

Figure 4.1: *Business logo of LWC.*

In order to develop appropriate layout and scheduling models for the Loubser Wood Components (LWC) factory, it is necessary to have a clear understanding of LWC products, objectives and main production processes. The objective of this chapter is to provide the reader with the information necessary to gain this understanding. It is against the background provided in this chapter that the assumptions made during the development of the layout and scheduling models (presented in Chapters 5 and 6 respectively) should be understood.

4.1 Introduction to LWC

LWC focuses on the manufacturing of high quality wooden components, typically used in the manufacturing of doors, cabinets, counters and furniture. Components typically comprise four parts: a chipboard or super–wood centre, solid wooden edges, a veneer cover and an acid catalysed lacquer layer of varnish. A graphical representation of a typical wooden component, as manufactured by LWC, is presented in Figure 4.2. LWC manufactures a large variety of wooden components. The main components manufactured are presented in §4.4. There is also a series of routine contract work options on specific machines that have to be taken into consideration during the scheduling process on the LWC floor. However, before describing these products and contract work in detail, the layout of the machines and the workforce in the factory

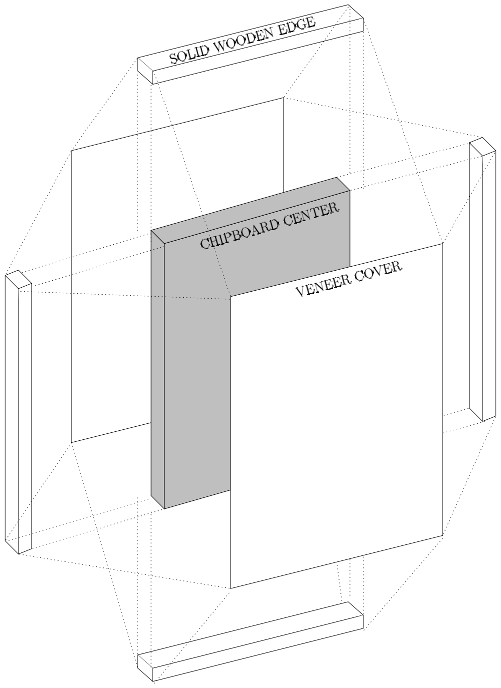


Figure 4.2: *A 3D–plan of how a typical component manufactured by the LWC is constructed.*

are described in §4.2 and §4.3.

The LWC factory is located in Okavango Park (28 Eagle Street) situated in Brackenfell, about 60 km from the city of Cape Town and 30 km from Cape Town International Airport, South Africa. The facade of the factory is shown in Figure 4.3, while a map of the location of the factory relative to the N1 freeway is shown in Figure 4.4.

Certain important operational aspects of the factory, the factory layout, machines used and staff employed by LWC are introduced in the following sections.

4.2 Functionality and Layout of Machines at LWC

A floor plan of the factory, together with its dimensions, is shown in Figure 4.5. The factory is divided into two functional areas linked by means of a ramp with an incline, due to the fact that the two factory floors are not on the same vertical level.

Raw materials are delivered at the roller door on the upper factory floor, as indicated in Figure 4.6. Finished orders are collected at the roller door on the lower factory floor. Orders usually have to be processed by the machines on the top floor before they are processed by the machines on the lower floor. However, this is not always the case due to the large variety of products manufactured by LWC. The machines, their functionalities, capacities and sizes are described next.

There are 15 different machines or processing stations on the LWC floor. Eight machines are positioned on the upper factory floor and the remaining seven are positioned on the lower floor, as shown in Figure 4.7. The machines positioned in the upper half of the factory are the

(a) Panel Saw,

Figure 4.3: *The LWC factory facade on Eagle Street. The factory, offices and parking lot are visible. The large door on the right is the delivery door and the large door on the left the dispatch door.*

Figure 4.4: *The situation of the LWC factory relative to the N1 (scale* 1cm : 9.61km*).*

(b) Radial Arm Saw,

(c) Ripper,

(d) Planer,

(e) Four–side Planer,

(f) Spindle,

(g) Edge Sander and

(h) Assembly Station.

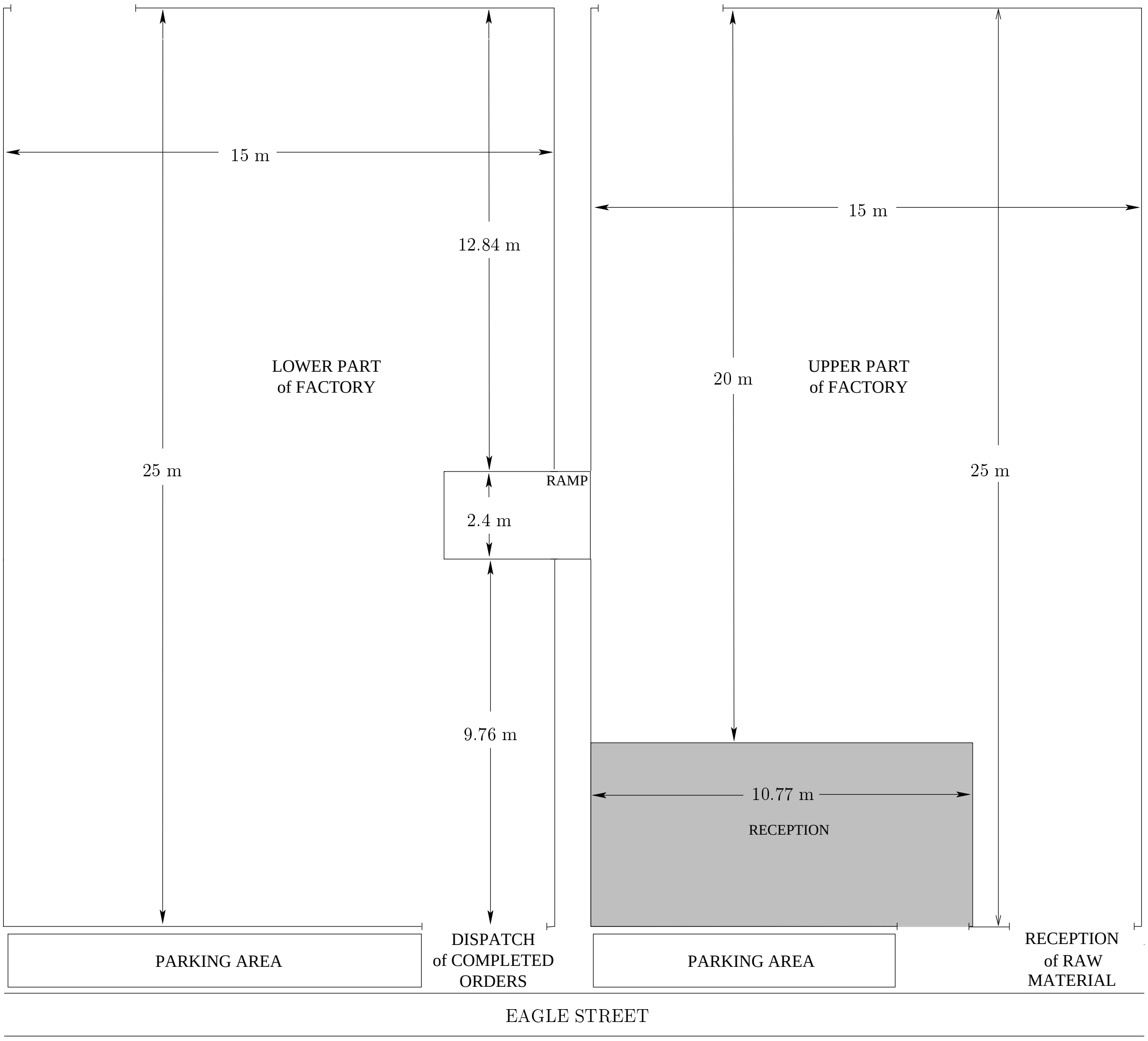


Figure 4.5: *The dimensions on the layout of the LWC factory.*

Pictures of these machines are presented in Figures 4.8(a)–(h). As mentioned earlier, most components manufactured by LWC have a super–wood or chipboard center. The Panel Saw (Figure 4.8(a)) is used to cut raw super–wood and chipboard panels into smaller sizes, as required by the cutting list associated with an order, created by management, directly after an order is accepted. Each order has a unique cutting list consisting of the dimensions of the components ordered, as well as a layout (drawn to scale) of how the components should be cut out of the raw chipboard or super–wood panels so as to prevent unnecessary off–cuts. The Panel Saw is partially immovable, because the calibration of the blades is very sensitive to motion and it takes approximately 4 working days to re–calibrate the blades to precision. The Panel Saw at LWC can cut approximately 500 running metre[1] [rm] of wood in 8 hours. This rate was obtained without taking into account the physical movement of material onto and from the machine. The Panel Saw has a *processing size* of 32.700 m^2. The processing size of a machine is the size necessary for the machine to operate, including the space needed for workers to move

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[1] The unit *running metres* may be converted to m^2, using the conversion rule that 8 rm is approximately 1 m^2. The unit running metre was created and is used by LWC in quotations. The management of LWC came up with this estimation to approximate the length of edging used by an order.

Figure 4.6: *The roller door on the upper LWC factory floor, where raw materials are delivered.*

comfortably around it.

Most components also have a set of solid wooden edges that are attached to them. The sizes of these edges depend on the sizes of the individual components in the order, as specified on the cutting list. The edges (prepared in advance) are cut to the correct sizes on the Radial Arm Saw (see Figure 4.8(b)), which has a capacity to cut approximately 160 rm of wood in 8 hours. The Radial Arm Saw has a processing size of 3.854 m^2 and is positioned near the Panel Saw. These solid wooden edges are prepared from unplaned logs delivered from the sawmill. The wooden logs have to be planed before they can be used in the manufacturing process. The Four–side Planer is used to plane these logs and has a capacity to plane approximately 1 600 rm of wood in 8 hours. The Four–side Planer is shown in Figure 4.8(e) and has a processing size of 21.790 m^2. This machine creates a significant amount of dust when in process and is expensive to start up. Therefore it is only used when large amounts of wood need to be planed (from orders in which more than 100 rm of planing is required) and is positioned far from the spray–booths, which require relatively dust free environments.

After the unplaned logs have been prepared at the Four–side Planer, they may be used to manufacture solid wooden edges, or they may be kept in inventory, as seen in Figure 4.9(a), until solid wooden edges or panels are required. The solid wooden edges are created by means of the Ripper, seen in Figure 4.8(c), which cuts the logs along their lengths into thin strips. The Ripper cuts long and thin (typically 5 mm) edges, depending on demand, and these edges are stored for use at a later stage, as shown in Figure 4.9(b). The Ripper has a capacity to cut approximately 800 rm of wood in 8 hours and a processing size of 9.380 m^2.

The smaller Planer, shown in Figure 4.8(d), is positioned next to the Ripper and is used when edges are not available in inventory or if edges of a different width to those in inventory are required from an order, in which case logs are planed to the same thickness as the width required by the edges. This machine has a capacity of approximately 800 rm per 8 hour period and has a processing size of 11.144 m^2. The smaller Planer is also used when a small number of logs needs to be planed, which typically occurs when a customer requests the use of a special wood type. In such cases the Four–side Planer is too expensive to start up.

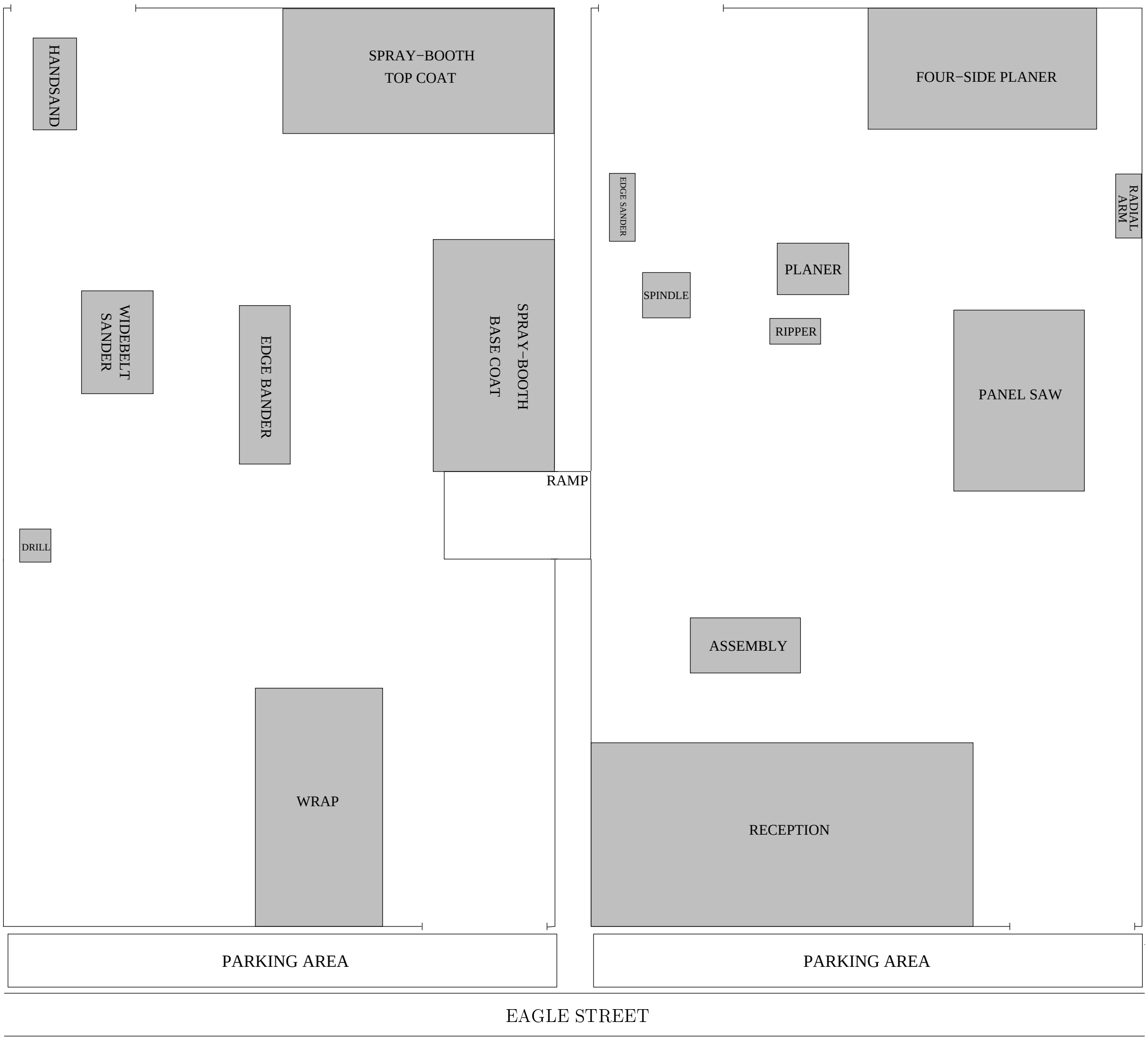


Figure 4.7: *The layout of the machines on the LWC factory floor.*

The Spindle, shown in Figure 4.8(f), is positioned to the left of the Ripper and Planer in Figure 4.7 and is used to create mortises and tenons in solid wooden frames during the manufacturing process of doors. Examples of a wooden frame and the mortises and tenons the Spindle creates are shown Figures 4.10(a), (b) and (c). The Spindle has a capacity to create approximately 900 rm of mortises or tenons in 8 hours and has a processing size of 4.049 m^2.

The Edge Sander (shown in Figure 4.8(g)), next to the Spindle on the upper floor and against the wall separating the upper and lower floors, is used to sand large volumes of edges already fixed to chipboard or super–wood centres. However, edges may also be hand sanded (at the Handsand Area on the lower half of the factory floor), due to different profiles that are applied to edges, which differ from order to order as preferred by the client. The Edge Sander has a capacity to sand approximately 35 m^2 in 8 hours and has a processing size of 0.726 m^2.

The last machine or processing station on the upper floor of the factory is the Assembly Station (see Figure 4.8(h)), where components are glued together, if necessary. This station has a capacity to assemble approximately 25 m^2 of wooden parts in 8 hours, has a processing size of 17.500 m^2 and consists of 2 tables and 9 clamps to hold parts of components together while

(a) *Panel Saw*

(b) *Radial Arm Saw*

(c) *Ripper*

(d) *Planer*

Figure 4.8: *Machines on the upper half of the LWC factory floor.*

they are permanently assembled.

The lower half of the factory is home to the:

(a) Base Coat Spray–booth,

(b) Top Coat Spray–booth,

(c) Edge Bander,

(d) Wrapping Unit,

(e) Drill,

(f) Widebelt Sander and

(g) Handsand Area.

(e) *Four–side Planer* (f) *Spindle*

(g) *Edge Sander* (h) *Assembly Station*

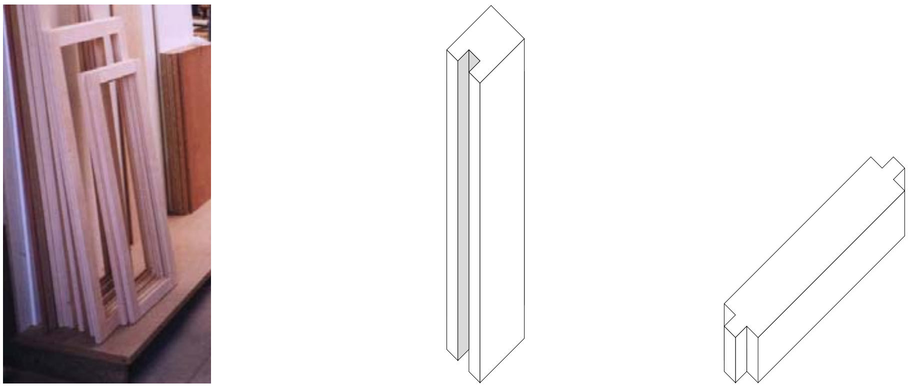
Figure 4.8 (continued)*: Machines on the upper half of the LWC factory floor.*

Pictures of these machines are shown in Figures 4.11(a)–(g). LWC owns 2 spray–booths which are airtight, dust–free in which components can be sprayed efficiently. Extractor fans in the roof and floor of these spray–booths ensure airtight zones. Most components require a base coat of varnish and a high quality varnish top coat. Components are sprayed inside a spray–booth by a qualified spray–painter, as seen in Figure 4.12(a). After the components have been sprayed they dry on racks (Figure 4.12(b)) inside the booths for a specified period. The drying period varies with the different mediums sprayed. A fixed total of approximately 20 m^2 sprayed wood can dry inside the Top Coat Spray–booth at any one time and therefore, if an order is too large to fit into the booth, it is sprayed in two or more batches. The Top and Base Coat Spray–booths (Figure 4.11(a)–(b)) both have a capacity to spray approximately 20 m^2 in 8 hours. The Top Coat Spray–booth has a processing size of 25.746 m^2, whereas the Base Coat Spray–booth has a processing size of 30.105 m^2.

Before components are sprayed in the spray–booths they are usually sanded either by hand or at

(a) *Solid wooden logs kept in inventory.* (b) *Solid wooden edges kept in inventory.*

Figure 4.9: *Solid wooden logs and edges kept in inventory, to be used at a later stage.*



(a) *Wooden frame manufactured.* (b) *Mortise in a frame.* (c) *Tenon in a frame.*

Figure 4.10: *Frames manufactured as a part of a door and a Mortise and Tenon created at the Spindle.*

the Widebelt Sander (Figure 4.11(f)). The Widebelt Sander has three main functions. The first function is to calibrate sand solid wooden panels to precisely the required thickness. Chipboard or super–wood panels are also calibrate sanded to the correct thickness, but with different settings on the machine. The veneering or fine sanding function is the third function which is used when components with a veneered cover already attached to them require sanding to ensure that their surfaces are even before they go to the Top or Base Coat Spray–booth. Components are also veneer or fine sanded after the base coat of varnish has dried. The Widebelt Sander has an average setup time of 9 minutes between tasks requiring different sanding functions. The Widebelt Sander has a capacity to calibrate sand approximately 40 m^2 of solid wooden panels in 8 hours, or approximately 80 m^2 of board components in 8 hours and to veneer or fine sand approximately 450 m^2 of components in 8 hours. The processing size of the Widebelt Sander is 17.023 m^2.

The Edge Bander, positioned near the Base Coat Spray–booth, attaches edges to the chipboard or super–wood centres of a component. Depending on the type of component, a solid

(a) *Top Coat Spray–booth* (b) *Base Coat Spray–booth*

(c) *Edge Bander* (d) *Wrapping Unit*

Figure 4.11: *Machines on the lower half of the LWC factory floor.*

wooden or veneer edge is glued to the chipboard or super–wood centre under high pressure and temperature. The solid wooden edges are inserted into the machine (Figure 4.13), before the component's side is pressed against the machine and rolls on a conveyor belt while an edge is attach to the component, as seen in Figure 4.11(c). The Edge Bander has a capacity to attach approximately 700 rm of edges to components in 8 hours and has a processing size of 32.716 m^2.

Some components and orders require the drilling of holes where, for example, hinges need to be affixed. These holes are created with the Drill seen in Figure 4.11(e), which is positioned near the Widebelt Sander. The Drill has a capacity to drill approximately 200 holes in 8 hours and has a processing size of 3.432 m^2.

After the base coat varnish has dried the components normally require sanding in order to remove over–spray and to ensure a high quality product. The large surfaces are usually fine sanded on the Widebelt Sander, but edges of the components need to be hand sanded due to

(e) *Drill* (f) *Widebelt Sander*

(g) *Handsand Area* (h) *Dispatch Area*

Figure 4.11 (continued): *Machines on the lower half of the LWC factory floor.*

the variety of different profiles applied to the components with the hand–held Router at the Handsand Area, shown in Figure 4.11(g). The Handsand Area has a processing size of 17.5 m^2 and is situated near the Top Coat Spray–booth. The handsand capacity is approximately 45 m^2 of edges in 8 hours.

When an order is finished and ready to be delivered it is wrapped with bubble wrap at a Wrapping Unit, seen in Figure 4.11(d). This is to protect the manufactured components while they are transported to the client. LWC has the capacity to wrap approximately 80 m^2 of components in 8 hours. The Wrapping Unit has a processing size of 17.5 m^2. The completed components are dispatched to the client from the dispatch area seen in Figure 4.11(h).

Machines function on either single phase or three phase power supply. An indication of which type of power supply is required by each machine is given in Table 4.1.

(a) *Components sprayed by the spray–painter.* (b) *Components drying on the dryracks.*

Figure 4.12: *A spray–booth with a spray–painter and the dry racks.*

Figure 4.13: *Solid wooden edges are inserted into the Edge Bander before a worker guides the component through the Edge Bander.*

Machine/Centre	**Single Phase**	**Three Phase**
Panel Saw		×
Radial Arm	×	
Ripper		×
Planer		×
Four–side Planer		×
Spindle		×
Edge Sander	×	
Assembly Station	×	
Top Coat Spray–booth		×
Base Coat Spray–booth		×
Edge Bander		×
Wrapping Unit		×
Drill	×	
Widebelt Sander		×
Handsand Area	×	

Table 4.1: *An indication of which machines function by means of single phase and which by means of three phase power supply.*

4.3 LWC Factory Staff

Evert and Hannes Loubser are the owners and managing directors of the LWC factory. Their brother, Jaco Loubser, is responsible for the accounting side of the business and they employ a permanent secretary. Currently LWC also supplies jobs to 20 workers, of which 7 can operate specialized machines.

Each machine has a main operator or set of so–called *number 1* operators, who are trained or have developed the skills to operate a specific machine. LWC provided the author with a summary of workers and their skills. Each worker was assigned a number and the skill of each worker is shown in Table 4.2. In the columns the workers are listed in a descending order of priority to work on the respective machines. In the last column of the table workers are labeled as so–called *number 2* operators, which means that they are not as skilled as the number 1 operators of that specific machine, but they may act as substitutes for the number 1 operators when these are unavailable. Some machines require an assistant in order to process efficiently and therefore workers are also assigned labels as assistants on some machines, as may be seen in Table 4.2. Workers 14, 18, 19 and 20 are general workers and assist throughout with the movement of raw material.

Machine/Centre	**# 1 Operator**	**Assistant**	**# 2 Operator**
Panel Saw	5	13	11,7,8,1
Radial Arm	12,11,8		5,7
Ripper	8,11	13	5,7,1
Planer	8,11	13	7,5
Four–side Planer			
Spindle	1,8	9,10,12	
Edge Sander	7		
Assembly Station	1,7,8,11,5		9,10,12
Top Coat Spray–booth	2		
Base Coat Spray–booth	17,3		2,7
Edge Bander	7,12		11,1
Wrapping Unit	9		7,12
Drill	7,1,8,11		9,10,12
Widebelt Sander	4		15
Handsand Area	6,9,10,15,16,3		13

Table 4.2: *Skills of the factory floor workers at LWC. No specific operator was assigned to the Four–side Planer as it functions very seldom and any operator type one could fill the position.*

4.4 Components Manufactured by LWC

The data associated with orders received and processed by LWC were not electronically available when the current project was initiated. The author therefore spent approximately 100 hours capturing the relevant data manually for the orders dispatch during the six month period (1 July 2002 – 31 December 2002) into electronic format. These data records consist of the following information fields, which were entered into a Microsoft Excel spreadsheet (See `2002OrdersReceived.xls` on the attached CD for the captured data):

- a description of the component type ordered,
- the number of component parts in an order,
- the length, width and thickness of each component part,
- an indication of whether the component requires a veneer cover,
- an indication of which edges (solid or veneer) are to be attached,
- the order date and

No	Description of the Component	Jul 2002	Aug 2002	Sep 2002	Oct 2002	Nov 2002	Dec 2002		Total m^2	Cum Total m^2	Cum %	%
1	Contract Calibrate Sand	1 145.05	1 688.44	1 512.89	2 644.74	917.38	389.73		8 298.21	8 298.21	37.67%	37.67%
2	Contract Cut	718.38	926.61	30.40	2 461.94	2958.69	34.64		7 130.65	15 428.86	70.04%	32.37%
3	Contract Veneer Sand	750.91	555.56	641.83	115.51	768.61	483.73		3 316.16	18 745.02	85.09%	15.05%
4	Veneer Over Edge	145.27	141.99	83.07	114.08	101.63	130.84		716.88	19 461.90	88.34%	3.25%
5	Contract Spray Lacquer Top and Base Coat	5.07	153.22	99.04	160.61	168.92			586.87	20 048.77	91.01%	2.66%
6	Contract Edging	79.22	86.44	32.69	53.38	235.94	33.66		521.35	20 570.16	93.37%	2.37%
7	Board Components		61.21	21.98	190.43	112.50	30.46		416.58	20 986.69	95.26%	1.89%
8	Shaker Doors	32.13	7.70	30.76	41.25	32.08	102.75		246.67	21 233.36	96.38%	1.12%
9	Contract Calibrate and Veneer Sand	54.98				16.64	90.01		161.63	2 1394.99	97.12%	0.73%
10	Contract Cut and Edge	17.30		99.44		1.10	35.95		153.79	21 548.78	97.82%	0.70%
11	Contract Plane all Round (PAR)	0.55		14.18	39.22	51.40	10.15		115.50	21 664.27	98.34%	0.52%
12	Contract Spray: Stain Top Coat	5.53		28.98	41.23	19.43			95.19	21 759.45	98.77%	0.43%
13	Contract Spray: Base Coat			1.43			44.48		45.90	21 805.36	98.98%	0.21%
14	Components on Edge	0.19		4.78	11.94	19.45	7.49		43.84	21 849.20	99.18%	0.20%
15	Contract Cut, Edge and Groove	29.16	8.87						38.03	21 887.23	99.35%	0.17%
16	Contract Cut and Calibrate Sand						28.79		28.79	21 916.02	99.48%	0.13%
17	Contract Spray: Base Coat and Route						25.60		25.60	21 941.62	99.60%	0.12%
18	Contract Cut and Spray					6.82	13.28		20.10	21 961.72	99.69%	0.09%
19	Contract Cut, Edge and Calibrate Sand					15.51			15.51	21 977.23	99.76%	0.07%
20	Contract Spray: Top and Base Coat and Edge Cut	3.13		6.74					9.88	21 987.11	99.80%	0.04%
21	Contract Edging and Calibrate Sand					9.79			9.79	21 996.89	99.85%	0.04%
22	Contract PAR, Rip and Groove						6.25		6.25	22 003.14	99.88%	0.03%
23	Contract PAR, Calibrate and Veneer Sand						6.01		6.01	22 009.16	99.90%	0.03%
24	Contract Spray: Top and Base Coat	3.58		0.06		1.81			5.45	22 014.61	99.93%	0.02%
25	Contract Cut and Assembly						5.01		5.01	22 019.62	99.95%	0.02%
26	Contract Cut, Veneer Sand and Edging						3.34		3.34	22 022.96	99.97%	0.02%
27	Contract PAR and Edging						2.93		2.93	22 025.85	99.98%	0.01%
28	Contract Spray: Lacquer Top and Base Coat and Calibrate and Veneer Sand					1.44			1.44	22 027.32	99.99%	0.01%
29	Contract Spray: Top and Base Coat and Edging						1.38		1.38	22 028.70	99.99%	0.01%
30	Contract Spray: Top and Base Coat, Calibrate and Veneer Sand	1.08							1.08	22 029.77	100.00%	0 00%
31	Contract Groove						0.20		0.20	22 029.97	100.00%	0.00%
32	Contract Cut and Route	0.13							0.13	22 030.10	100.00%	0.00%

Table 4.3: *Volumes of different components manufactured by LWC over the six month period 1 July 2002 – 31 December 2002.*

- the dispatch date.

Over this six month period 32 different kinds of components were manufactured. A summary of the volumes of the different components manufactured is presented in Table 4.3, which consists of a description of the 32 components and the volume (in m^2) of each type of component ordered for each month, ordered from the largest to the smallest total component volume. The last four columns contain the total volume (in m^2) of each component manufactured over the six month period along with a cumulative total volume of manufactured components and the cumulative percentage of manufactured components, as well as the percentage of the total volume of manufactured components. It is evident that the first 14 components accumulate to just over 99% of the manufactured components produced during the six months.

The majority of the work done by LWC is contract work (contracts with companies to sand all their products, for example, or to edge a certain number of components or to cut the components on the Panel Saw for external companies). However, LWC manufactures four complete components as well. They are called the *Veneer Over Edge components* (VOE), *Board components*, *Shaker Doors* and *Components on Edge* (COE). These four components require a veneer cover attached to the centre of the board — this is done at an external veneer factory, because LWC does not have the necessary equipment to attach these veneer covers. Therefore, as part of the processing sequence of these four products, they spend three days at an external Veneer Factory.

Figure 4.14: *The processing sequence of contract calibrate sanding of board components, shown on the factory floor layout of LWC.*

In the remainder of this section the 14 components, which comprise of 99% of the manufactured product volume at LWC, are discussed in a descending order of volumes manufactured over the six month period. The processing order of tasks in the manufacturing of each of these components is shown on the factory floor layout in order to provide the reader with an impression of the complexity of the processing sequences at LWC.

4.4.1 *Contract* Calibrate Sanding

One of the functions of the Widebelt Sander is to calibrate sand chipboard or super–wood components. During the six months for which data were captured, LWC did calibrate sanding contract work to a volume of 8 298.21 m^2, which constitutes 37.67 % of the total goods manufactured during the six month period. This contract work entails sanding chipboard or super–wood components to the correct thickness, as specified by the order. The processing sequence of this order type is shown in Figure 4.14, from which it may be seen that the raw chipboard or super–wood, already cut to the correct sizes at the reception door (in the upper half of the factory), are transported to the Widebelt Sander. After processing at this machine is complete it is taken to the dispatch door (in the lower half of the factory) to be collected by the client.

4.4.2 *Contract* Cutting

Almost a third of the components manufactured by LWC over the six month period for which data was captured consist of the cutting of raw chipboard or super–wood panels to specified sizes for clients. The processing sequence of this order type is shown in Figure 4.15. Raw chipboard or super–wood, arriving at the reception door, is cut to the correct size on the Panel Saw, as specified on a cutting list, and after being cut, is taken to the dispatch door to be collected by the client. If the customer does not provide his/her own chipboard or super–wood panels it is provided by LWC.

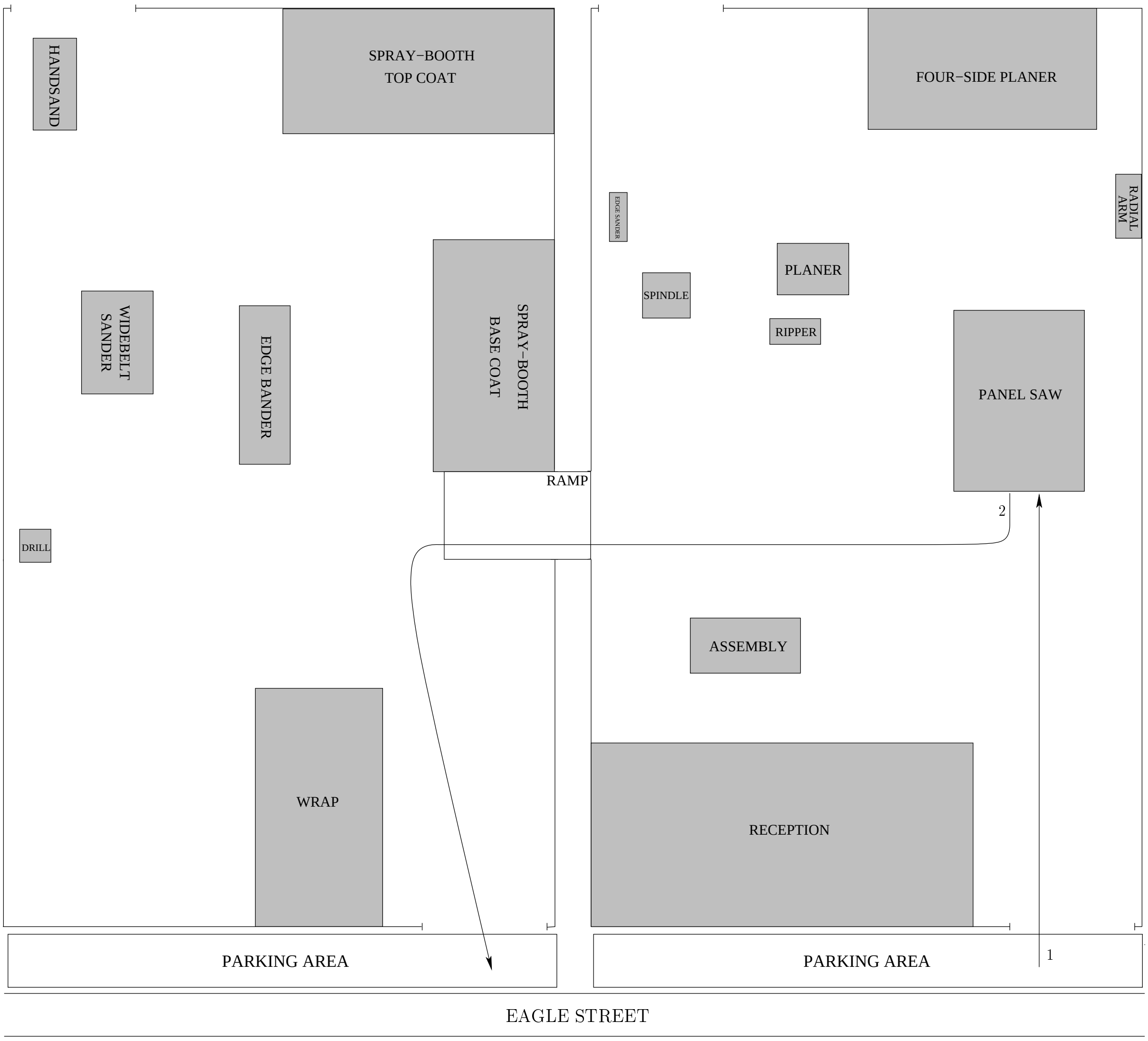


Figure 4.15: *The processing sequence of contract cutting of board components, shown on the factory floor layout of LWC.*

4.4.3 *Contract* Veneer Sanding

The veneer sanding component has exactly the same machine processing sequence as the contract calibrate sanding of board components, but the veneer sanding has a different processing time per m^2 and is therefore considered a different product. A total of 15.05 % of the manufactured goods over the six month period for which data were captured consist of the veneer sanding of components. The machine processing sequence of these types of orders is shown on the factory floor layout in Figure 4.16.

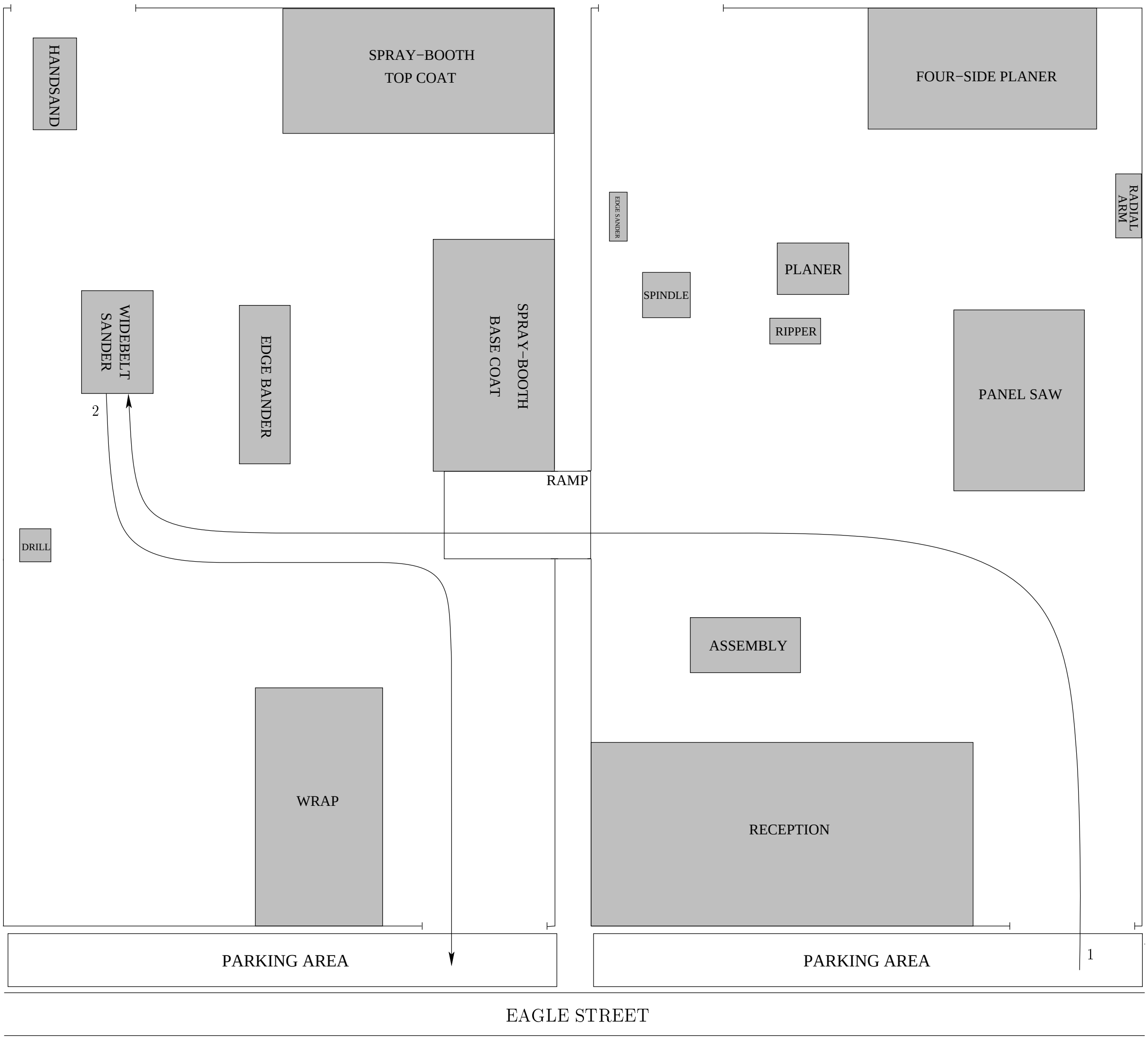
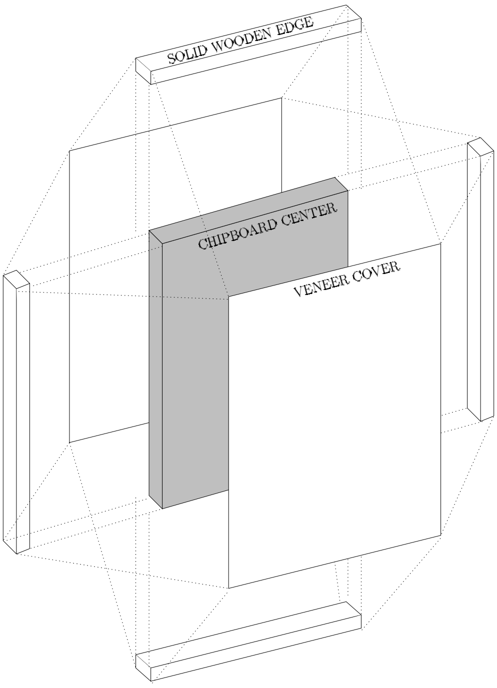


Figure 4.16: *The processing sequence of contract veneer sanding or fine sanding of board components, shown on the factory floor layout of LWC.*

4.4.4 Veneer Over Edge Components

A picture of a Veneer Over Edge (VOE) component, as manufactured by LWC, is shown in Figure 4.17(a) and in Figure 4.17(b) a sketch is shown of how the component is manufactured. This is a component with solid wooden edges attached to a chipboard centre and a veneer cover,

(a) *A typical VOE component.*



(b) *Manufacturing of the VOE component.*

Figure 4.17: *A typical VOE component manufactured by the LWC factory along with a 3D–plan of how it is constructed.*

which covers the edges of the component as well.

The processing sequence of this product is shown in Figure 4.18 as well as in Table 4.4. The numbers in the table correspond to the numbers at the starting points of the arrows in Figure 4.18. As an order for a VOE component or set of VOE components arrive at LWC a cutting list is constructed by management to show the sizes of the components and how the components should be cut from the raw 2 750 mm × 1 850 mm chipboard panels. The cutting list is provided to the Panel Saw operator when this order is scheduled to begin processing and the components are cut to the correct sizes.

As shown in Figure 4.17(b), this component has solid wooden edges. Depending on the type and color of the veneer cover preferred by the customer, a certain type of solid wooden edge is required. After the components are cut to the correct sizes on the Panel Saw, strips of edges are cut on the Ripper from solid wooden logs when edges of the correct size or wood type are

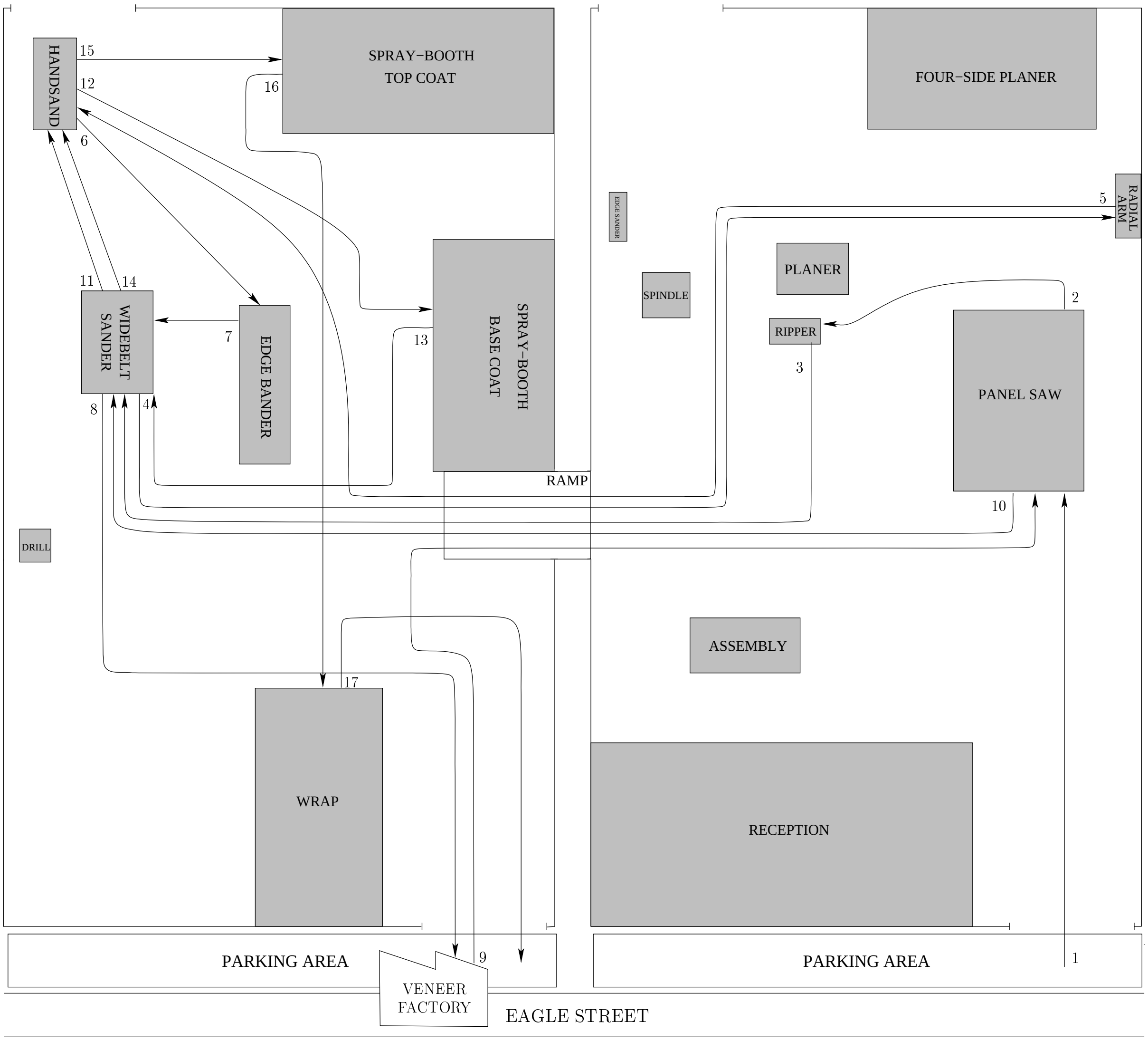


Figure 4.18: *The processing sequence of Veneer Over Edge components, shown on the factory floor layout of LWC.*

not in stock. These edges are then calibrate sanded to the correct thickness on the Widebelt Sander, before they are cut to the correct length (as specified on the cutting list) on the Radial Arm Saw. Before the edges are attached to the chipboard centres at the Edge Bander they require hand sanding to ensure a high quality finish for the product. The chipboard panels with the edges attached are then calibrate sanded again to ensure that there are no rough edges or glue on the surface of the chipboard panels, before they are transported to the external veneer factory where the veneer covers, as specified by the customer, are attached.

When the order returns after three days, excess veneer is first trimmed from the components at the Panel Saw, before the components are veneer sanded on the Widebelt Sander and the edges hand sanded at the Handsand Area to prepare them for the spay process. In cases where components require different edge–profiles they are applied at this stage with a Router at the Handsand Area, before the order is taken to the Base Coat Spray–booth where the varnish base coat is applied to the components. When the components have dried they are taken to the Widebelt Sander, where they are veneer sanded to remove over–spray on the components, whereas over–spray is removed from the edges at the Handsand Area. At this stage the components are ready to receive the final top coat of varnish inside the Top Coat Spray–booth. The components are left to dry there after which they are bubble wrapped at the Wrapping Unit, before the client is notified that his/her order is ready to be collected.

No	Machine/Centre	Task
1	Reception	Order is received and cutting list constructed.
2	Panel Saw	Chipboard panels are cut to the correct sizes.
3	Ripper	Solid wooden edges are created from the correct type of wood.
4	Widebelt Sander	Calibrate sanding of the edges to the correct thickness.
5	Radial Arm Saw	Edges are cut to the correct length.
6	Handsand Area	Edges are hand sanded before inserted into the Edge Bander.
7	Edge Bander	Edges are attached to chipboard centres.
8	Widebelt Sander	Chipboard panels with edges are calibrate sanded.
9	Veneer Factory	Veneer covers are attached to chipboard centres.
10	Panel Saw	Excess veneer is trimmed off.
11	Widebelt Sander	Veneer covers are veneer sanded.
12	Handsand Area	Edges are hand sanded and the correct profile is applied to edges.
13	Base Coat Spray–booth	Varnish base coat is sprayed.
14	Wildbelt Sander	Over–spray is removed with veneer sanding.
15	Handsand Area	Edges are sanded to remove over–spray.
16	Top Coat Spray–booth	Varnish top coat is sprayed.
17	Wrapping Unit	Components are wrapped.

Table 4.4: *Machine processing sequence for a VOE component.*

4.4.5 *Contract* Spraying of Lacquer Top and Base Coat

LWC also does contract work, consisting of spraying an acid catalyzed base and top coat onto wooden components. Components are delivered at the reception door before they are sprayed in the Base Coat Spray–booth. They are left to dry in the Base Coat Spray–booth and are then veneer sanded on the Widebelt Sander before the final top coat is applied in the Top Coat Spray–booth. The machine processing sequence of these components is shown in Figure 4.19.

4.4.6 *Contract* Edging

The Edge Bander at LWC has a high processing capacity and management is therefore seeking more contract work to be performed on this machine than the current 2.37 % of manufactured components. The machine processing sequence of contract work done on the Edge Bander is shown on the factory floor layout of LWC in Figure 4.20.

The components arrive at the reception door, after which the veneer edges are inserted into the Edge Bander where they are glued to the components under high temperature and pressure. Finally the components are taken to the dispatch door where they are to be collected by the client.

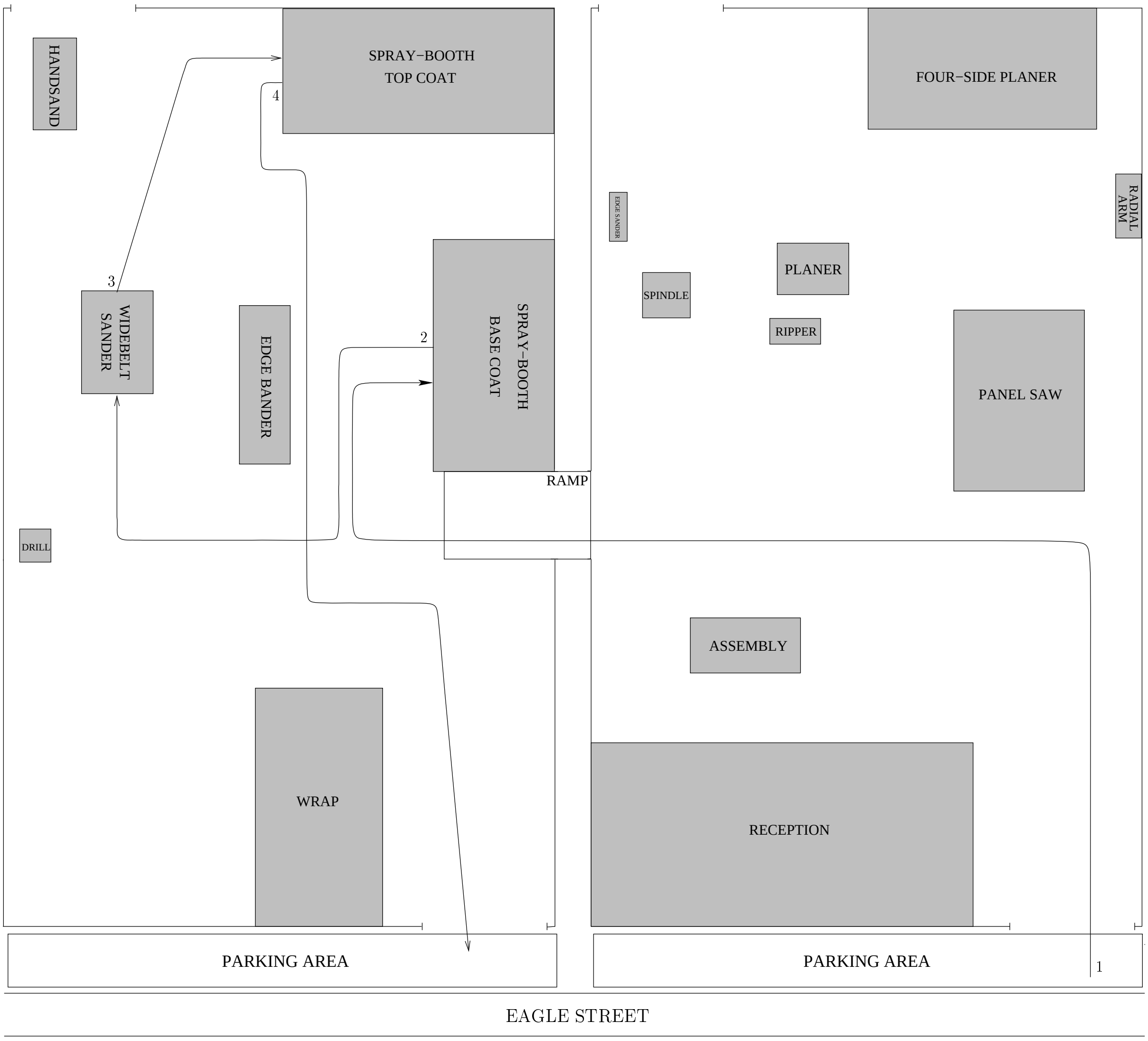


Figure 4.19: *The processing sequence of contract spaying of a lacquer top and base coat to board components, shown on the factory floor layout of LWC.*

4.4.7 Board Components

A picture of a typical Board component, as manufactured by LWC, is shown in Figure 4.21(a) and in Figure 4.21(b) a sketch is shown of how the component is manufactured. Board components are typically used along with VOE components when kitchen cupboards are constructed. Board components consist of 2.0 mm or 0.6 mm veneer edges attached to a chipboard centre and a veneer cover. The processing sequence of Board components is given in Table 4.5 and shown graphically on the factory floor layout in Figure 4.22.

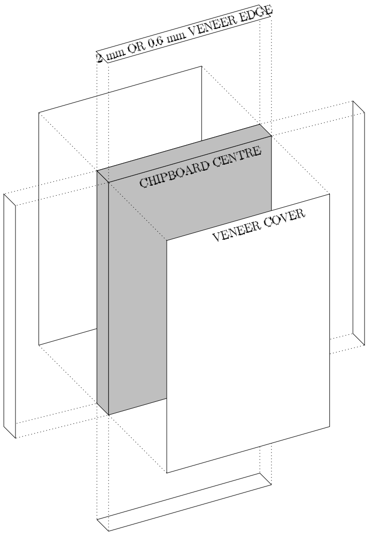
When an order is received for a Board component or set of Board components, raw chipboard panels are sent to an external Veneer Factory for three days, while a cutting list is produced by the management of LWC. Upon return of the veneer covered panels, the components are cut to their required sizes at the Panel Saw, as specified by the cutting list. Board components have veneer edges, which are attached at the Edge Bander after which the veneer covered components are veneer sanded on the Widebelt Sander to prepare them for the spaying process. After the

Figure 4.20: *The processing sequence of the contract edging, shown on the factory floor layout of LWC.*

No	Machine/Centre	Task
1	Reception	Order received, raw chipboard panels sent to Veneer Factory and cutting list constructed.
2	Panel Saw	Upon return of veneer covered panels, they are cut to the correct sizes.
3	Edge Bander	Veneer edges are attached to chipboard centres.
4	Widebelt Sander	Veneer covers are veneer sanded.
5	Base Coat Spray–booth	Varnish base coat is sprayed.
6	Wildbelt Sander	Over–spray is removed with veneer sanding.
7	Handsand Area	Edges are sanded to remove over–spray.
8	Top Coat Spray–booth	Varnish top coat is sprayed.
9	Wrapping Unit	Components are wrapped.

Table 4.5: *Machine processing sequence for Board components.*

(a) *A typical Board component.*



(b) *The construction of Board components.*

Figure 4.21: *A typical Board component and its construction.*

base coat has dried, over–spray is removed by veneer sanding the components on the Widebelt Sander and hand sanding the edges at the Handsand Area. At this stage the components are ready to receive a varnish top coat in the Top Coat Spray–booth, after which components are wrapped at the Wrapping Unit once they have dried in the Top Coat Spray–booth. They are then ready to be collected by the client.

4.4.8 Shaker Door Components

A Shaker Door is typically used as part of a set of kitchen cupboard doors. A picture of a Shaker Door is shown in Figure 4.23(a) and in Figure 4.23(b) a sketch of how a typical Shaker Door component is manufactured, is shown. The processing sequence of a typical Shaker Door component is given in Table 4.6 and shown graphically on the factory floor layout in Figure 4.24.

When an order is received for a set of Shaker Door components an order is placed at an external Veneer Factory to veneer a 9 mm board on the outside with a grade A veneer and on the inside with a grade C veneer. This is done, because it is typically not that important that the inside of the kitchen cupboards are of high quality and this arrangement saves cost. While LWC waits three days for the finished veneer products to arrive at the reception area from the external Veneer Factory, solid wooden frames are constructed.

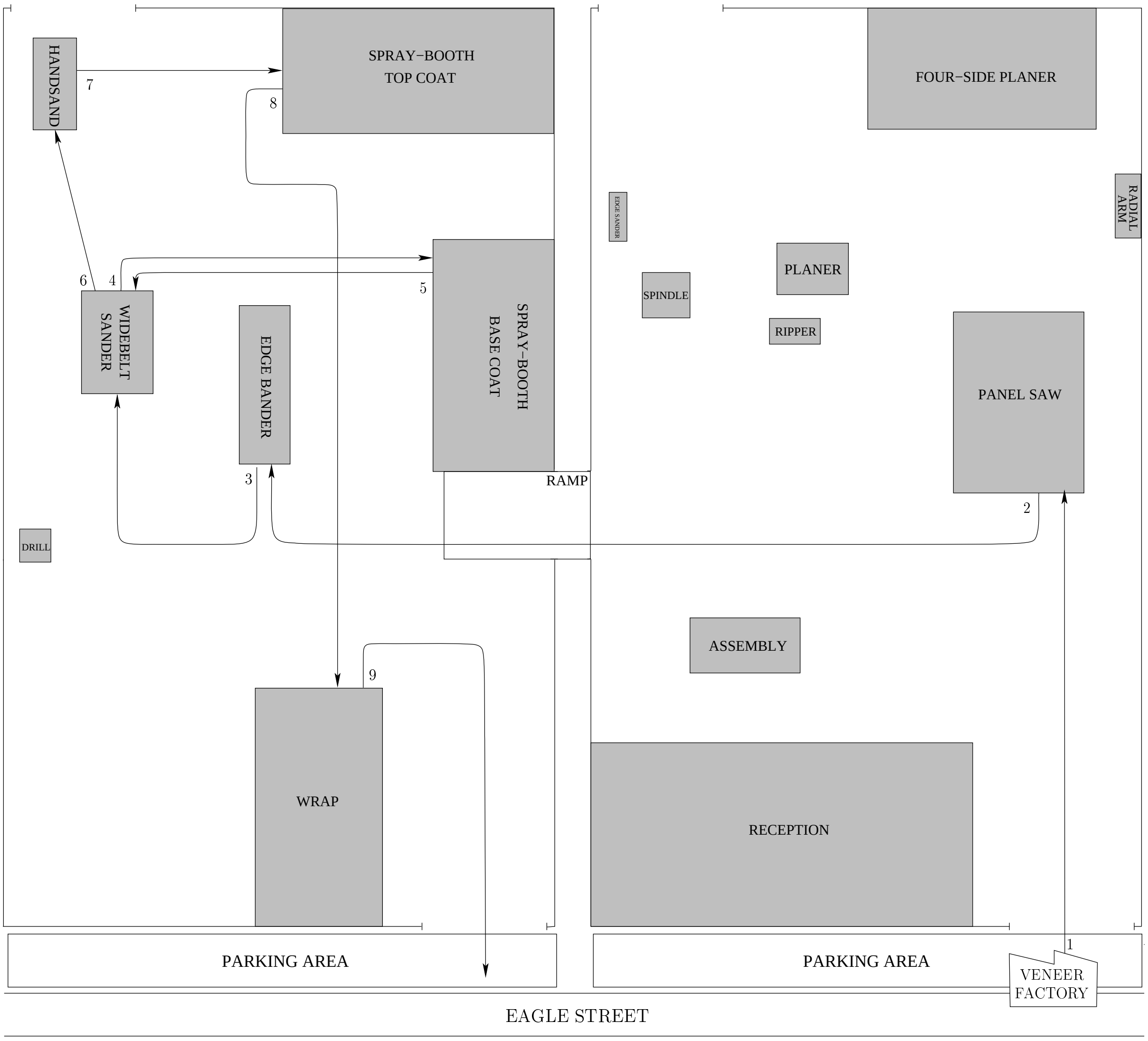
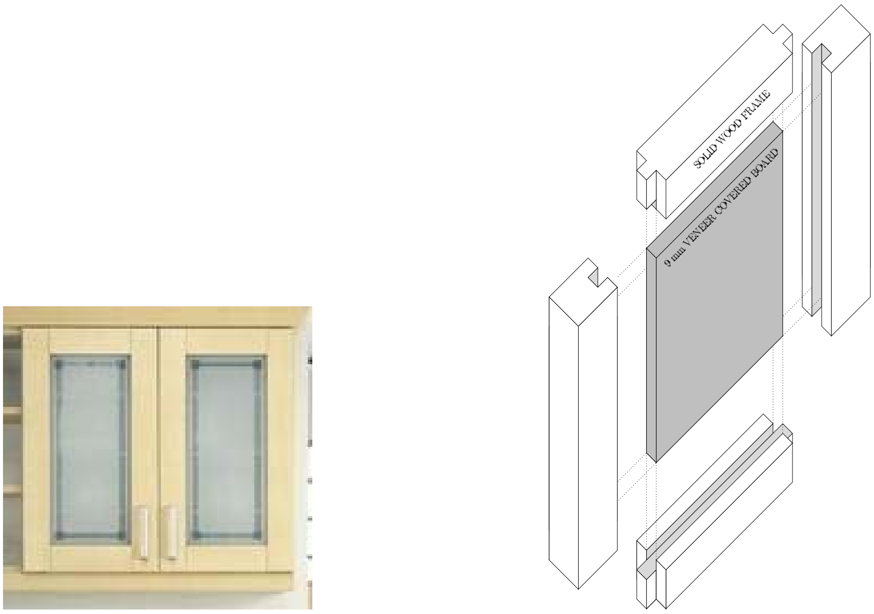


Figure 4.22: *The processing sequence of a typical Board component, shown on the factory floor layout of LWC.*

The solid wooden frames are constructed by first cutting solid wooden logs in stock at the Panel Saw into the correct sizes, as specified on the cutting list. The frames, consisting of four separate parts, are then calibrate sanded on the Widebelt Sander to the correct thickness, before a mortise is inserted into each frame part on the Spindle. The frame parts are cut into the correct lengths, as specified on the cutting list, before a tenon is created at the two edges of the shorter frame parts, to fit into the mortises in the other frame parts, as shown in Figure 4.23(b).

At this stage the veneer covered boards should arrive at the reception door. These boards are now cut into smaller parts (as specified on the cutting list) at the Panel Saw. The smaller boards are then veneer sanded at the Widebelt Sander before they are merged with the solid wooden frame at the Assembly Station. To prepare the Shaker Door components for spraying they are calibrate and veneer sanded at the Widebelt Sander and the edges are hand sanded at the Handsand Area. The profile preferred by the client is also added to the edges with the Router at the Handsand Area. The components are then taken to be sprayed with a base coat



(a) *A typical Shaker Door component.* (b) *Construction of a Shaker Door component.*

Figure 4.23: *A picture of a typical Shaker Door component and its construction.*

No	Machine/Centre	Task
1	Reception	Order is received and a cutting list is constructed.
2	Panel Saw	Solid wooden frames are cut out of logs.
3	Widebelt Sander	Frames are sanded to the correct thickness.
4	Spindle	Mortises are inserted into frame parts.
5	Panel Saw	Frame parts are cut to the correct lengths.
6	Spindle	Tenons are created at the ends of the two shorter edges.
7	Panel Saw	Veneer boards, returning from the Veneer Factory, are cut into correct sizes as specified by the cutting list.
8	Widebelt Sander	Smaller boards are veneer sanded.
9	Assembly Station	Components are assembled by fixing frames to the boards.
10	Widebelt Sander	Components are calibrate sanded.
11	Widebelt Sander	Components are veneer sanded.
12	Handsand Area	Edges are sanded to prepare for the spray process.
13	Base Coat Spray–booth	Varnish base coat is sprayed.
14	Handsand Area	Over–spray is removed from the whole product.
15	Top Coat Spray–booth	Varnish top coat is sprayed.
16	Drill	Holes are drilled for hinges.
17	Wrapping Unit	Components are wrapped.

Table 4.6: *Machine processing sequence for a Shaker Door component.*

of varnish at the Base Coat Spray–booth. When the base coat has dried the over spray is removed by hand sanding the whole component at the Handsand Area, before it is taken to the Top Coat Spray–booth to receive the final varnish coat. Before the components are wrapped and dispatched to the client, holes for hinges are drilled into the components.

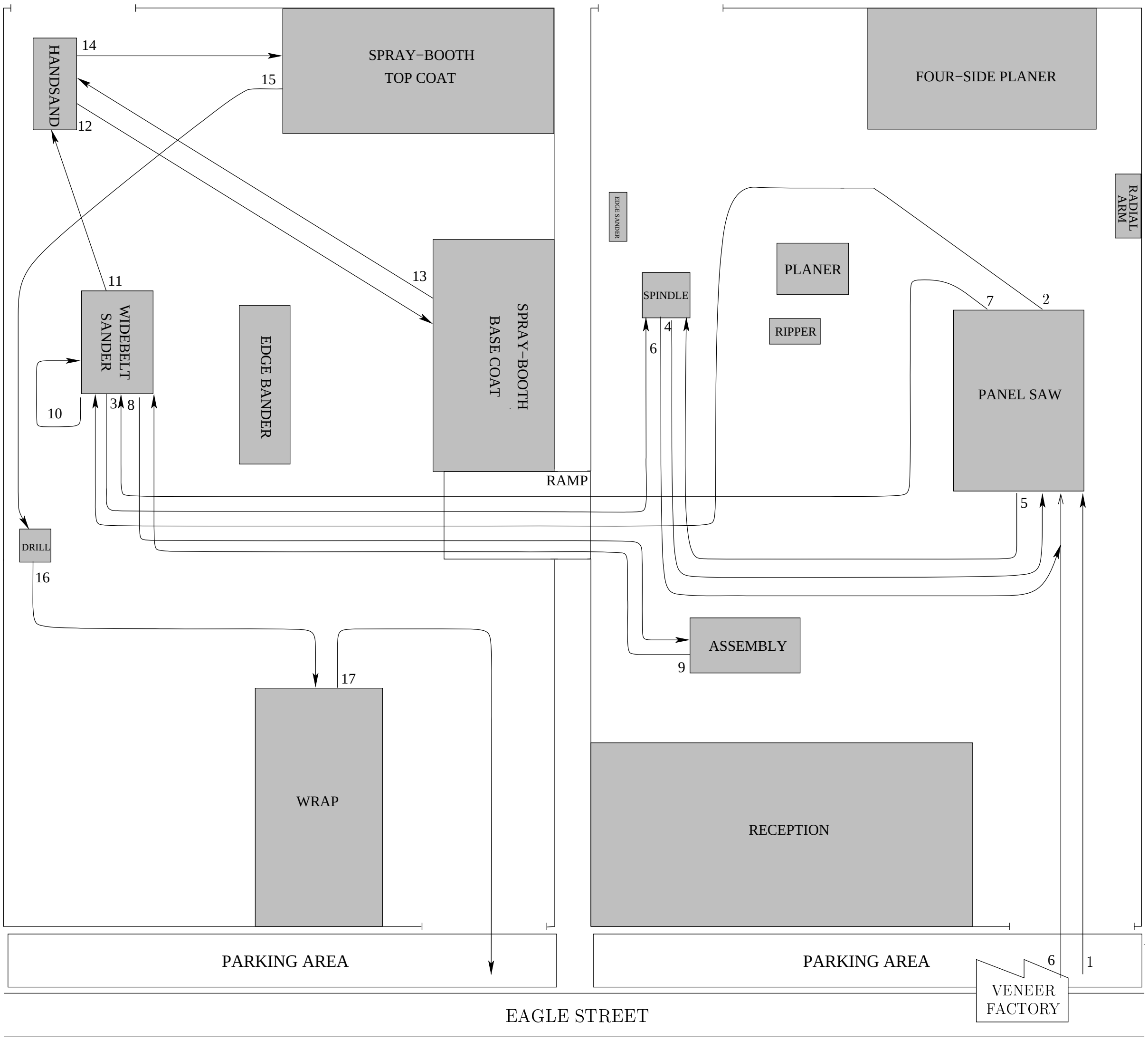


Figure 4.24: *The processing sequence of a typical Shaker Door component, shown on the factory floor layout of LWC.*

4.4.9 *Contract* Board Calibrating and Veneer Sanding

LWC also does contract work consisting of calibrate sanding chipboard or super–wood to the correct thickness and then veneer sanding it to smoothen the surface further on the Widebelt Sander. In this case the components are delivered at the reception door before they are sanded twice on the Widebelt Sander with a certain fixed setup time between the calibrate and veneer sanding, because the sandpaper roll has to be changed. The machine processing sequence of these components is shown graphically on the LWC factory floor layout in Figure 4.25.

4.4.10 *Contract* Cutting and Edging

As mentioned earlier, LWC has a large capacity with respect to Edge Banding and one of the components processed on the Edge Bander constitutes cut and edge contract work, which forms a total of 0.70 % of the total manufactured goods. Raw 2 750 mm × 1 850 mm chipboard panels,

Figure 4.25: *The processing sequence of contract calibrating and veneer sanding of chipboard components, shown on the factory floor layout of LWC.*

from LWC stock, are cut to the correct dimensions, as specified by a cutting list produced by management directly after the order was accepted. After all the boards are cut to the specified sizes, 2 mm or 0.6 mm thick veneer edges are attached to the necessary edges of the components on the Edge Bander, as indicated on the cutting list. These components are taken to the dispatch door directly after the edges have been attached. The machine processing sequence of these components is shown graphically on the LWC factory floor layout in Figure 4.26.

4.4.11 *Contract* Planing all Round (PAR)

A total of 0.52 % of all manufactured goods are components which have to be planed on all four sides. If such an order consists of more than 100 rm of solid wood, the order is processed on the Four–side Planer, but in most cases the order is smaller than 100 rm and is then processed on the smaller Planer. If all four sides of a solid wooden log have to be planed it means that the log has to be cut to the desired dimensions, width and thickness, before it can be used. Clients

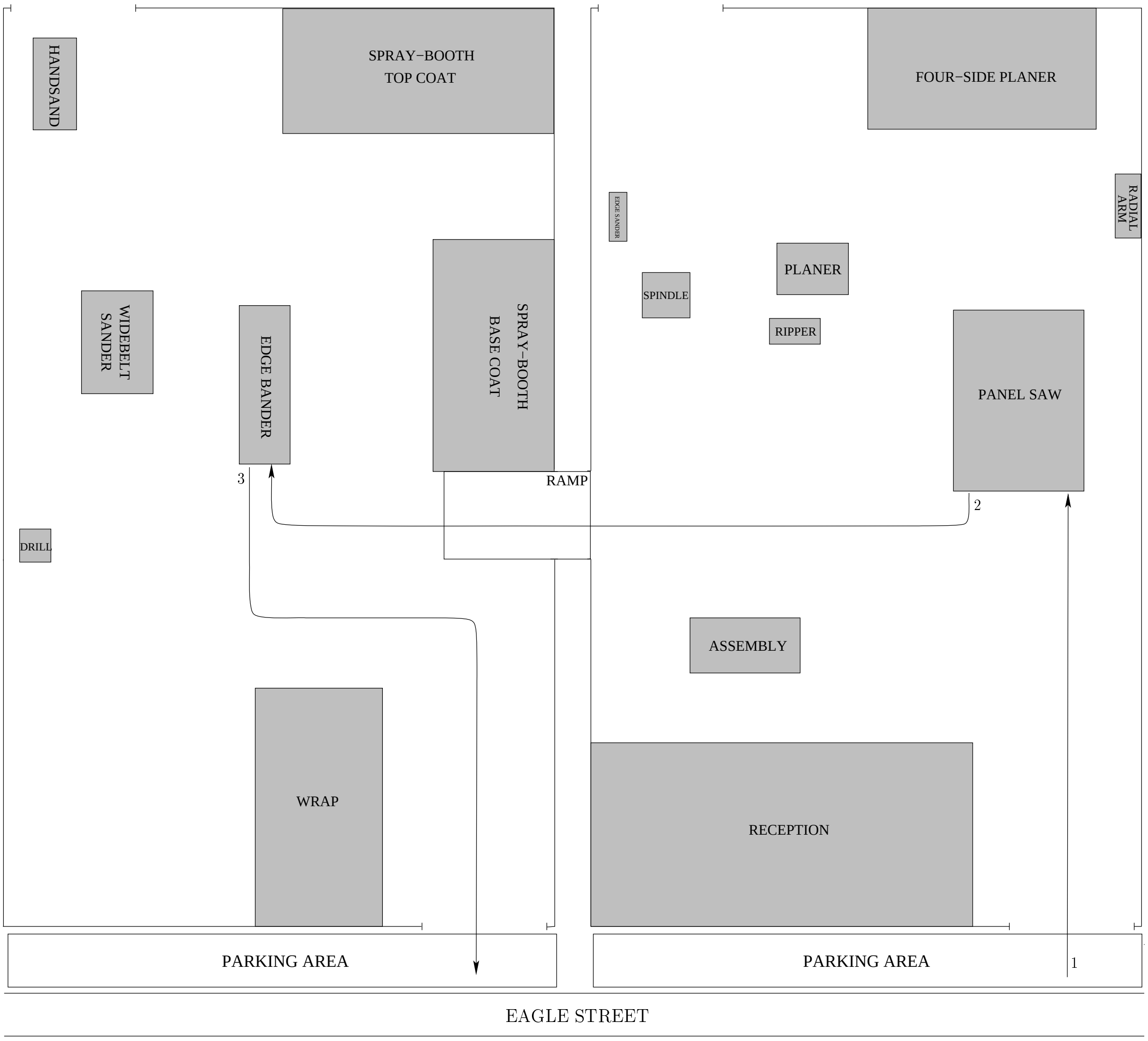


Figure 4.26: *The processing sequence of contract cutting and edging of chipboard components, shown on the factory floor layout of LWC.*

who do not have the tools to plane their logs request that LWC perform this and sub–sequently deliver the raw solid wood at the reception door. Otherwise LWC uses their own logs in stock. After the logs have been planed on the Planer they are taken directly to the dispatch door. The machine processing sequence of these components is shown graphically on the LWC factory floor layout in Figure 4.27.

4.4.12 *Contract* Spraying: Staining Top Coat

LWC possess a very efficient Top Coat Spray–booth and 0.43 % of all the manufactured components are contract work in the Top Coat Spray–booth in which top coats of components are stained. Components are stained when they are sprayed with a substance that allows the components to appear darker than they really are. Components that have to be stained in the Top Coat Spray–booth are delivered at the reception door and are taken directly to the Top Coat Spray–booth to be sprayed. When the components have dried completely they are taken to the

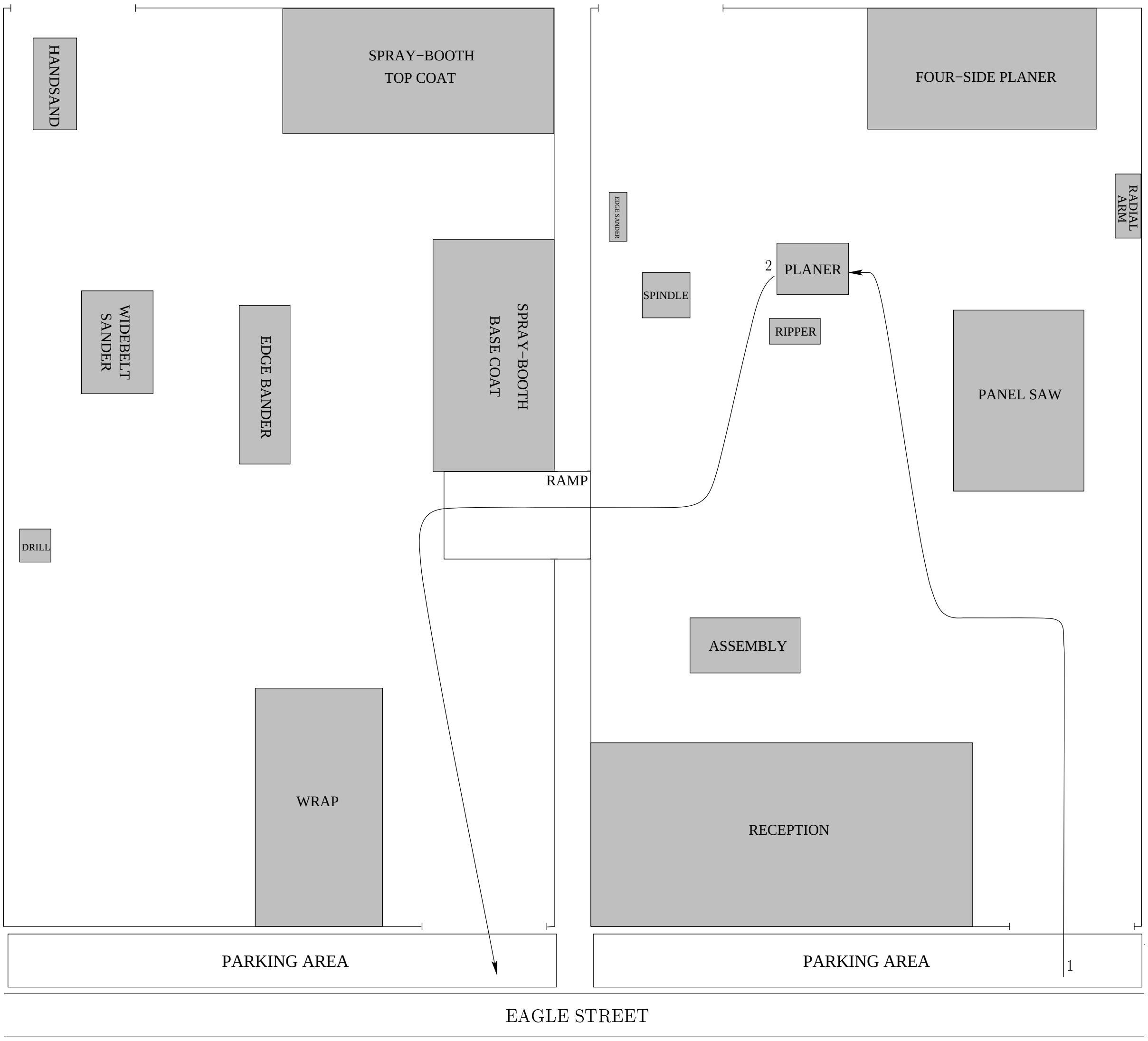


Figure 4.27: *The processing sequence of the contract planing all round of solid wooden logs, shown on the factory floor layout of LWC.*

dispatch door. The machine processing sequence of these components is shown graphically on the LWC factory floor layout in Figure 4.28.

4.4.13 *Contract* Spraying: Base Coat

A small percentage (0.21 %) of the total volume of manufactured components consists of contract work done in the Base Coat Spray–booth. Components are delivered at the reception door and taken directly to the Base Coat Spray–booth, where a base coat of varnish or other substance is sprayed onto the components, as requested by the client. If the components have dried they are taken directly to the dispatch door. The machine processing sequence of these components is shown graphically on the LWC factory floor layout in Figure 4.29.

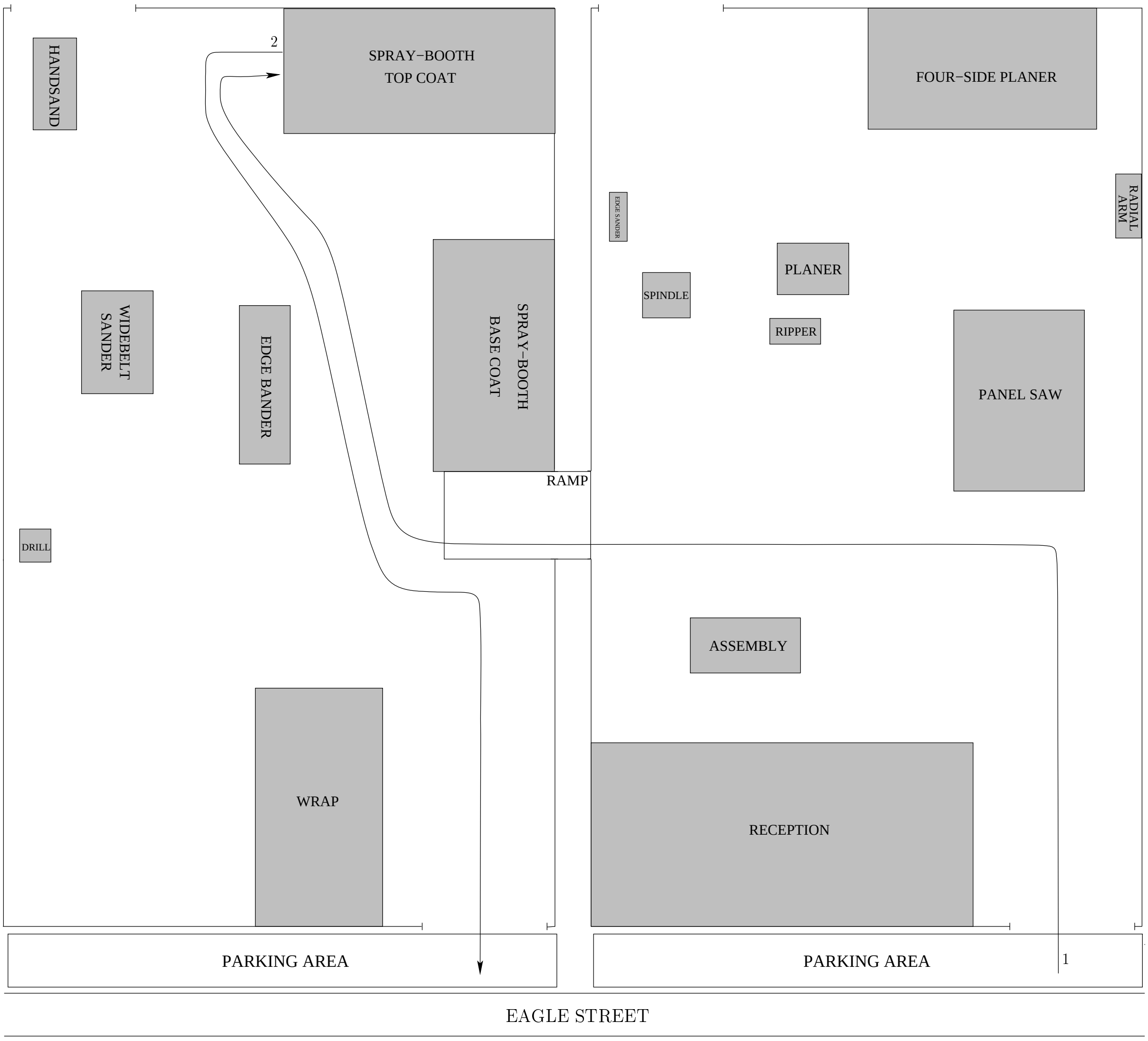


Figure 4.28: *The processing sequence of contract spraying or staining at the Top Coat Spray–booth, shown on the factory floor layout of LWC.*

4.4.14 Components on Edge (COE)

COE components are not manufactured very often (0.20 % of the total manufactured component volume). A picture of a COE component is shown in Figure 4.30(a) and in Figure 4.30(b) a sketch is shown of how a typical COE component is manufactured. The processing sequence of a typical COE component is given in Table 4.7 and is shown graphically on the LWC factory floor layout in Figure 4.31.

If an order for a COE component or a set of COE components is received a cutting list for the sizes and how the components should be cut out of the raw chipboard or super–wood panels is created by the management of LWC. The components are then cut according to these dimensions on the Panel Saw, after which they are taken directly to an external Veneer Factory where a veneer cover is attached to the components. When the components return to the factory after three days they are taken to the Panel Saw, where the excess veneer is trimmed before a veneer edge of 2 mm or 0.6 mm is attached on the Edge Bander. The veneer covers are veneer sanded

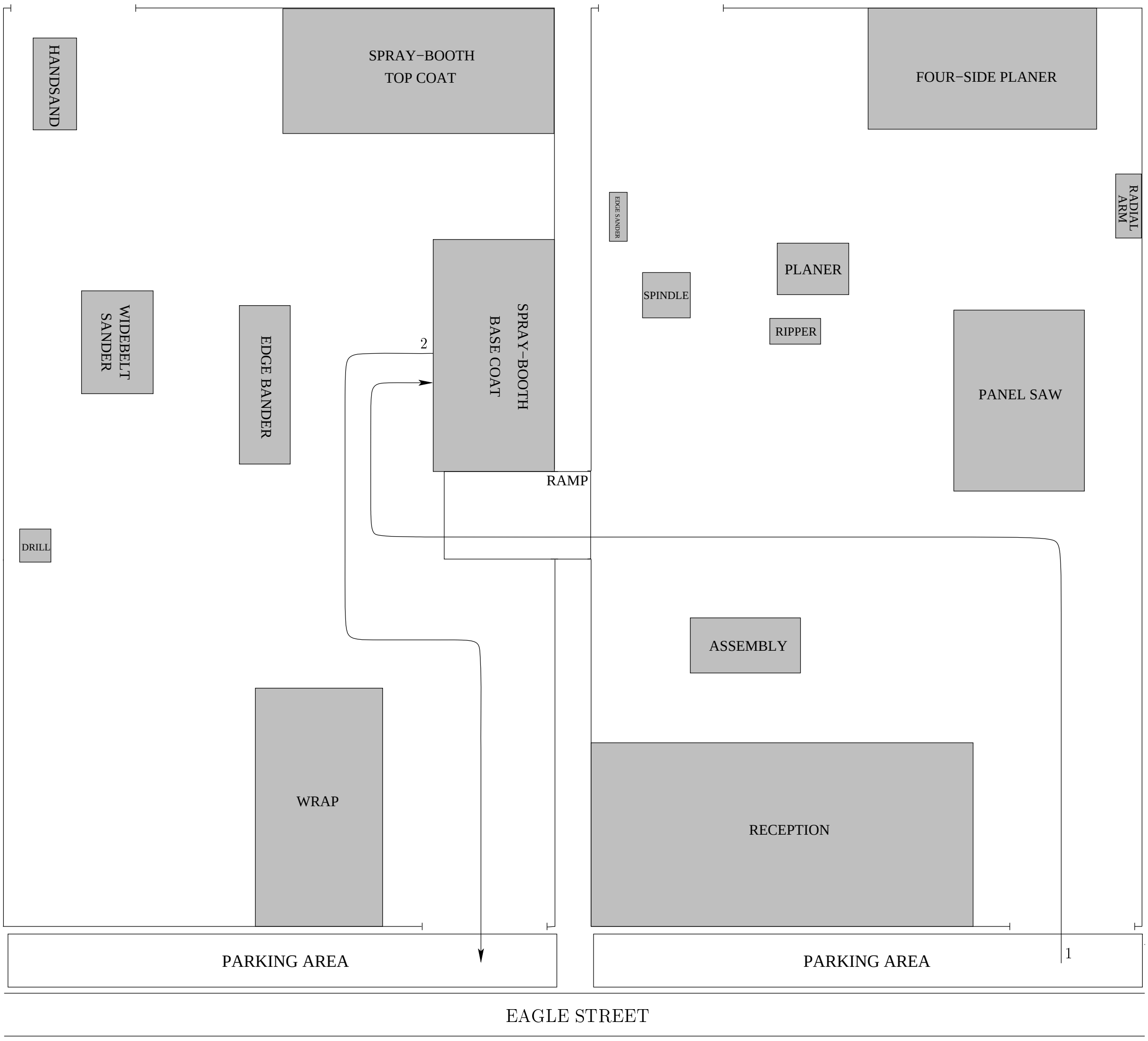
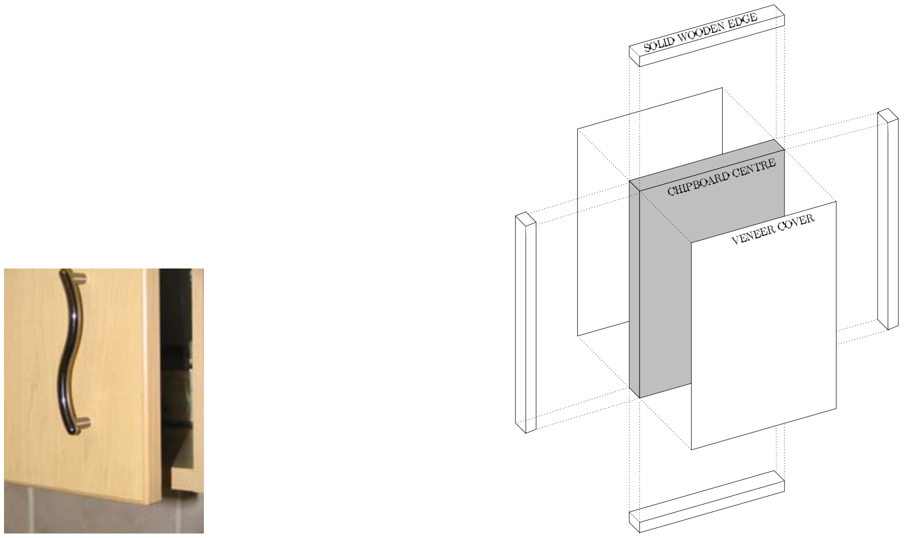


Figure 4.29: *The processing sequence of contract spraying at the Base Coat Spray–booth, shown on the factory floor layout of LWC.*

No	Machine/Centre	Task
1	Reception	Order is received and a cutting list constructed.
2	Panel Saw	Chipboard panels are cut to the correct sizes.
3	Veneer Factory	Veneer covers are attached to chipboard centres.
4	Panel Saw	Excess veneer is trimmed off.
5	Edge Bander	Veneer edges are attached to chipboard components.
6	Widebelt Sander	Veneer covers are veneer sanded.
7	Wrapping Unit	Components are wrapped.

Table 4.7: *The machine processing sequence for the COE component.*

on the Widebelt Sander before the components are wrapped at the Wrapping Unit and the client is notified that his/her order is ready for collection.



(a) *A picture of a COE component.* (b) *The construction of a COE component.*

Figure 4.30: *A picture of a typical COE component and its construction.*

4.5 The Situation at LWC Prior to this Study

Currently LWC uses a variety of computer packages in order to streamline its operations (such as Microsoft Word, Excel and Project Manager, as well as Autocad R14), but no computer packages are used as an aid for scheduling processing tasks on machines, or to evaluate or improve the layout of the facility.

LWC orders approximately thirty 2 750 mm × 1 830 mm × 16 mm raw chipboards each month and thirty 2 750 mm × 1 830 mm × 18 mm raw chipboards approximately every three months, whereas approximately thirty 2 750 mm × 1 830 mm × 16 mm supper–wood panels are ordered every second month. Solid wooden logs are ordered as shown in Table 4.8. Currently LWC is not experiencing any inventory management problems and there always seems to be sufficient stock on hand for the orders received.

Type of wood	**Times ordered per year**	**Approximate Sizes Ordered**
Oak	1	1 – 1.5 m^3
Cherry	4	1 – 1.5 m^3
Maple	4	1 – 1.5 m^3
Pink Beech	1	1 – 1.5 m^3
White Beech	1	1 – 1.5 m^3
Jarrah	4	1 – 1.5 m^3
African Mahogany	1	1 – 1.5 m^3

Table 4.8: *Sizes and quantities of solid wood that LWC orders per year.*

The clients of LWC are guaranteed that their orders will be completed 15 working days after the order is accepted. If an order is received and accepted after 12:00 on a particular day, the first day of processing will be the following working day. Clients of LWC have to provide a 50% deposit before processing of their order may commence. Due to this deposit, clients seldom

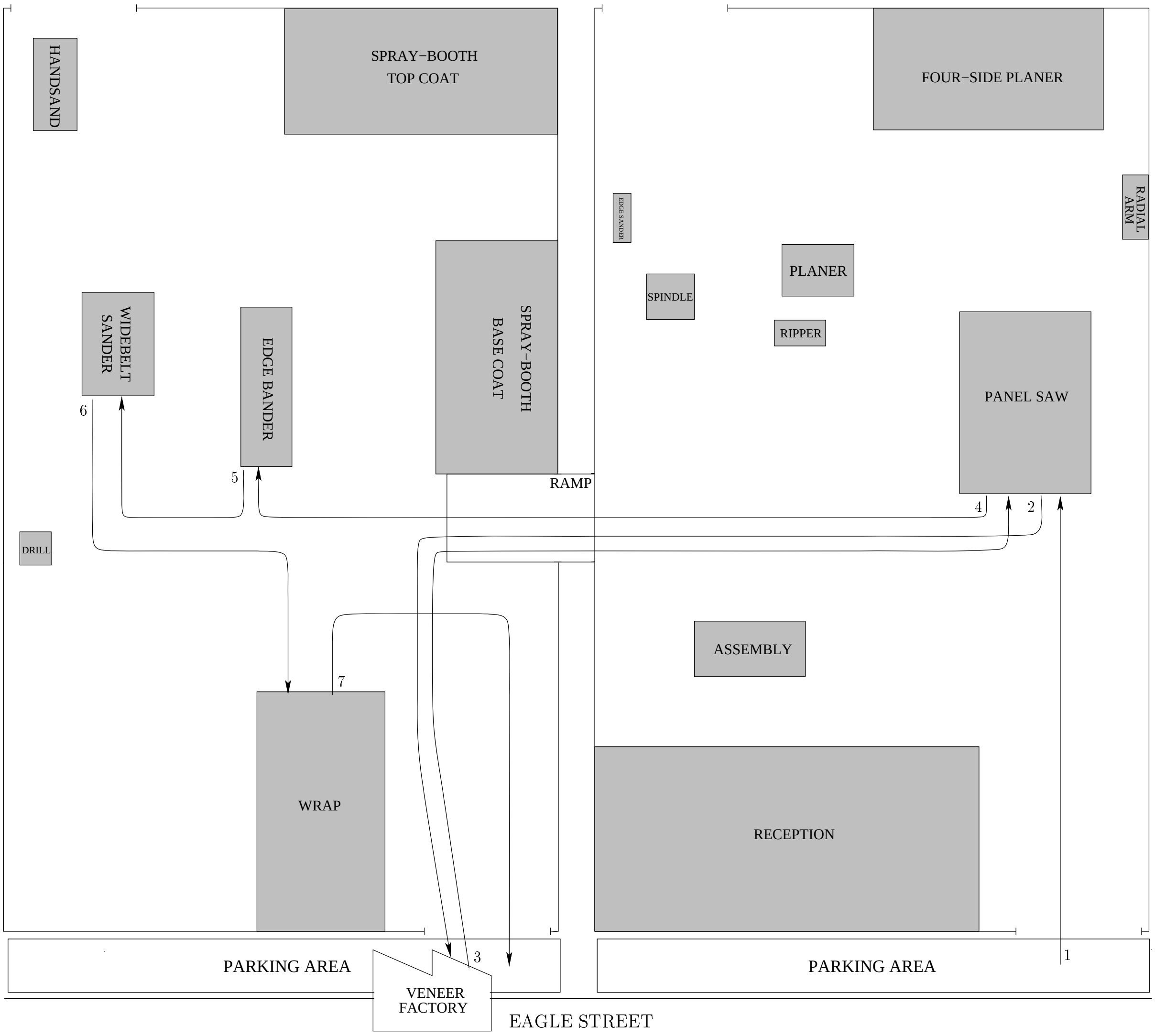


Figure 4.31: *The processing sequence of a typical COE component, shown on the factory floor layout of LWC.*

cancel their orders, but in rare cases when this does occur the processing tasks of the relevant orders are terminated immediately, or the order is completed to be sold to other clients.

Some clients are larger and are hence considered more important than other clients, therefore orders by these clients have to be satisfied at all costs. Their orders are deemed superior to all other orders currently processed by machines on the factory floor.

The scheduling of production tasks is performed manually with the aid of an adjusted Gantt chart on a large white board, as shown in Figure 4.32. When bottlenecks occur, the management adjusts the Gantt chart manually. When a particular order is completed the order is wiped from the white board. Every morning, before the commencement of work, the head worker of each department along with the management of LWC meet to discuss the processing schedule for that particular day. During each day problems with the schedule are also reported to the management of LWC.

The management of LWC has observed a large number of bottlenecks on the factory floor which

Figure 4.32: *The Gantt chart currently used for scheduling machine processes at LWC.*

have caused undesirable delays in deliveries. The main causes of the bottlenecks were perceived to be:

- the large variety of product types that add considerable complexity to the scheduling process,
- the large variety of product sizes, that adds considerable complexity to the scheduling process,
- single machines, which may perform multiple tasks with different setup times,
- machines which may only function under human supervision,
- unpredictable delays at machines (such as material that have to be collected for other jobs) and
- a limited number of workers specialized to work with specific machines.

The workers at LWC work vast amounts of overtime due to late orders, large contracts promised to be delivered within a short time and bottlenecks on the factory floor. Due to this overtime, workers often become exhausted and dissatisfied with their work environment.

4.6 Chapter Summary

The LWC management is faced with a large number of challenges concerning the factory floor layout and the scheduling of tasks at each machine. They manufacture a number of different products, each following a different machine processing sequence. In this chapter the products, objectives and main production processes at the LWC were discussed. The objective in this thesis is to obtain an ideal solution for the daily challenges faced by LWC management and to design a DSS, to aid in their decision making process.

Chapter 5

The Layout Problem at Loubser Wood Components

In this chapter the methodology discussed in §3.1 is applied to the specific layout problem of Loubser Wood Components (LWC), as described in §4.2. As mentioned in Chapter 4, LWC utilizes a process layout, because it manufactures a large variety of products, but a low volume of each product. This chapter opens with the application of a conventional approach to resolve the layout problem at LWC. This is followed, in §5.2.1, by the application of two exact, computer–aided approaches towards solving the layout problem at LWC. However, these approaches are shown to be impractical, in view of their worst case complexities. Finally, a heuristic approach is applied to the layout problem at LWC in §5.2.2, and the chapter closes in §5.3 with an appraisal and comparison of results of the different methods.

5.1 The Conventional Approach

The conventional approach towards solving layout problems was discussed in general in §3.1.1. The first step in applying the conventional approach is to determine the space required for each centre, which also includes working area, aisles and space for in–process inventory. Since each centre at the LWC plant consists of a small machine, the term *centre* will henceforth be exchanged in favor of *machine*. The space required for each machine at the LWC plant is presented in Table 5.1 and was determined by physically measuring the machines and workspace required by each machine, as well as through discussions with the management and workforce at LWC [131]. Throughout the remainder of this chapter individual machines will be referred to by their numbers indicated in Table 5.1.

The dimensions of the factory were described in detail in §4.2. The current layout at the plant is reprinted in Figure 5.1, to facilitate referencing.

LWC supplied the author with production data for the six months July 2002 to December 2002 (see attached CD). By taking into account all the different jobs processed by the factory during this time period and using the task sequence of each job, the flows of production materials between all pairs of machines (in m^2 per six month period) were approximated. To incorporate the fixed locations of the reception and dispatch doors, two dummy machines were added to the set of machines. These two dummy machines, called *Receive* and *Dispatch*, were numbered 0 and 16 respectively. The resulting from–to matrix for LWC is presented in Table 5.2.

No	**Machine**	**Length [mm]**	**Width [mm]**	**Area [m^2]**
1	Panel Saw	4 970	6 580	32.703
2	Radial Arm	4 700	820	3.854
3	Ripper	1 400	6 710	9.380
4	Planer	1 400	7 960	11.144
5	Four–side Planer	3 410	6 390	21.790
6	Spindle	3 115	1 300	4.0495
7	Edge Sander	1 320	550	0.726
8	Assembly Station	3 500	5 000	17.500
9	Base Coat Spray–booth	6 285	4 790	30.105
10	Top Coat Spray–booth	3 410	7 550	25.746
11	Edge Bander	7 385	4 430	32.716
12	Wrapping Unit	5 000	3 500	17.500
13	Drill	3 900	880	3.432
14	Widebelt Sander	8 820	1 930	17.023
15	Handsand Area	3 500	5 000	17.500

Table 5.1: *The spatial requirements for each machine on the LWC factory floor as on the 11th of December 2002. These spaces include working area, aisles and space for in–process inventory.*

From–to Matrix

	To																
From	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	0	9 651.50	0	0	130.68	0	0.20	0	0	169.50	95.19	531.13	0	0	11 775.99	0	0
1	0	0	0	0	0	963.55	318.12	0	5.14	20.10	0	667.75	0	0	995.68	71.46	7 184.37
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	716.88	0
3	0	0	0	0	0	0	6.25	0	0	0	0	0	0	0	716.88	0	0
4	0	0	0	6.25	0	0	0	0	0	0	0	2.93	0	0	6.01	0	115.50
5	0	0	0	716.88	0	0	0	0	0	0	0	0	0	0	246.67	0	0
6	0	564.79	0	0	0	0	0	0	0	0	0	0	0	0	0	0	44.48
7	0	0	0	0	0	0	0	0	0	0	71.46	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	246.67	963.55	30.74
9	0	0	0	0	0	0	0	0	25.60	0	626.18	0	0	0	1 133.46	318.12	733.41
10	0	0	0	0	0	0	0	0	0	0	0	11.25	1 204.92	246.67	2.51	0	707.60
11	0	9.88	0	0	0	0	38.03	0	0	0	0	0	0	0	1 202.60	0	682.78
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1 495.42
13	0	0	0	0	0	0	0	0	0	0	0	0	246.67	0	0	0	0
14	0	0	716.88	0	0	0	246.67	0	1 210.21	416.58	0	3.34	43.84	0	0	1 133.46	12 555.50
15	0	0	0	0	0	0	0	71.46	0	1 035.00	1 380.13	716.88	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5.2: *The from–to matrix of LWC, which indicates the flow of production material (in m^2) per six month period between the machine pairs, based on the six month period June 2002 – December 2002.*

The flow–chart corresponding to the from–to matrix in Table 5.2, is given in Table 5.3. Note that the flow–chart has a triangular form due to the fact that each entry in the flow–chart is the sum of the flows of production material in both directions between two machines.

When constructing the rel–chart corresponding to the flow–chart in Table 5.3, the first step is to assign the codes in Table 3.2 to specific flow intervals. The codes were assigned to the intervals as indicated in Table 5.4 and were used to construct the rel–chart in Table 5.5. The intervals were determined during a discussion with the management of LWC [131]. It is evident that it is unimportant (U) for two machines with no flow of production material between them to be located close together. Considering the large number of zeros in Table 5.3, most of the entries in the rel–chart are U. Figure 5.2 shows a frequency distribution of the remaining codes, A, E, I, O and X in the rel–chart.

The next step in the conventional method is to construct a graphical representation of the

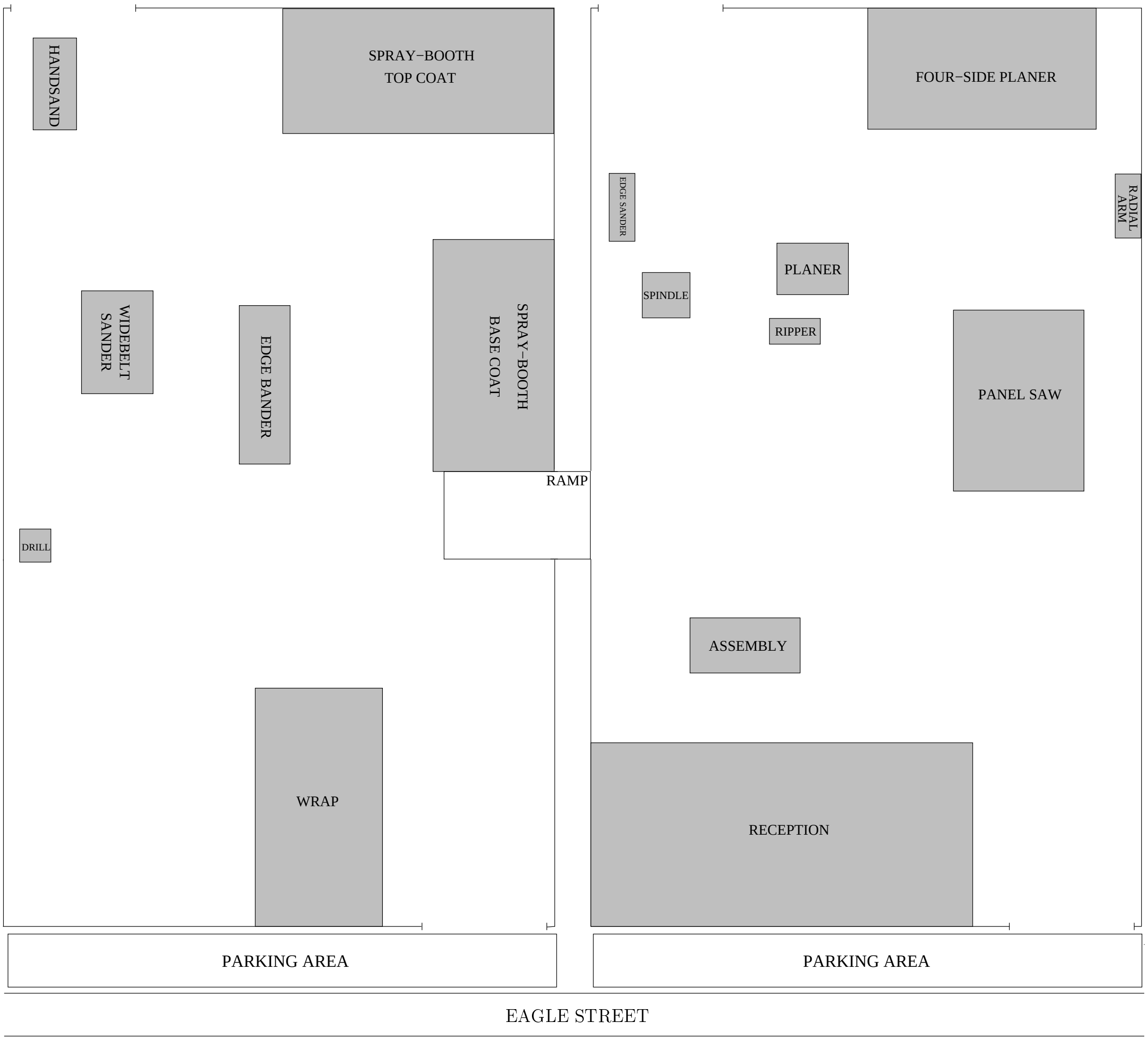


Figure 5.1: *The factory layout at the LWC plant, as on 17 October 2002.*

Flow–chart

	Machines																
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0		9 651.50	0	0	130.68	0	0.2	0	0	169.50	95.19	531.13	0	0	11 775.99	0	0
1			0	0	0	963.55	882.91	0	5.15	20.10	0	677.63	0	0	995.68	71.46	7 184.37
2				0	0	0	0	0	0	0	0	0	0	0	716.88	716.88	0
3					6.25	716.88	6.25	0	0	0	0	0	0	0	716.88	0	0
4						0	0	0	0	0	0	2.93	0	0	6.01	0	115.50
5							0	0	0	0	0	0	0	0	246.67	0	0
6								0	0	0	0	38.03	0	0	246.67	0	44.48
7									0	0	71.45	0	0	0	0	71.46	0
8										25.60	0	0	0	0	1 456.88	963.55	30.74
9											626.18	0	0	0	1 550.04	1 353.13	733.41
10												11.252	1 204.917	246.67	2.51	1 380.12	707.60
11													0	0	1 205.94	716.88	682.78
12														246.67	43.84	0	1 495.42
13															0	0	0
14																1 133.46	12 555.49
15																	0
16																	

Table 5.3: *The flow–chart of LWC, indicating the total flow (measured in* m^2 *per six month period) between machine pairs. The flow–chart corresponds to the from–to matrix in Table 5.2.*

Code	Priority	Interval	Value
A	Absolutely necessary	2 001 – 13 000	4
E	Especially important	1 001 – 2 000	3
I	Important	101 – 1 000	2
O	Ordinary	0 – 100	1
U	Unimportant	0	0
X	Undesirable		–1

Table 5.4: *The codes (reproduced from Table 3.2) assigned to intervals of applicable flows of production material [measured in* m^2 *per six month period] at LWC.*

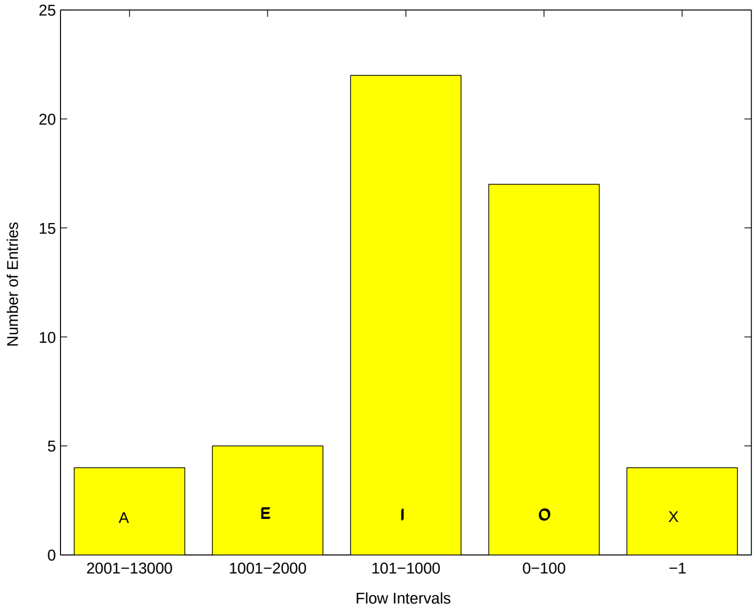


Figure 5.2: *A bar chart representation of the number of entries in the rel–chart in Table 5.5 within each interval associated with the labels, presented in Table 5.4.*

factory layout. This was achieved by first constructing the value chart corresponding to the rel–chart in Table 5.5, after which the measure of importance of each machine was determined. The resulting value chart corresponding to the rel–chart of LWC is shown in Table 5.6. The measure of importance of an individual machine was determined by adding all the values in the row and column of the specific machine in the value chart in Table 5.6.

A closeness graph, corresponding to the value chart, could now be drawn, as shown in Figure 5.3. The closeness graph was used to draw a feasible layout. It is not possible to construct a graph without line crossings[1], because of the size of and intersecting flow properties of the problem. The fact that the two dummy machines are fixed and on the boundary makes the problem more intricate.

The fourth step in the conventional method is to determine the effectiveness of the closeness graph by constructing an effectiveness evaluation chart. This may be achieved by dividing the factory floor into a grid of blocks of a certain size and by approximating the number of blocks necessary for each machine. The LWC factory floor was divided into block sizes of

---

[1] The closeness graph has $p = 17$ nodes and $q = 51$ edges; by Corollary 9.2 in Evans, *et al.* [71] the closeness graph cannot be a planar graph (have zero crossings), because $51 = q > 3p - 6 = 45$.

Rel–chart

	Machines																
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0		A	U	U	I	U	O	U	U	I	O	I	U	U	A	U	U
1			U	U	U	I	I	U	O	O	U	I	U	U	I	O	A
2				U	U	U	U	U	U	U	U	U	U	U	I	I	U
3					O	I	O	U	U	U	U	U	U	U	I	U	U
4						U	U	U	U	U	U	O	U	U	O	U	I
5							U	U	U	U	U	U	U	U	I	U	U
6								U	U	U	U	O	U	U	I	U	O
7									U	U	O	U	U	U	U	O	U
8										O	U	U	U	U	E	I	O
9											I	U	U	U	X	X	I
10												O	E	I	X	X	I
11													U	U	E	I	I
12														I	O	U	E
13															U	U	U
14																E	A
15																	U
16																	

Table 5.5: *The rel–chart corresponding to the flow–chart of LWC in Table 5.3.*

Value chart

	Machines																	
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	**Measure of importance**
0		4	0	0	2	0	1	0	0	2	1	2	0	0	4	0	0	16
1			0	0	0	2	2	0	1	1	0	2	0	0	2	1	4	19
2				0	0	0	0	0	0	0	0	0	0	0	2	2	0	4
3					1	2	1	0	0	0	0	0	0	0	2	0	0	6
4						0	0	0	0	0	0	1	0	0	1	0	2	7
5							0	0	0	0	0	0	0	0	2	0	0	6
6								0	0	0	0	1	0	0	2	0	1	8
7									0	0	1	0	0	0	0	1	0	2
8										1	0	0	0	0	3	2	0	7
9											2	0	0	0	-1	-1	2	6
10												1	3	2	-1	-1	2	10
11													0	0	3	2	2	14
12														2	1	0	3	9
13															0	0	0	4
14																3	4	**33**
15																	0	16
16																		20

Table 5.6: *The value chart of LWC corresponding to the rel–chart in Table 5.5.*

$2.272\,\text{m} \times 2.500\,\text{m} = 5.680\,\text{m}^2$. The approximate number of these blocks required for each machine in the factory is shown in Table 5.7. Next, a feasible layout for the closeness graph in Figure 5.3 was constructed. The effectiveness evaluation chart of this feasible layout, given in Figure 5.4, is shown in Table 5.8. The individual entries of the effectiveness evaluation chart consist of the values in the value chart with the same indices, multiplied by the rectilinear distance (measured in blocks) between the machine in the row and the machine in the column, as seen in Figure 5.4. The layout in Figure 5.4 has an effectiveness measure of 215, whereas the effectiveness measure of the current layout at LWC is 557, which gives an improvement of 342 measurement units, or 61.40%.

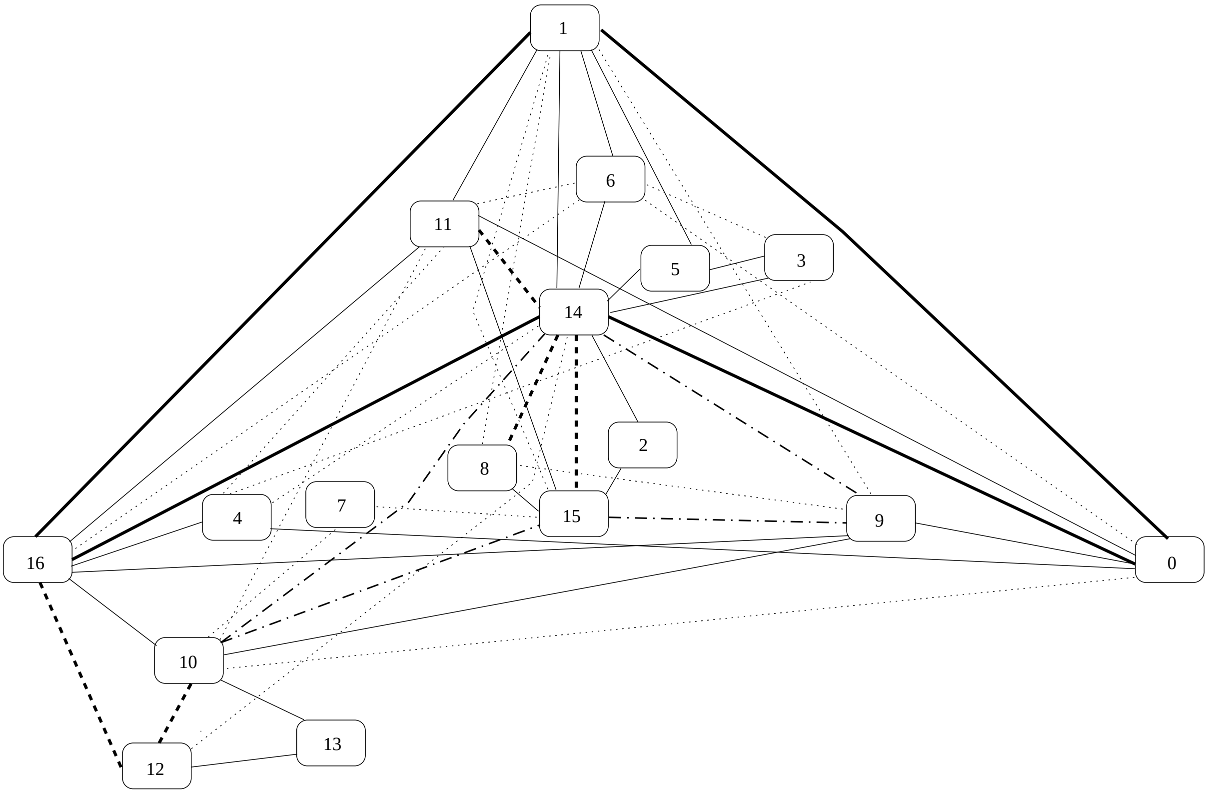


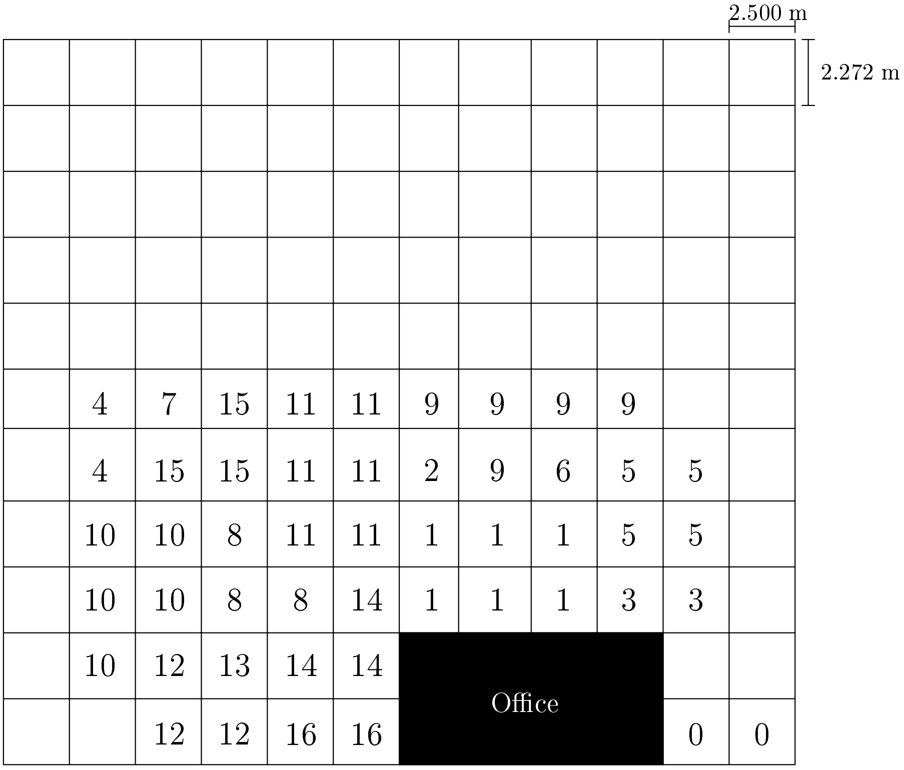
Figure 5.3: *A closeness graph of the LWC plant layout corresponding to the value chart in Table 5.6. Thick solid lines represent four–relationships between machines, thick dotted lines represent three–relationships, thin solid lines represent two–relationships and thin dotted lines represent one–relationships between machines. Dash–dotted lines represent minus one–relationships.*

The concluding step is to construct a two dimensional or three dimensional template on which manual changes may be affected in order to arrive at a final template. The template constructed from Figure 5.4 may be seen in Figure 5.5, which has an effectiveness measure of 298 and therefore translates to an improvement of 46.49% from the layout observed at 17 October 2002 [130]. It is important to note that the machines have their normal sizes and are closer to the walls with more space between the machines. The fact that the factory consists of two floors which are connected by means of a ramp, as described in §4.1, complicated the drawing considerably and decreased the effectiveness of the layout. Due to the fact that this method aims to pack all the machines as tightly as possible, the Edgebander and Radial Arm were posisioned in front of the ramp, as may be seen in Figure 5.5. The last step was therefore to make manual changes to the layout (for example, moving machines away from positions which should not be occupied by machines, like the areas in front of the doors and ramp).

Considering the layout in Figure 5.5, one may note that the Widebelt Sander was originally positioned close to the Base Coat Spray–booth. The managers of LWC mentioned that they would prefer all sanders to be away from the spray–booths, because the sanders produce dust which may land on newly sprayed items, decreasing the quality of the final product. It was therefore decided to move the Widebelt–sander and Handsand area further away from the spray–booths. All the machines were also moved closer to the walls to ensure easy and comfortable movement between the machines, as shown in Figure 5.6 (which has an effectiveness measure of 320 resulting in an improvement of 42.54% from the current layout presented in Figure 5.1).

No	Machine	Blocks
0	Receive	2
1	Panel Saw	6
2	Radial Arm	1
3	Ripper	2
4	Planer	2
5	Four–side Planer	4
6	Spindle	1
7	Edge Sander	1
8	Assembly Station	3
9	Spray–booth Base Coat	5
10	Spray–booth Top Coat	5
11	Edge Bander	6
12	Wrapping Unit	3
13	Drill	1
14	Widebelt Sander	3
15	Handsand Area	3
16	Dispatch	2

Table 5.7: *The number of blocks of size* 5.680 m^2 *required for each machine in the grid layout at LWC.*



	4	7	15	11	11	9	9	9	9		
	4	15	15	11	11	2	9	6	5	5	
	10	10	8	11	11	1	1	1	5	5	
	10	10	8	8	14	1	1	1	3	3	
	10	12	13	14	14	Office					
		12	12	16	16					0	0

Figure 5.4: *A feasible layout for the factory floor at LWC, corresponding to the closeness graph in Figure 5.3.*

One of the disadvantages of this method is that it was primarily designed to be used with single floor facility problems, and not for the special cases when facilities consist of more than one

Effectiveness Evaluation Chart

	Machines																	
No	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total
0		*4×3*	*0*	*0*	*2×12*	*0*	*1×5*	*0*	*0*	*2×5*	*1×9*	*2×7*	*0*	*0*	*4×6*	*0*	*0*	98
1			*0*	*0*	*0*	*2×0*	*2×0*	*0*	*1×1*	*1×0*	*0*	*2×0*	*0*	*0*	*2×0*	*1×3*	*4×2*	12
2				*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*2×2*	*2×2*	*0*	4
3					*1×9*	*2×0*	*1×2*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*2×3*	*0*	*0*	17
4						*0*	*0*	*0*	*0*	*0*	*0*	*1×2*	*0*	*0*	*1×5*	*0*	*2×6*	19
5							*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*2×4*	*0*	*0*	8
6								*0*	*0*	*0*	*0*	*1×2*	*0*	*0*	*2×4*	*0*	*1×6*	16
7									*0*	*0*	*1×1*	*0*	*0*	*0*	*0*	*1×0*	*0*	1
8										*1×4*	*0*	*0*	*0*	*0*	*3×0*	*2×0*	*0*	4
9											*2×5*	*0*	*0*	*0*	*-1×3*	*-1×2*	*2×5*	15
10												*1×2*	*3×0*	*2×1*	*-1×2*	*-1×0*	*2×3*	7
11													*0*	*0*	*3×0*	*2×0*	*2×2*	4
12														*2×0*	*1×1*	*0*	*3×0*	1
13															*0*	*0*	*0*	0
14																*3×3*	*4×0*	9
15																	*0*	0
16																		0
	Effectiveness evaluation measure																	215

Table 5.8: *The effectiveness evaluation chart of the feasible layout for LWC, given in Figure 5.4.*

floor, as is the case with LWC. Another disadvantage is that the closeness graph requires manual construction. Hence, if the factory management wishes to implement this method and requires frequent redesigns of their facility, this graph should be redrawn by the manager of the facility with every new design. For more than 10 machines it is a challenge to construct a graph that results in a good effectiveness measure. The more experienced user of this method will typically produce a better layout than an in–experienced user. Furthermore, a specific user may even produce two different layouts for the same problem on two different days. The conventional technique may therefore be viewed as a very user–dependent or inconsistent method. Hence the need arises to rather use a more analytical modelling process.

5.2 Computer–Aided Approaches

A number of exact and heuristic methods that have traditionally been used to solve general layout problems were discussed in §3.1.2. In this section these methods are applied to the LWC factory floor layout.

5.2.1 Exact Methods

In §3.1.2.1 two exact methods were discussed (the mathematical programming model with a discrete layout and the mathematical programming model with a continuous layout). Application of both these models were attempted with respect to the factory floor layout of LWC.

(i) *Mathematical Programming Model with a Discrete Layout*
Two mathematical programming models capable of solving the discrete layout problem were presented in §3.1.2.1. These were the quadratic assignment problem (QAP) and the quadratic set–covering approach suggested by Bazaraa [21]. The QAP approach was designed primarily for layout problems in which all machines have the same size. However, the machines at the LWC factory have varying sizes and therefore it was decided

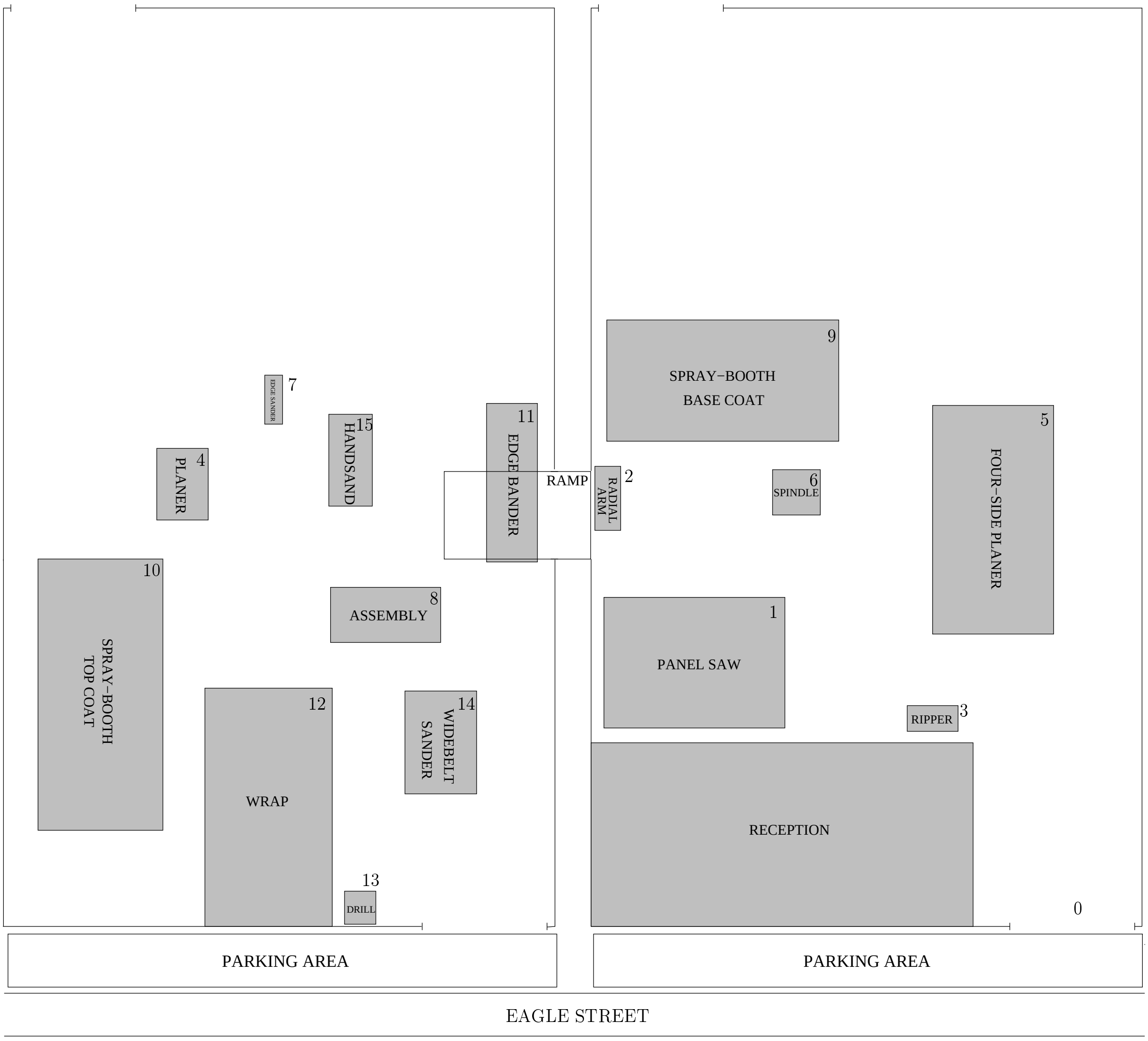


Figure 5.5: *Template of the factory floor layout of LWC, corresponding to the feasible layout in Figure 5.4.*

that it would be impossible to apply the QAP approach to their layout problem, without simplifying the problem to an unrealistic representation of their situation. Therefore only the quadratic set–covering approach, which incorporates different machine sizes, was applied to the LWC layout problem. This method reduces the number of candidate locations for each machine to the set of feasible locations for that specific machine. Therefore the number of location combinations for the layout is smaller.

Before the quadratic set–covering approach could be applied to the LWC factory floor layout problem, the sets of candidate locations $I(i)$ for each of the machines $i = 1, 2, \ldots, 15$ had to be determined. Bazaraa divided the floorspace into blocks of equal size in order to determine the grid–points which form the candidate locations. The LWC factory floor was therefore divided into 12 blocks along the horizontal axis and 11 blocks along the vertical axis so as to obtain approximately square blocks, as utilized previously in the conventional approach. However, there were only 92 available locations for the placement of machines, because of the fact that the LWC factory consists of 2 factory floors connected by means

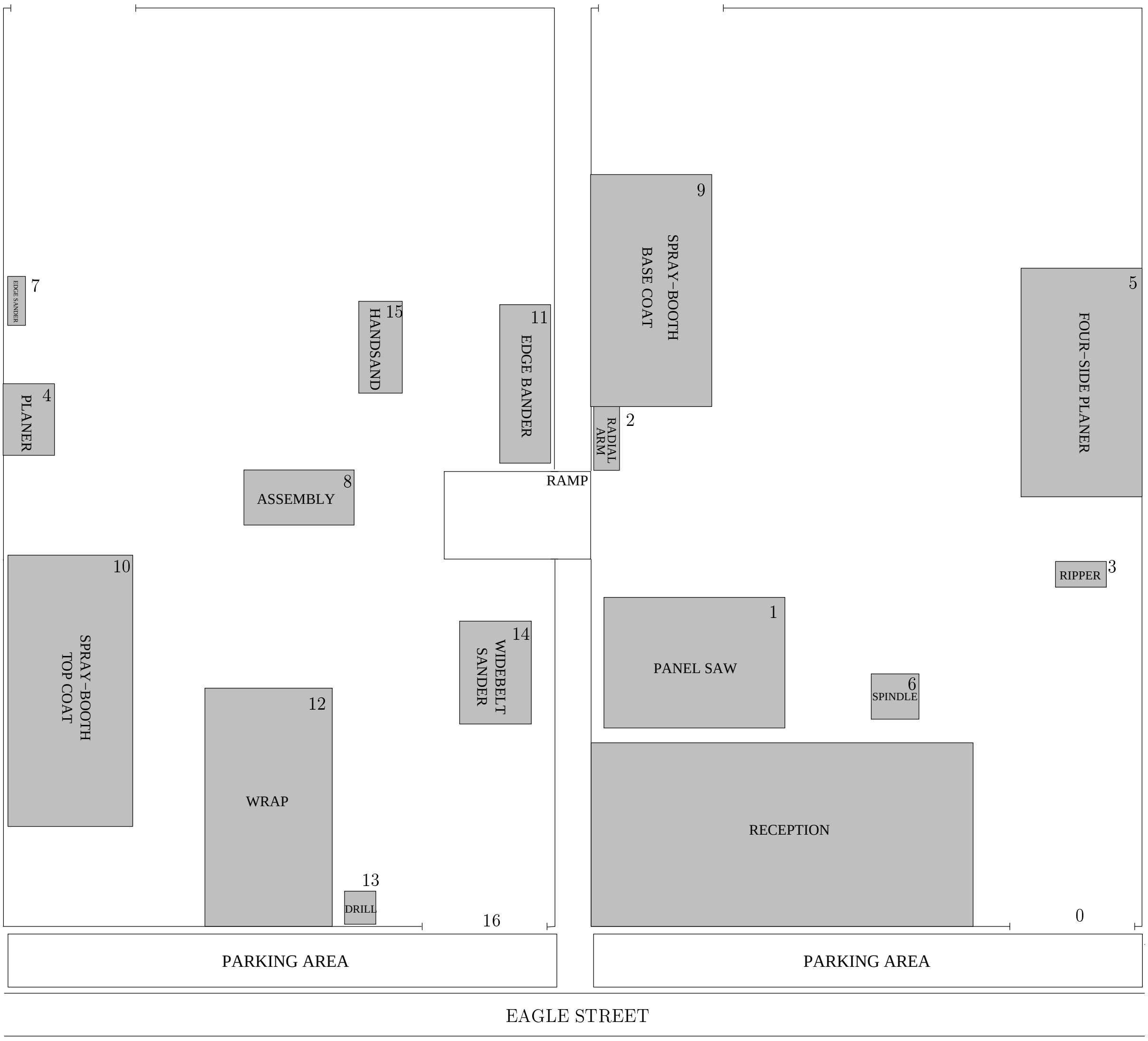


Figure 5.6: *The final layout for LWC, after manual changes have been made to the layout in Figure 5.5.*

of a ramp and because of a 5 m × 10 m office space, which is a permanent structure (see Figure 5.7).

One of the draw–backs of the set–covering approach is that one has to determine the candidate locations of each machine in advance. Each machine in the factory occupies a certain number of squares when positioned with its central point at a location (grid–point). Before the candidate locations for each machine could be determined the approximate number of blocks occupied by each machine had to be calculated. The number of blocks, in the vertical (horizontal) direction, of a specific machine was determined by dividing the machine length (width) dimension by the vertical (horizontal) dimension of a block and rounding up. The vertical dimension of the blocks was taken as 2.272 m and the horizontal dimension as 2.500 m. Note that a machine is positioned with its centre at a grid–point and therefore the number of blocks in the vertical and horizontal directions are both even. The number of blocks required by each machine was therefore rounded upward to the nearest even number. The number of blocks in the vertical and horizontal directions, and

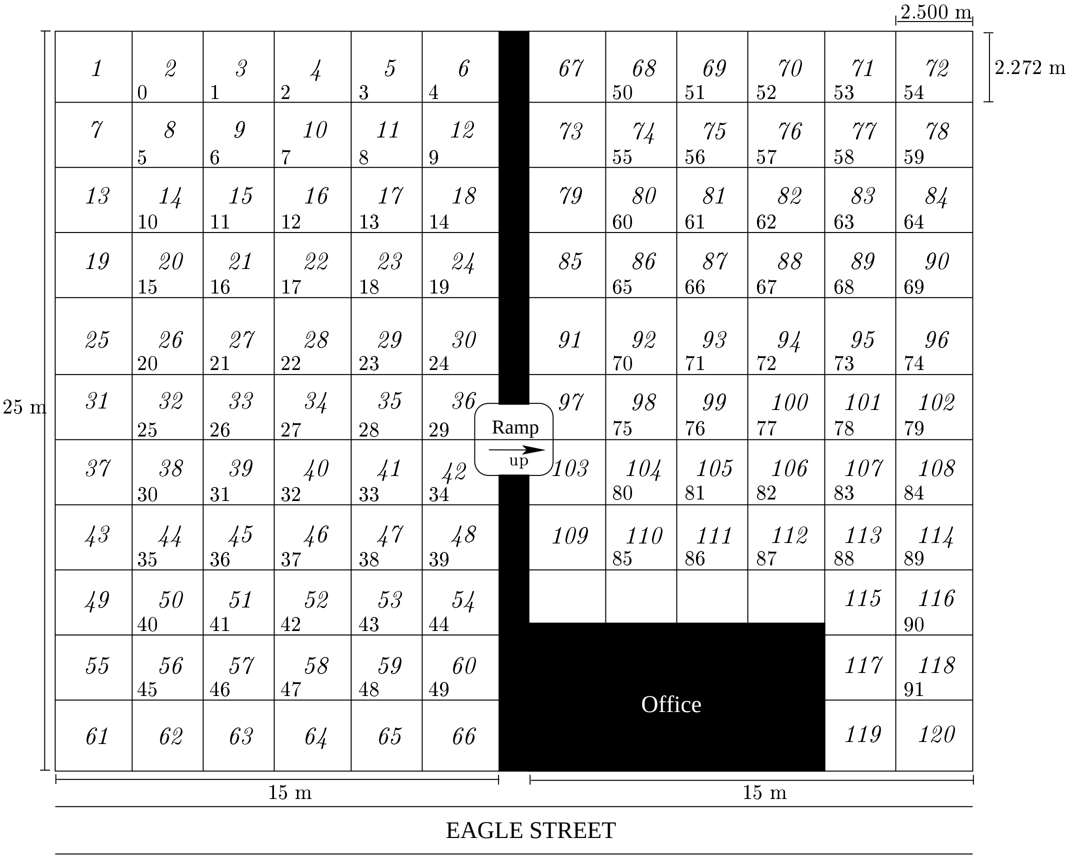


Figure 5.7: *The grid–points or candidate locations for machines at LWC, when there are 12 blocks in the horizontal direction and* 11 *in the vertical direction.*

the total number of blocks occupied by each machine are shown in Table 5.9. After the number of blocks occupied by each machine was calculated, the specific set, $\mathcal{S}_i(k)$ (as seen in Appendix C), of blocks occupied by machine i, when placed at a specific grid–point k, was determined. The blocks were numbered as indicated in Figure 5.7, where the numbers in the bottom lefthand corners of the blocks indicate the grid–point numbers and the italicized numbers in the centres of the blocks denote the block numbers.

There are other parameters that also had to be determined in advance. They are

$$\begin{aligned} d_{kh} &= \text{the rectilinear distance from the } k\text{–th to the } h\text{–th grid–points,} \\ f_{ij} &= \text{flow of production material between machines } i \text{ and } j, \\ F_{ik} &= \text{fixed cost of placing machine } i \text{ at location } k, \\ a_{ikt} &= \begin{cases} 1, & \text{if block } t \in \mathcal{S}_i(k) \\ 0, & \text{otherwise.} \end{cases} \end{aligned}$$

The a_{ikt} values for $i = 1, 2, \ldots, 15$, $k = 0, 1, \ldots, 91$ and $t = 1, 2, \ldots, 120$ followed directly from determining the sets $\mathcal{S}_i(k)$.

To incorporate the fact that the LWC factory floor consists of 2 floors on different heights, connected by means of a ramp with an incline, the rectilinear distance was used for grid–points which are on the same floor. In the case where the grid–points are on different floors the distance between two locations, d_{kh}, was determined as the sum of the rectilinear distances between each point and the ramp added to one of two weights associated with

No	Machine	Length [mm]	Width [mm]	Vertical Blocks	Horizontal Blocks	Total Blocks
1	Panel Saw	4 970	6 580	2	2	4
2	Radial Arm	4 700	820	2	2	4
3	Ripper	1 400	6 710	2	2	4
4	Planer	1 400	7 960	2	4	8
5	Four–side Planer	3 410	6 390	2	2	4
6	Spindle	3 115	1 300	2	2	4
7	Edge Sander	1 320	550	2	2	4
8	Assembly Station	3 500	5 000	2	2	4
9	Base Coat Spray–booth	6 285	4 790	2	2	4
10	Top Coat Spray–booth	3 410	7 550	2	4	8
11	Edge Bander	7 385	4 430	4	2	8
12	Wrapping Unit	5 000	3 500	2	2	4
13	Drill	3 900	880	2	2	4
14	Widebelt Sander	8 820	1 930	4	2	8
15	Handsand Area	3 500	5 000	2	2	4

Table 5.9: *The number of blocks occupied by each machine when machines are positioned with their central points at grid–points.*

the ramp, namely R_u when transporting material up the ramp and R_d when transporting material down the ramp. The value of R_u was taken to be 0, 100 m, 500 m and 1 000 m, therefore solving 4 separate problems, whereas the value of R_d was taken to be a factor of the cost of going up the ramp. This factor was taken to be $0, 1, 1.5$ and 2, and therefore solving a total of 16 different problems. These weights associated with the ramp were incorporated, because transporting material up the ramp was observed to be very expensive, due to a large number of workers needed to push a trolley containing production material up the ramp, and in doing so had to abandon their other duties. To the contrary, transporting material down the ramp was even more expensive, because the trolley built up momentum when pushed down the ramp and had to be slowed down by a larger number of workers at the bottom end of the ramp. The fact that the up and down weights associated with the ramp were different led to the distance matrix being asymmetric. As an example, Figure 5.8 shows a graphical representation of the distance measure between the 42–nd and 57–th grid–points when they are not on the same floor. Since the distance d_{kh} was measured in metres, it was necessary to measure the weights R_u and R_d in metres as well. It was difficult to convert the effort of workers, the time it took and the losses due to abandoned posts when moving material up and down the ramp, to metre units. Therefore a variable $\rho \in [0, 1]$, which represented an importance measure of the ramp weight, was incorporated, which could be varied during sensitivity analyses. The distance between the k–th and h–th grid–points, with k on the lower factory floor and h on the upper floor, was therefore

$$d_{kh} = \rho(d_{k,ramp} + d_{ramp,h}) + (1 - \rho)R_u,$$

whilst for the case where grid–point k was on the upper floor and grid–point h on the lower floor, the distance was taken as

$$d_{kh} = \rho(d_{k,ramp} + d_{ramp,h}) + (1 - \rho)R_d.$$

The next variable calculated was the flow of production material f_{ij} [in m^2 per time unit]

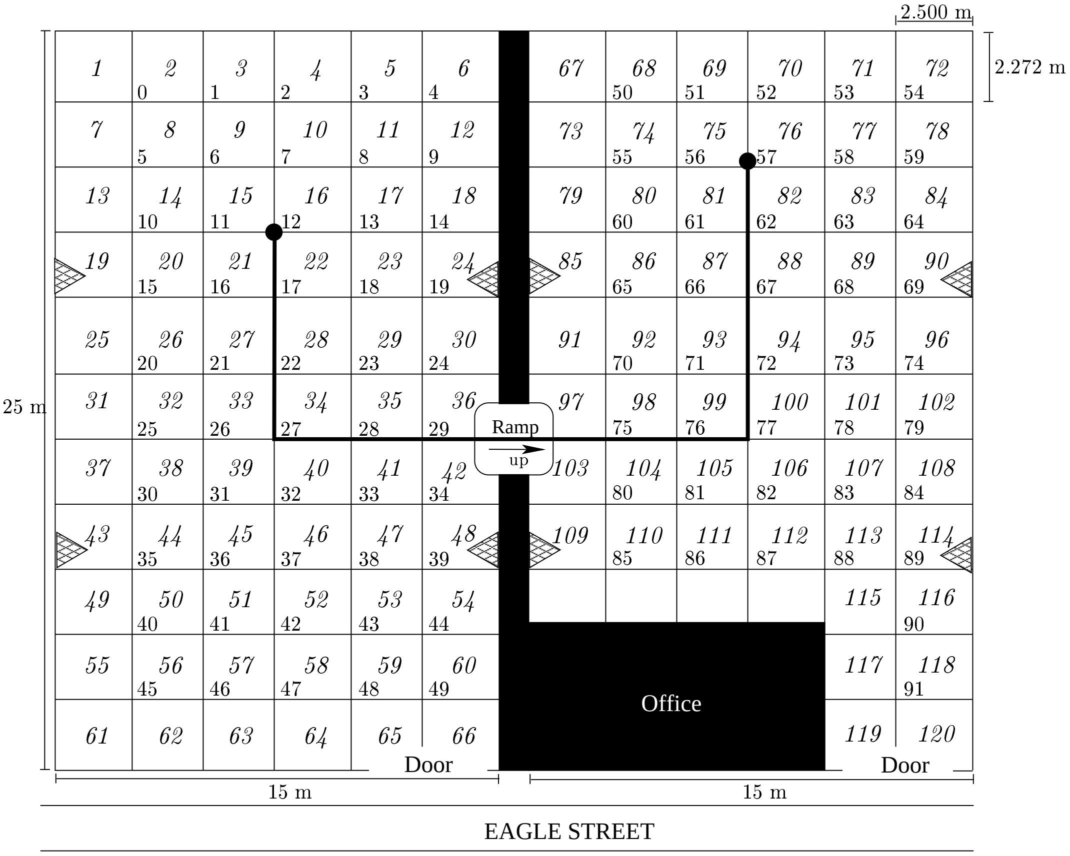


Figure 5.8: *A graphical representation of the distance measure between grid–point* 42 *and grid–point* 57*, which are on separate floors in the LWC factory.*

between machines i and j for $i, j \in \{1, 2, \ldots, 15\}$. The time unit was taken to be six months. The flow was calculated in exactly the same way as discussed in §5.1 and is shown in Table 5.2.

Installation of machines in factories usually incurs a high cost. This was discussed with the management of LWC and they approximated the cost of relocating each machine [131]. Due to the the constraint that some machines require 3–phase electrical cables, the relocation cost of some of the machines depended on the distance from the power supply. The cost of a 3–phase cable is approximately R200 per metre. The approximated relocation cost for each machine, as indicated by the management of LWC, is shown in Table 5.10.

As mentioned in Chapter 3 the objective of the model is to minimize material–handling cost as well as the relocation cost of machines. Let

$$X_{ik} = \begin{cases} 1, & \text{if machine } i \text{ is placed at location } k \\ 0, & \text{otherwise.} \end{cases}$$

Then the model has the objective of minimizing

$$Z = \theta \left(\sum_{i=1}^{15} \sum_{j=1}^{15} \sum_{k=1}^{I(i)} \sum_{h=1}^{I(j)} f_{ij} X_{ik} X_{jh} d_{kh} \right) + (1 - \theta) \left(\sum_{i=1}^{15} \sum_{k=1}^{I(i)} F_{ik} X_{ik} \right), \tag{5.1}$$

where $I(i)$ is the set of candidate locations for machine i, if the points of raw material reception and of product dispatch are ignored. $\theta \in [0, 1]$ is a scaling variable introduced

No	Machine	Cost [Rands]
1	Panel Saw	500 + 200 per metre
2	Radial Arm	0
3	Ripper	500 + 200 per metre
4	Planer	500 + 200 per metre
5	Four–side Planer	500 + 200 per metre
6	Spindle	500 + 200 per metre
7	Edge Sander	0
8	Assembly Station	0
9	Base Coat Spray–booth	25 000
10	Top Coat Spray–booth	25 000
11	Edge Bander	500 + 200 per metre
12	Wrapping Unit	500 + 200 per metre
13	Drill	0
14	Widebelt Sander	500 + 200 per metre
15	Handsand Area	0

Table 5.10: *The relocation cost for machines, estimated by the managers of LWC [131]. Cost given per metre are to be measured from the power supplies which are located as indicated by the triangular symbols in Figure 5.8.*

to compensate for the different units of the two terms in the objective function. In §3.1.2.1(i) a general discussion was presented on how this objective function was obtained (see (3.8)). However, the flows of production material from the reception area to the 15 machines and from the 15 machines to the dispatch workstation are very large and may not be ignored. As already mentioned, two dummy machines, machine ‘0’ representing reception and machine ‘16’ representing dispatch, were included into the set of machines. These machines were considered stationary and machine ‘0’ was positioned at the last grid–point in the right–hand side of the LWC factory floor (grid–point 91), and machine ‘16’ at the last grid–point on the lower level of the LWC factory floor (grid–point 49). The flow, f_{0j} for all $j = 1, \ldots, 15$ and $f_{i\,16}$ for all $i = 1, \ldots, 15$ had to be incorporated into the objective function. The flows between all the machines and the dummy machines are shown in Table 5.11.

Flow

	To																
From	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	0	9 651.50	0	0	130.68	0	0.20	0	0	169.50	95.19	531.13	0	0	11 775.99	0	0
1	0	0	0	0	0	963.55	318.12	0	5.14	20.10	0	667.75	0	0	995.68	71.46	7 184.37
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	716.88	0
3	0	0	0	0	0	0	6.25	0	0	0	0	0	0	0	716.88	0	0
4	0	0	0	6.25	0	0	0	0	0	0	0	2.93	0	0	6.01	0	115.50
5	0	0	0	716.88	0	0	0	0	0	0	0	0	0	0	246.67	0	0
6	0	564.79	0	0	0	0	0	0	0	0	0	0	0	0	0	0	44.48
7	0	0	0	0	0	0	0	0	0	0	71.46	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	246.67	963.55	30.74
9	0	0	0	0	0	0	0	0	25.60	0	626.18	0	0	0	1 133.46	318.12	733.41
10	0	0	0	0	0	0	0	0	0	0	0	11.25	1 204.92	246.67	2.51	0	707.60
11	0	9.88	0	0	0	0	38.03	0	0	0	0	0	0	0	1 202.60	0	682.78
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1 495.42
13	0	0	0	0	0	0	0	0	0	0	0	0	246.67	0	0	0	0
14	0	0	716.88	0	0	0	246.67	0	1 210.21	416.58	0	3.34	43.84	0	0	1 133.46	12 555.50
15	0	0	0	0	0	0	0	71.46	0	1 035.00	1 380.13	716.88	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5.11: *The from–to matrix of LWC, which indicates the flow of production material (measured in m^2 per six month period) between the machine pairs.*

The new objective was therefore to minimize

$$\begin{aligned} Z = \theta \Bigg(& \sum_{i=1}^{15}\sum_{j=1}^{15}\sum_{k=1}^{I(i)}\sum_{h=1}^{I(j)} f_{ij}X_{ik}X_{jh}d_{kh} + \sum_{j=1}^{15}\sum_{k=1}^{I(j)} f_{0j}X_{jk}d_{91,\,k} \\ & + \sum_{i=1}^{15}\sum_{k=1}^{I(i)} f_{i\,16}X_{ik}d_{k,\,49} \Bigg) + (1-\theta)\left(\sum_{i=1}^{15}\sum_{k=1}^{I(i)} F_{ik}X_{ik}\right) \end{aligned} \qquad (5.2)$$

subject to

$$\left.\begin{array}{rl} \sum_{i=1}^{15} X_{ik} \leq 1, & k = 0, 1, \ldots, 91, \\ \sum_{k=1}^{I(i)} X_{ik} = 1, & i = 1, 2, \ldots, 15, \\ \sum_{i=1}^{15}\sum_{k=1}^{I(i)} a_{ikt}X_{ik} \leq 1, & \text{for each block } t, \\ X_{ik} \in \{0, 1\}, & k = 1, 2, \ldots, I(i) \text{ and } i = 1, 2, \ldots, 15. \end{array}\right\} \qquad (5.3)$$

The model (5.2)–(5.3) consists of 1 380 integral variables, and 226 non–trivial constraints. Since traditional methods used to solve integer programs, such as the well–known branch–and–bound method, tend to have an execution time which is exponential in the number of variables and constraints, the model could not be solved within a realistic timespan and there was no software available that could solve a problem of this magnitude, resulting in an abandonment of the set–covering approach of Bazaraa [21] towards resolving the layout problem at LWC. An attempt was made to solve the model with the aid of the **Lingo 8.0** program which makes provision for only 300 variables and 150 constraints.

(ii) *Mathematical Programming Model with a Continuous Layout*
The mathematical programming model with a continuous layout, due to Patsiatzis & Papageorgiou [150], incorporates the possibility of multiple–floor layout designs and was discussed in general in §3.1.2.1(ii). The LWC factory consists of two floors, connected by a 3 metre ramp. The difference in height between the floors, is one metre. In contrast to the discrete layout approach, this model also allows machines to rotate through an angle of 90°, and therefore the machines in the final layout do not always have the same orientation as in the current layout. In this model ℓ_i $(i = 1, \ldots, 15)$ represents the dimension of machine i along the horizontal axis, whilst w_i $(i = 1, \ldots, 15)$ represents the dimension of machine i along the vertical axis, depending on the machine orientation. However, the fixed physical dimensions α_i and β_i $(i = 1, \ldots, 15)$ of each machine are shown in Table 5.12.

Two sets of constraints were introduced to incorporate the orientation O_i of machine i,

$$\ell_i = \alpha_i O_i + \beta_i(1 - O_i), \quad i = 1, \ldots, 15, \quad \text{and} \qquad (5.4)$$

$$w_i = \alpha_i + \beta_i - \ell_i, \quad i = 1, \ldots, 15, \qquad (5.5)$$

where

$$O_i = \begin{cases} 1, & \text{if } \alpha_i\text{, the length of machine } i\text{, is parallel to the horisontal axis,} \\ 0, & \text{otherwise.} \end{cases}$$

The flows of production material between machines $i, j \in \{1, \ldots, 15\}$ are indicated by the parameters C_{ij}^{c} in this model. The costs of transporting production materials vertically between machines (*i.e.*, between floors) are incorporated in the parameters C_{ij}^{v}. In the case of LWC, the machines placed on the same floor all occupied the same level and hence no vertical costs were incurred, but if machines were to be placed on different floors

No	**Machine**	α_i [mm]	β_i [mm]
1	Panel Saw	4 970	6 580
2	Radial Arm	4 700	820
3	Ripper	1 400	6 710
4	Planer	1 400	7 960
5	Four–side Planer	3 410	6 390
6	Spindle	3 115	1 300
7	Edge Sander	1 320	550
8	Assembly Station	3 500	5 000
9	Base Coat Spray–booth	6 285	4 790
10	Top Coat Spray–booth	3 410	7 550
11	Edge Bander	7 385	4 430
12	Wrapping Unit	5 000	3 500
13	Drill	3 900	880
14	Widebelt Sander	8 820	1 930
15	Handsand Area	3 500	5 000

Table 5.12: *Physical dimensions (in* mm*) of machines on the LWC factory floor, as on 17 October 2002.*

and production material had to be transported between the floors, a cost for transferring material upwards or downwards over the ramp was incurred. C^v_{ij} was taken as the flow of production material between the machines added to a constant value c_1 (measured in metres) which represents an estimate of the additional cost incurred when going up the ramp, but measured in the unit of horizontal distance. Here c_1 was taken to be $0, 100, 500$ and $1\,000$ during separate applications of the model as in the previous section.

The objective of the mathematical programming model with a continuous layout is also to minimize the material–handling and relocation cost of machines. The relocation cost of machine i, I_i, is shown in Table 5.13, and the value of the parameter G, which denotes the cost per metre of a 3–phase cable at the LWC factory, is R200 as before. An additional binary variable

$$N_i \;=\; \begin{cases} 1, & \text{if machine } i \text{ requires a } 3\text{–phase cable,} \\ 0, & \text{otherwise,} \end{cases}$$

not included in the formulation in §3.1.2.1(ii), was incorporated into this model to account for the fact that not all machines require a 3–phase electrical cable. The relocation cost of machine i is now given by

$$F_i = I_i + GN_ix_i, \qquad i = 1, \ldots, 15,$$

where x_i is the vertical coordinate of machine i. Let X_i and Y_i be the current coordinates of the machines on the LWC factory floor. The objective function of the continuous layout mathematical programming model, discussed in §3.1.2.1(ii) and applied to the LWC factory floor layout relocation problem with $M = 10\,000$, $X^{\max} = 30\,\text{m}$ and $Y^{\max} = 25\,\text{m}$, is therefore to minimize

$$Z \;=\; \sum_{i=1}^{15} \sum_{\substack{j=1 \\ j\neq i \\ f_{ij}=1}}^{15} \left(C^c_{ij}T_{ij} + C^v_{ij}(D_{ij} + U_{ij})\right) + \sum_{i=1}^{15} F_i, \tag{5.6}$$

No	**Machine**	**Relocation Cost I_i**	**3–phase cable?**
1	Panel Saw	500	yes
2	Radial Arm	0	no
3	Ripper	500	yes
4	Planer	500	yes
5	Four–side Planer	500	yes
6	Spindle	500	yes
7	Edge Sander	0	no
8	Assembly Station	0	no
9	Base Coat Spray–booth	25 000	no
10	Top Coat Spray–booth	25 000	no
11	Edge Bander	500	yes
12	Wrapping Unit	500	yes
13	Drill	0	no
14	Widebelt Sander	500	yes
15	Handsand Area	0	no

Table 5.13: *Relocation costs of machines at the LWC factory, together with an indication whether a machine requires a 3–phase electrical cable or not.*

subject to

$$\left.\begin{array}{rl} \sum_{k=1}^{2} V_{ik} = 1, & i = 1,\ldots,15, \\ Z_{ij} \geq V_{ik} + V_{jk} - 1, & i = 1,\ldots,14,\ j = i+1,\ldots,15, \\ & k = 1 \text{ or } 2, \\ Z_{ij} \leq 1 - V_{ik} + V_{jk}, & i = 1,\ldots,14,\ j = i+1,\ldots,15, \\ & k = 1 \text{ or } 2, \\ Z_{ij} \leq 1 + V_{ik} - V_{jk}, & i = 1,\ldots,14,\ j = i+1,\ldots,15, \\ & k = 1 \text{ or } 2, \end{array}\right\} \tag{5.7}$$

$$\left.\begin{array}{rl} x_i - x_j + 10\,000(1 - Z_{ij} + E1_{ij} + E2_{ij}) \geq \frac{\ell_i + \ell_j}{2}, & i = 1,\ldots,14,\ j = i+1,\ldots,15, \\ x_i - x_j + 10\,000(2 - Z_{ij} - E1_{ij} + E2_{ij}) \geq \frac{\ell_i + \ell_j}{2}, & i = 1,\ldots,14,\ j = i+1,\ldots,15, \\ y_i - y_j + 10\,000(2 - Z_{ij} + E1_{ij} - E2_{ij}) \geq \frac{w_i + w_j}{2}, & i = 1,\ldots,14,\ j = i+1,\ldots,15, \\ y_i - y_j + 10\,000(3 - Z_{ij} - E1_{ij} - E2_{ij}) \geq \frac{w_i + w_j}{2}, & i = 1,\ldots,14,\ j = i+1,\ldots,15, \\ R_{ij} - L_{ij} = x_i - x_j, & \forall (i,j) : f_{ij} = 1, \\ A_{ij} - B_{ij} = y_i - y_j, & \forall (i,j) : f_{ij} = 1, \\ U_{ij} - D_{ij} = 1\,000 \sum_{k=1}^{2} k(V_{ik} - V_{jk}), & \forall (i,j) : f_{ij} = 1, \\ x_i \geq \frac{\ell_i}{2}, & i = 1,\ldots,15, \\ y_i \geq \frac{w_1}{2}, & i = 1,\ldots,15, \\ x_i + \frac{\ell_i}{2} \leq 30, & i = 1,\ldots,15, \\ y_i + \frac{w_i}{2} \leq 25, & i = 1,\ldots,15, \end{array}\right\} \tag{5.8}$$

where

$$F_i \geq 0 \qquad i = 1,\ldots,15, \tag{5.9}$$

$$F_i \leq M(X_i - x_i)(Y_i - y_i) \qquad i = 1, \ldots, 15. \tag{5.10}$$

$$\ell_i = \alpha_i O_i + \beta_i(1 - O_i), \qquad i = 1, \ldots, 15, \tag{5.11}$$

$$w_i = \alpha_i + \beta_i - \ell_i, \qquad i = 1, \ldots, 15, \tag{5.12}$$

$$T_{ij} = R_{ij} + L_{ij} + A_{ij} + B_{ij} + U_{ij} + D_{ij}, \qquad \forall (i,j) : f_{ij} = 1, \tag{5.13}$$

$$l_i, w_i, x_i, y_i > 0 \qquad i = 1, \ldots, 15, \tag{5.14}$$

$$R_{ij}, L_{ij}, A_{ij}, B_{ij}, U_{ij}, D_{ij}, T_{ij} > 0 \qquad i, j = 1, \ldots, 15, \tag{5.15}$$

$$V_{ik}, Z_{ik}, O_{ik} \in \{0, 1\} \qquad i = 1, \ldots, 15 \text{ and } k = 1, 2. \tag{5.16}$$

This model differs from the one presented in §3.1.2.1(ii) in the sense that a relocation problem is presented with equation (5.9) and (5.10) ensuring that the installation cost of a machine at its current location is zero. The mathematical programming model for a continuous layout problem is a linear model bar the integral constraints, whereas the discrete layout model is a quadratic model if the integral constraints are ignored. It may therefore be expected that the continuous model could be solved faster than the discrete model, but because of the large worst case complexity measure due to the integral constraints this is not the case. The model (5.6)–(5.16) consists of 2 956 variables, of which 858 are integral, as well as 1 830 constraints. Since traditional methods used to solve integer programs, such as the well–known branch–and–bound method, tend to have an execution time which is exponential in the number of variables and constraints, the model could also not be solved within a realistic timespan. In addition to this there was no cost–effective software available that could solve a problem of this magnitude, leading to an abandonment of this continuous layout model approach towards solving the layout problem at LWC.

The layout problem at the LWC plant is clearly too large to solve via an exact method, using off–the–shelf optimization packages that are available commercially. It was therefore decided to apply heuristic methods instead that could be used to improve the factory floor layout at LWC, although not necessarily leading to an optimal layout.

5.2.2 A Heuristic Method

A *hybrid tabu search* method was applied to the discrete layout model, as proposed by Bazaraa [21] and described in §3.1.2.1(i), with the additional possibility of changing the orientation of the machines.

The neighborhood of a specific layout is the change in position and/or orientation of a randomly selected machine from its current position and orientation. Due to the randomness contained in the selection of the neighborhood this local search method should not be referred to as a pure tabu search method, but rather as a hybrid tabu search method. A recency–based memory structure was used, where a move was labeled tabu–active for a pre–specified number of moves (called the tabu list length) after its execution and the search was terminated after a fixed number of iterations.

The search started out from a randomly chosen initial layout. As in the discussion of the exact solution of the model proposed by Bazaraa [21] and applied in §5.2.1(i), an extra weight was added to the distance between the grid–points not positioned on the same floor, due to the additional cost incurred by workers abandoning their machines to aid in the transportation of production material up and down the ramp. As before, a weight R_u was added when transporting material up the ramp, and a weight R_d, when transporting material down the ramp.

As in §5.2.1(i) the distance from a point k on the lower floor to a point h on the upper floor was therefore taken to be

$$d_{kh} = \rho(d_{k,ramp} + d_{ramp,h}) + (1-\rho)R_u,$$

whilst for the case where grid–point k is on the upper floor and grid–point h on the lower floor, the distance was taken as

$$d_{kh} = \rho(d_{k,ramp} + d_{ramp,h}) + (1-\rho)R_d.$$

A variable $\rho \in [0,1]$, which represents an importance measure of the ramp weight, was incorporated, and was varied during a sensitivity analysis (as will be discussed later in this section) due to the fact that the ramp weight is not easily quantifiable. The objective was therefore to minimize

$$\begin{aligned} Z = \theta & \left(\sum_{i=1}^{15}\sum_{j=1}^{15}\sum_{k=1}^{I(i)}\sum_{h=1}^{I(j)} f_{ij}X_{ik}X_{jh}d_{kh} + \sum_{j=1}^{15}\sum_{k=1}^{I(j)} f_{0j}X_{jk}d_{19,\,k} \right. \\ & \left. + \sum_{i=1}^{15}\sum_{k=1}^{I(i)} f_{i16}X_{ik}d_{k,\,49} \right) + (1-\theta)\left(\sum_{i=1}^{15}\sum_{k=1}^{I(i)} F_{ik}X_{ik} \right) \end{aligned} \tag{5.17}$$

subject to

$$\left. \begin{array}{rl} \sum_{i=1}^{15} X_{ik} \leq 1, & k = 0,1,\ldots,91, \\ \sum_{k=1}^{I(i)} X_{ik} = 1, & i = 1,2,\ldots,15, \\ \sum_{i=1}^{15}\sum_{k=1}^{I(i)} a_{ikt}X_{ik} \leq 1, & \text{for each block } t, \\ X_{ik} \in \{0,1\}, & k = 1,2,\ldots,I(i) \text{ and } i = 1,2,\ldots,15, \end{array} \right\} \tag{5.18}$$

where $\theta \in [0,1]$ is a scaling variable to compensate for the different units of the terms in the objective function and (5.17) and (5.18) are the same as (5.2) and (5.3) respectively . The possible locations for each machine with both orientations were determined in advance and, as in the discussion of the exact methods, the other parameters that were also determined in advance include

$$\begin{aligned} d_{kh} &= \text{the distance from the } k\text{–th to the } h\text{–th grid–points,} \\ f_{ij} &= \text{flow of production material between machines } i \text{ and } j, \\ F_{ik} &= \text{fixed cost of placing machine } i \text{ at location } k, \\ a_{ikt} &= \begin{cases} 1, & \text{if block } t \in \mathcal{S}_i(k) \\ 0, & \text{otherwise.} \end{cases} \end{aligned}$$

The problem was solved for two grid sizes, a grid with 12 horizontal blocks and 11 vertical blocks and a grid with 22 horizontal blocks and 21 vertical blocks.

The historical flow over the period June 2002 – December 2002 of production material between machines is shown in Table 5.2, the installation costs in Table 5.10 and the a_{ikt} values for $i = 1,2,\ldots,15$, $k = 0,1,\ldots,91$ and $t = 1,2,\ldots,120$ (in the case of a grid with 12 horizontal blocks and 11 vertical blocks as shown in Figure 5.7) or $i = 1,2,\ldots,15$, $k = 0,1,\ldots,371$ and $t = 1,2,\ldots 427$ (in the case of a grid with 22 horizontal blocks and 21 vertical blocks) followed directly from determining the $\mathcal{S}_i(k)$ sets, as shown in Appendix C.

The efficiency of a search was tested for both grid sizes by performing a total of 550 tabu search runs. Each run resulted from a fixed combination of the parameters listed in Table 5.14, and each run consisted of 20 tabu search replications, using random initial layouts and terminating after 100 moves were executed (these values were determined through experimentation yielding an acceptable level of convergence). The objective function value of the replication producing the best result and the corresponding initial layout's objective function value for each run are presented for the different grid sizes (12×11 and 22×21) in Tables 5.15 and 5.16 respectively for $\theta = 0$, in Tables 5.17 and 5.18 for $\theta = 0.5$ and in Tables 5.20 and 5.21 for $\theta = 1.0$.

Parameter	**Description**	**Values**
R_u	The additional cost of moving production material up the ramp	$0, 100, 500, 1\,000$
q	Scalar value used to indicate the correlation between R_u and R_d where $R_d = q \times R_u$	$1, 1.5, 2$
θ	Weight of installation *vs* transportation cost	$0, 0.5, 1$
ρ	Weight of ramp cost *vs* flow of production material cost	$0, 0.5, 1$
$f_{\max}$	Tabu list length (tabu tenure)	$5, 15, 30, 50, 75$

Table 5.14: *Ranges of parameter values resulting in* 550 *hybrid tabu search runs by which the efficiency of a search was tested for both grid sizes.*

Consider the problem with 12 blocks horizontally and 11 blocks vertically, where $\theta = 0$. This is the case where only the installation cost is taken into account in the objective function. The results obtained for this problem are shown in Table 5.15, where the smallest obtained objective function value of 54 200 was achieved when a tabu list length of 50 moves was used. The searches in Table 5.15 ran, on average, 1 hour and 40 minutes[2]. The objective function values after each move of the replication producing the best layout obtained, are presented in Figure 5.9 by the solid line. The crosses (stars, circles) indicate the maximum (minimum, average) objective function value after each move, computed over all 20 replications. The best objective function value obtained for each tabu list length is presented in Table 5.15, along with the objective function value for the initial layout from which it was derived and the total improvement obtained.

Now consider the problem with 22 blocks horizontally and 21 blocks vertically, where $\theta = 0$ (*i.e.*, only the installation costs of machines are again considered). The smallest objective function value obtained was of 54 000. On average it took 1 hour and 41 minutes to obtain a final layout for a 22×21 grid with $\theta = 0$. The same best objective function value was obtained for all 5 different tabu list lengths. An improvement of 5 000 was obtained from a random initial layout

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[2] The numerical work presented in this section was in certain instances computationally rather taxing, and hence all replications were run on a Linux–based MOSIX cluster workstation. MOSIX is a set of enhancements of the Linux kernel for supporting cluster computing. The core of MOSIX consists of adaptive (on–line) resource sharing (load–balancing, memory ushering and I/O optimization) algorithms and a pre–emptive process migration mechanism that allows a cluster of workstations and servers (nodes) to work cooperatively as if part of a single system. The cluster may include a large number (up to 65 535) of nodes, which can be any combination of workstations, servers or single–processors of any speed. MOSIX is implemented within the Linux kernel and it maintains compatibility with standard Linux, hence there is no need to modify any user–level files, programs or binaries. When activated, normal Linux processes may be allocated and migrated automatically and transparently to other nodes within the cluster in order to achieve a better resource usage of the cluster. As the demands for resources change across the cluster, processes may migrate again, as many times as necessary, to continue optimizing the overall resource usage [18]. More specifically, the MOSIX cluster used for numerical work in this section consisted of more than 50 CPUs that include Celeron 900 MHz and Intel Celeron 1 GHz processors (each with 256 MB memory) as well as a single Intel Pentium 4 1.5 GHz master node processor (with 512 MB memory), while the collection of stand–alone computers consisted of a Pentium 3 800 MHz dual processor and a Pentium 3 600 MHz dual processor (each with 512 MB memory), a Celeron 700 MHz (with 256 MB memory) and 59 Pentium 133 MHz processors (each with 64 MB memory).

No	Tabu List Length	Initial Objective Function Value	Best Objective Function Value	Improvement
1	5	55 600	54 600	1 000
2	15	55 400	54 400	1 000
3	30	55 400	55 400	1 000
4	50	55 800	54 200	1 600
5	75	55 800	54 600	1 200

Table 5.15: *Objective function values obtained for $\theta = 0$ on a grid of* 12 *blocks horizontally and* 11 *blocks vertically.*

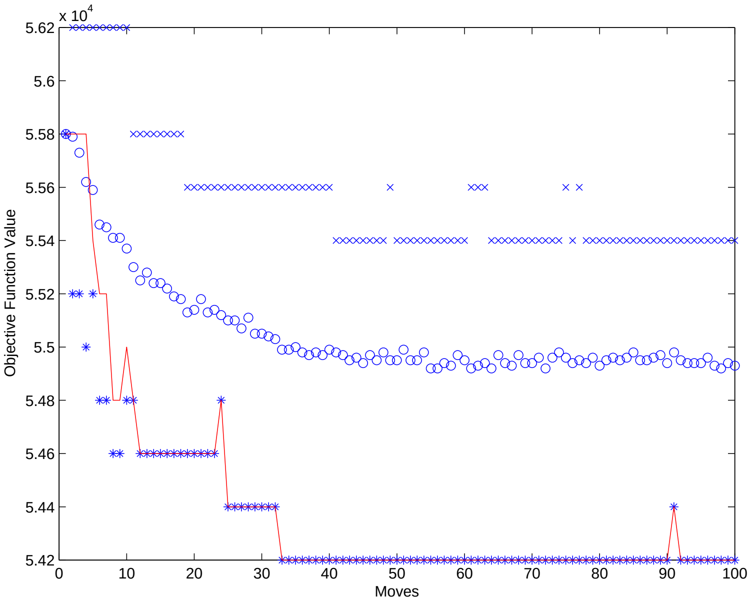

Figure 5.9: *The moves for run number* 4 *of the hybrid tabu search in Table* 5.15 *with $\theta = 0$ and a grid of* 12×11 *blocks. The crosses (stars, circles) indicate the maximum (minimum, average) objective function values after each move, computed over all* 20 *replications. The solid line shows the objective function value after each move of the replication producing the best layout obtained.*

with an objective function value of 59 000 in the case where the tabu list length was 50 moves.

The best objective function values obtained for each different tabu list length are presented in Table 5.16, along with the corresponding objective function values for the initial random layout from which they were derived and the total improvement obtained. The objective function values after each move of the replication producing the best improvement obtained from the initial layout, are presented in Figure 5.10 by the solid line. The crosses (stars, circles) indicate the maximum (minimum, average) installation cost after each move, computed over all 20 replications.

Next, consider the problem with 12 blocks horizontally and 11 blocks vertically and $\theta = 0.5$. All the search runs evaluated for the different combinations of variables are shown in Table 5.17, and a three dimensional representation of the smallest objective function values obtained over all 20 replications of each run is shown in Figure 5.11, with the x and y–axis values mapped to the parameter value combinations indicated in Tables 5.19(a) and (b). On average it took 1 hour, 6 minutes and 6 seconds to obtain a final layout for a 12×11 grid with $\theta = 0.5$. It

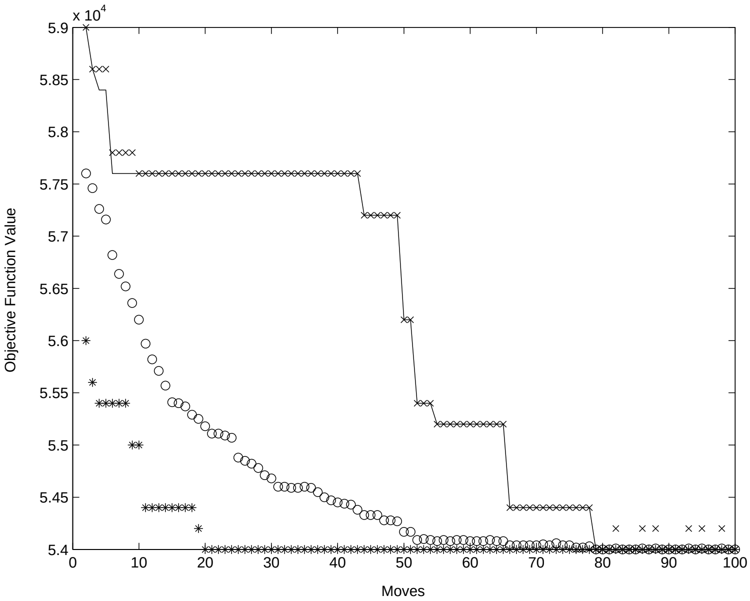

Figure 5.10: *The moves for run number four of the hybrid tabu search in Table 5.16 with $\theta = 0$ and a grid of 22×21 blocks. The crosses (stars, circles) indicate the maximum (minimum, average) objective function values after each move, computed over all 20 replications. The solid line shows the objective function value of each move of the replication in run number four producing the best layout with objective function value 54 000.*

No	Tabu List Length	Initial Objective Function Value	Best Objective Function Value	Improvement
1	5	57 800	54 000	3 800
2	15	57 600	54 000	3 600
3	30	57 000	54 000	3 000
4	50	59 000	54 000	5 000
5	75	58 800	54 000	4 800

Table 5.16: *Objective function values obtained for $\theta = 0$ on a grid of 22 blocks horizontally and 21 blocks vertically.*

is evident from the three dimensional map that the choice of the tabu list length does not significantly affect the objective function values obtained.

The best objective function value of 467 494 was obtained for run 119 in Table 5.17 and the objective function values obtained after each move in the replication of this run producing the smallest objective function value are shown in Figure 5.12 by means of a solid line. The crosses (stars, circles) indicate the maximum (minimum, average) objective function value after each move, computed over all 20 replications. Incorporating the cost of the flow of production material between the machines and the cost of flow across the ramp equally (*i.e.*, $\rho = 0.5$) the best objective function value of 898 664 was achieved during run number eight in Table 5.17. In the case where only the ramp cost was incorporated in the objective function and no flow of production material, (*i.e.*, $\rho = 0$) the best obtained objective function value of 1 304 930 was achieved during run number five in Table 5.17. The best improvement (7 241 500) for the problem on a 12×11 grid with $\theta = 0.5$ was for run 123 in Table 5.17.

If the problem with 22 blocks horizontally and 21 blocks vertically is considered, where $\theta = 0.5$,

No	Ramp Cost Up	q	ρ	Tabu list Length	Initial Objective	Best Objective		No	Ramp Cost Up	q	ρ	Tabu list Length	Initial Objective	Best Objective
1	100	1.0	0.0	5	1 879 510	1 304 990		2	100	1.0	0.0	15	1 967 270	1 337 060
3	100	1.0	0.0	30	1 686 260	1 308 530		4	100	1.0	0.0	50	1 998 570	1 341 170
5	100	1.0	0.0	75	1 838 230	1 304 930		6	100	1.0	0.5	5	1 307 880	920 006
7	100	1.0	0.5	15	1 263 760	924 523		8	100	1.0	0.5	30	1 264 530	898 664
9	100	1.0	0.5	50	1 256 530	906 175		10	100	1.0	0.5	75	1 153 420	911 692
11	100	1.0	1.0	5	538 788	478 983		12	100	1.0	1.0	15	621 424	496 815
13	100	1.0	1.0	30	670 528	499 193		14	100	1.0	1.0	50	552 972	487 139
15	100	1.0	1.0	75	635 214	471 858		16	100	1.5	0.0	5	2 378 030	1 904 800
17	100	1.5	0.0	15	2 552 480	1 930 010		18	100	1.5	0.0	30	2 489 240	1 877 270
19	100	1.5	0.0	50	2 383 810	1 889 010		20	100	1.5	0.0	75	2 525 690	1 872 470
21	100	1.5	0.5	5	1 637 660	1 205 570		22	100	1.5	0.5	15	1 579 300	1 196 410
23	100	1.5	0.5	30	1 734 840	1 193 190		24	100	1.5	0.5	50	1 617 380	1 192 850
25	100	1.5	0.5	75	1 557 090	1 187 050		26	100	1.5	1.0	5	795 749	488 929
27	100	1.5	1.0	15	810 974	470 778		28	100	1.5	1.0	30	602 049	504 303
29	100	1.5	1.0	50	621 148	473 082		30	100	1.5	1.0	75	616 488	489 706
31	100	2.0	0.0	5	3 039 230	2 464 950		32	100	2.0	0.0	15	3 097 110	2 457 530
33	100	2.0	0.0	30	3 202 370	2 439 050		34	100	2.0	0.0	50	2 997 110	2 431 510
35	100	2.0	0.0	75	3 204 490	2 464 000		36	100	2.0	0.5	5	2 046 000	1 460 400
37	100	2.0	0.5	15	1 875 690	1 480 470		38	100	2.0	0.5	30	1 941 850	1 472 650
39	100	2.0	0.5	50	1 931 950	1 514 760		40	100	2.0	0.5	75	1 849 690	1 473 690
41	100	2.0	1.0	5	576 339	485 584		42	100	2.0	1.0	15	606 295	490 982
43	100	2.0	1.0	30	605 110	490 917		44	100	2.0	1.0	50	575 676	475 634
45	100	2.0	1.0	75	700 765	506 615		46	500	1.0	0.0	5	7 917 460	5 883 990
47	500	1.0	0.0	15	8 760 070	5 908 700		48	500	1.0	0.0	30	8 267 190	5 903 310
49	500	1.0	0.0	50	7 423 140	5 878 110		50	500	1.0	0.0	75	7 054 630	5 915 340
51	500	1.0	0.5	5	4 302 850	3 204 430		52	500	1.0	0.5	15	4 541 720	3 211 680
53	500	1.0	0.5	30	4 086 580	3 193 060		54	500	1.0	0.5	50	4 274 080	3 172 140
55	500	1.0	0.5	75	4 193 330	3 192 720		56	500	1.0	1.0	5	599 276	493 547
57	500	1.0	1.0	15	650 876	468 156		58	500	1.0	1.0	30	569 634	475 386
59	500	1.0	1.0	50	550 247	486 024		60	500	1.0	1.0	75	654 548	482 751
61	500	1.5	0.0	5	13 118 000	8 721 190		62	500	1.5	0.0	15	11 213 000	8 725 710
63	500	1.5	0.0	30	12 048 000	8 719 750		64	500	1.5	0.0	50	11 850 400	8 718 190
65	500	1.5	0.0	75	11 187 100	8 711 010		66	500	1.5	0.5	5	6 463 910	4 617 980
67	500	1.5	0.5	15	6 468 630	4 621 010		68	500	1.5	0.5	30	5 949 820	4 616 190
69	500	1.5	0.5	50	6 195 460	4 602 300		70	500	1.5	0.5	75	6 057 750	4 634 160
71	500	1.5	1.0	5	700 313	474 752		72	500	1.5	1.0	15	638 646	488 121
73	500	1.5	1.0	30	656 213	482 849		74	500	1.5	1.0	50	726 301	496 519
75	500	1.5	1.0	75	666 808	501 715		76	500	2.0	0.0	5	14 317 800	11 547 700
77	500	2.0	0.0	15	15 047 100	11 519 700		78	500	2.0	0.0	30	15 874 600	11 584 600
79	500	2.0	0.0	50	14 787 900	11 564 700		80	500	2.0	0.0	75	13 758 100	11 520 700
81	500	2.0	0.5	5	7 065 200	6 014 370		82	500	2.0	0.5	15	7 177 320	6 014 780
83	500	2.0	0.5	30	7 021 550	6 033 270		84	500	2.0	0.5	50	7 778 840	6 017 400
85	500	2.0	0.5	75	6 940 360	6 020 380		86	500	2.0	1.0	5	599 238	479 658
87	500	2.0	1.0	15	662 107	486 582		88	500	2.0	1.0	30	633 034	469 277
89	500	2.0	1.0	50	805 674	500 204		90	500	2.0	1.0	75	535 611	480 748
91	1 000	1.0	0.0	5	15 232 500	11 631 200		92	1 000	1.0	0.0	15	14 566 000	11 608 900
93	1 000	1.0	0.0	30	15 609 500	11 602 300		94	1 000	1.0	0.0	50	14 230 900	11 611 900
95	1 000	1.0	0.0	75	15 363 800	11 614 400		96	1 000	1.0	0.5	5	9 060 810	6 044 540
97	1 000	1.0	0.5	15	7 781 100	6 079 650		98	1 000	1.0	0.5	30	8 185 140	6 074 500
99	1 000	1.0	0.5	50	8 634 440	6 056 710		100	1 000	1.0	0.5	75	8 252 520	6 041 000
101	1 000	1.0	1.0	5	680 573	489 109		102	1 000	1.0	1.0	15	590 598	482 733
103	1 000	1.0	1.0	30	679 388	480 306		104	1 000	1.0	1.0	50	574 923	500 589
105	1 000	1.0	1.0	75	779 610	498 582		106	1 000	1.5	0.0	5	23 307 400	17 256 200
107	1 000	1.5	0.0	15	23 584 100	17 293 700		108	1 000	1.5	0.0	30	19 385 500	17 244 400
109	1 000	1.5	0.0	50	21 988 100	17 255 500		110	1 000	1.5	0.0	75	23 079 700	17 249 300
111	1 000	1.5	0.5	5	10 767 300	8 918 150		112	1 000	1.5	0.5	15	12 332 000	8 874 930
113	1 000	1.5	0.5	30	11 366 400	8 880 240		114	1 000	1.5	0.5	50	12 599 000	8 894 180
115	1 000	1.5	0.5	75	12 278 600	8 906 170		116	1 000	1.5	1.0	5	623 542	494 983
117	1 000	1.5	1.0	15	612 379	504 301		118	1 000	1.5	1.0	30	656 622	473 276
119	1 000	1.5	1.0	50	741 038	467 494		120	1 000	1.5	1.0	75	628 470	482 210
121	1 000	2.0	0.0	5	28 570 400	22 902 200		122	1 000	2.0	0.0	15	29 874 100	22 886 100
123	1 000	2.0	0.0	30	30 125 000	22 883 500		124	1 000	2.0	0.0	50	31 245 500	22 901 200
125	1 000	2.0	0.0	75	28 449 800	22 877 000		126	1 000	2.0	0.5	5	16 139 200	11 710 000
127	1 000	2.0	0.5	15	15 248 300	11 714 300		128	1 000	2.0	0.5	30	16 875 200	11 697 100
129	1 000	2.0	0.5	50	16 818 700	11 701 200		130	1 000	2.0	0.5	75	15 560 000	11 708 200
131	1 000	2.0	1.0	5	756 363	495 458		132	1 000	2.0	1.0	15	639 358	491 864
133	1 000	2.0	1.0	30	701 973	495 110		134	1 000	2.0	1.0	50	649 893	498 687
135	1 000	2.0	1.0	75	818 895	498 917								

Table 5.17: *Objective function values obtained for the* 135 *runs of the hybrid tabu search in which* $\theta = 0.5$ *on a grid of* 12 *blocks horizontally and* 11 *blocks vertically.*

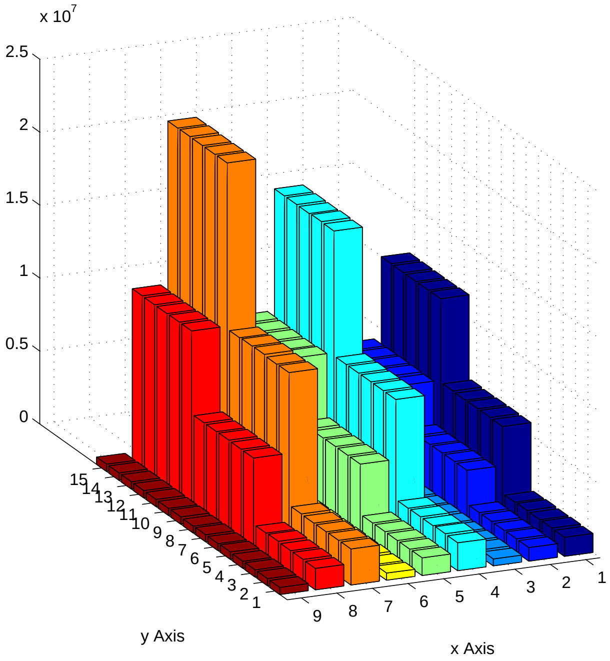

Figure 5.11: *Smallest objective function values obtained over all* 20 *replications of each run of the hybrid tabu search represented in Table 5.17, where the parameter values map to the x and y values as explained in Tables 5.19(a) and (b).*

the runs performed for the different combinations of variables are shown in Table 5.18, with a three dimensional representation of the smallest objective function values obtained over all 20 replications of each run as shown in Figure 5.14, where the x and y–axis values mapped to the same parameter values as indicated in Tables 5.19(a) and (b). On average it took 2 hours and 23 minutes to obtain a final layout. Again it is evident from the three dimensional map that the choice of the tabu list length does not affect the objective function values significantly. The best objective function value of 431 801 was obtained during run 45 in Table 5.18 for the problem where no ramp cost was incorporated, but only the cost of the flow of production material over a rectilinear distance between the machines. The objective function values obtained for each move of this run are presented in Figure 5.13 by the solid line. The crosses (stars, circles) indicate the maximum (minimum, average) objective function value after each move, computed over all 20 replications.

Incorporating the cost of production material flow between the machines and the cost of flow across the ramp equally (*i.e.*, $\rho = 0.5$) the best objective function value of 900 106 was obtained during run 10 in Table 5.18. In the case where only the ramp cost was incorporated in the objective function (*i.e.*, $\rho = 0$) the best objective function value of 1 299 100 was obtained during run five in Table 5.18. The best improvement (4 403 000) over all runs on the 22 × 21 grid with $\theta = 0.5$ was obtained during run 124 in Table 5.18.

Next, consider the problem with 12 blocks horizontally and 11 blocks vertically, and with $\theta = 1.0$. All the runs evaluated for the different combinations of variables are shown in Table 5.20, and a three dimensional representation of the smallest objective function values obtained over all 20 replications of each run is shown in Figure 5.16, with the x and y–axis values mapped to the parameter values as indicated in Tables 5.19(a) and (b). On average it took 41 minutes to obtain a final layout for a 12 × 11 grid with $\theta = 1.0$. Again, it is evident from Figure 5.16

No	Ramp Cost Up	q	ρ	Tabu list Length	Initial Objective	Best Objective		No	Ramp Cost Up	q	ρ	Tabu list Length	Initial Objective	Best Objective
1	100	1.0	0.0	5	1 807 380	1 310 720		2	100	1.0	0.0	15	1 866 870	1 305 630
3	100	1.0	0.0	30	1 992 790	1 317 510		4	100	1.0	0.0	50	1 758 900	1 313 190
5	100	1.0	0.0	75	1 903 820	1 299 100		6	100	1.0	0.5	5	1 333 520	906 997
7	100	1.0	0.5	15	1 226 350	907 692		8	100	1.0	0.5	30	1 237 290	906 091
9	100	1.0	0.5	50	1 258 060	1 084 580		10	100	1.0	0.5	75	1 425 830	900 106
11	100	1.0	1.0	5	883 487	473 194		12	100	1.0	1.0	15	691 114	473 048
13	100	1.0	1.0	30	655 410	475 079		14	100	1.0	1.0	50	797 920	478 285
15	100	1.0	1.0	75	719 783	473 835		16	100	1.5	0.0	5	2647 190	1 883 660
17	100	1.5	0.0	15	2 835 960	1 881 560		18	100	1.5	0.0	30	2 423 680	1 887 750
19	100	1.5	0.0	50	2 565 870	1 874 750		20	100	1.5	0.0	75	2 408 870	1 863 310
21	100	1.5	0.5	5	1 599 840	1 190 100		22	100	1.5	0.5	15	1 573 660	1 134 880
23	100	1.5	0.5	30	1 720 900	1 189 930		24	100	1.5	0.5	50	1 437 650	1 181 020
25	100	1.5	0.5	75	1 541 670	1 180 730		26	100	1.5	1.0	5	712 390	468 448
27	100	1.5	1.0	15	943 128	461 364		28	100	1.5	1.0	30	802 018	466 267
29	100	1.5	1.0	50	624 830	470 493		30	100	1.5	1.0	75	878 933	454 766
31	100	2.0	0.0	5	3 453 110	2 441 030		32	100	2.0	0.0	15	3 035 800	2 436 170
33	100	2.0	0.0	30	3 126 360	2 460 160		34	100	2.0	0.0	50	3 394 440	2 436 030
35	100	2.0	0.0	75	3 250 310	2 414 960		36	100	2.0	0.5	5	1 992 980	1 465 010
37	100	2.0	0.5	15	2 079 040	1 469 640		38	100	2.0	0.5	30	1 964 390	1 487 900
39	100	2.0	0.5	50	1 841 770	1 453 010		40	100	2.0	0.5	75	1 929 950	1 475 250
41	100	2.0	1.0	5	691 568	467 524		42	100	2.0	1.0	15	669 064	464 909
43	100	2.0	1.0	30	845 856	464 302		44	100	2.0	1.0	50	563 054	467 960
45	100	2.0	1.0	75	987 303	431 801		46	500	1.0	0.0	5	7 976 470	5 837 280
47	500	1.0	0.0	15	9 068 220	5 773 660		48	500	1.0	0.0	30	8 933 540	5 762 850
49	500	1.0	0.0	50	7 892 890	5 696 560		50	500	1.0	0.0	75	7 896 540	5 686 930
51	500	1.0	0.5	5	4 191 090	3 180 930		52	500	1.0	0.5	15	4 677 530	3 168 210
53	500	1.0	0.5	30	4 596 170	3 190 270		54	500	1.0	0.5	50	4 475 800	3 189 200
55	500	1.0	0.5	75	4 563 350	3 175 420		56	500	1.0	1.0	5	699 762	472 674
57	500	1.0	1.0	15	674 688	463 267		58	500	1.0	1.0	30	629 400	461 460
59	500	1.0	1.0	50	821 398	465 969		60	500	1.0	1.0	75	650 958	469 653
61	500	1.5	0.0	5	12 741 600	8 586 480		62	500	1.5	0.0	15	12 018 100	8 472 550
63	500	1.5	0.0	30	11 481 200	8 688 130		64	500	1.5	0.0	50	12 813 200	8 496 480
65	500	1.5	0.0	75	12 785 000	8 576 910		66	500	1.5	0.5	5	6 534 120	4 555 810
67	500	1.5	0.5	15	5 544 380	4 577 220		68	500	1.5	0.5	30	6 295 620	4 536 210
69	500	1.5	0.5	50	5 917 700	4 614 750		70	500	1.5	0.5	75	6 051 980	4 549 810
71	500	1.5	1.0	5	835 993	467 858		72	500	1.5	1.0	15	956 910	472 073
73	500	1.5	1.0	30	735 285	463 237		74	500	1.5	1.0	50	753 716	482 764
75	500	1.5	1.0	75	844 486	466 969		76	500	2.0	0.0	5	13 392 500	11 349 600
77	500	2.0	0.0	15	15 493 700	11 334 800		78	500	2.0	0.0	30	14 567 700	11 353 400
79	500	2.0	0.0	50	15 224 100	11 461 000		80	500	2.0	0.0	75	14 399 900	11 353 400
81	500	2.0	0.5	5	8 088 340	5 933 050		82	500	2.0	0.5	15	7 986 460	5 951 750
83	500	2.0	0.5	30	8 785 300	5 919 240		84	500	2.0	0.5	50	7 997 020	5 957 410
85	500	2.0	0.5	75	7 484 730	5 902 510		86	500	2.0	1.0	5	791 819	458 738
87	500	2.0	1.0	15	632 827	479 345		88	500	2.0	1.0	30	730 164	475 890
89	500	2.0	1.0	50	826 583	472 243		90	500	2.0	1.0	75	713 401	463 617
91	1 000	1.0	0.0	5	17 216 900	11 326 800		92	1 000	1.0	0.0	15	15 904 200	11 333 600
93	1 000	1.0	0.0	30	17 810 700	11 331 600		94	1 000	1.0	0.0	50	16 194 100	11 317 100
95	1 000	1.0	0.0	75	17 153 300	11 369 000		96	1 000	1.0	0.5	5	9 048 650	5 965 510
97	1 000	1.0	0.5	15	9 012 430	5 997 440		98	1 000	1.0	0.5	30	7 787 050	5 965 430
99	1 000	1.0	0.5	50	9 241 460	5 977 690		100	1 000	1.0	0.5	75	8 609 030	6 021 820
101	1 000	1.0	1.0	5	776 150	455 486		102	1 000	1.0	1.0	15	929 883	490 208
103	1 000	1.0	1.0	30	671 374	471 884		104	1 000	1.0	1.0	50	901 563	471 059
105	1 000	1.0	1.0	75	602 472	473 822		106	1 000	1.5	0.0	5	23 824 800	16 913 000
107	1 000	1.5	0.0	15	22 862 100	16 931 100		108	1 000	1.5	0.0	30	23 008 200	16 896 300
109	1 000	1.5	0.0	50	24 912 700	16 935 400		110	1 000	1.5	0.0	75	22 667 500	16 890 100
111	1 000	1.5	0.5	5	11 596 100	8 761 380		112	1 000	1.5	0.5	15	11 548 300	8 712 810
113	1 000	1.5	0.5	30	11 504 100	8 716 220		114	1 000	1.5	0.5	50	10 684 700	8 849 020
115	1 000	1.5	0.5	75	12 261 800	8 796 250		116	1 000	1.5	1.0	5	713 574	466 120
117	1 000	1.5	1.0	15	729 554	435 954		118	1 000	1.5	1.0	30	829 510	463 446
119	1 000	1.5	1.0	50	575 941	472 218		120	1 000	1.5	1.0	75	626 553	468 465
121	1 000	2.0	0.0	5	28 171 700	22 473 400		122	1 000	2.0	0.0	15	31 254 800	22 487 500
123	1 000	2.0	0.0	30	28 782 200	22 397 100		124	1 000	2.0	0.0	50	26 871 200	22 468 200
125	1 000	2.0	0.0	75	30 913 600	22 457 900		126	1 000	2.0	0.5	5	14 098 300	11 538 000
127	1 000	2.0	0.5	15	15 108 200	11 520 700		128	1 000	2.0	0.5	30	16 655 700	11 508 000
129	1 000	2.0	0.5	50	13 181 700	11 507 900		130	1 000	2.0	0.5	75	15 507 900	11 494 600
131	1 000	2.0	1.0	5	754 021	464 654		132	1 000	2.0	1.0	15	724 603	476 415
133	1 000	2.0	1.0	30	791 417	458 965		134	1 000	2.0	1.0	50	685 830	462 866
135	1 000	2.0	1.0	75	720 729	470 889								

Table 5.18: *Objective function values obtained for all* 135 *runs of the hybrid tabu search in which* $\theta = 0.5$ *on a grid of* 22 *blocks horizontally and* 21 *blocks vertically.*

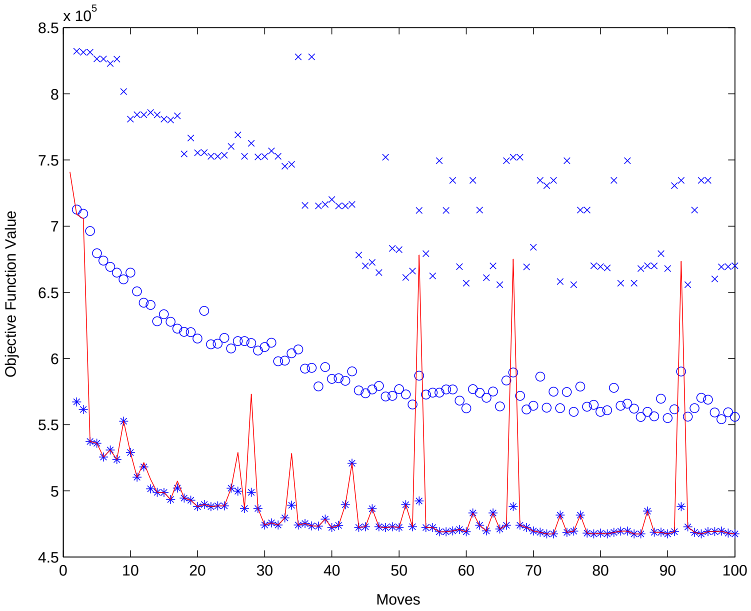

Figure 5.12: *The moves for run number* 119 *of the hybrid tabu search in Table 5.17 with* $\theta = 0.5$ *and a grid of* 12×11 *blocks. The crosses (stars, circles) indicate the maximum (minimum, average) objective function values after each move, computed over all 20 replications. The solid line shows the objective function value of each move of the replication producing the best layout obtained.*

that the choice of the tabu list length does not effect the objective function values significantly. The best objective function value of 882 743 was obtained during run 73 in Table 5.20 where $\rho = 1.0$, in other words no ramp cost was incorporated in the objective function, but only the cost of the flow of production material over a rectilinear distance between the machines. The objective function values obtained after each move of this run are presented in Figure 5.15 by means of a solid line. The crosses (stars, circles) indicate the maximum (minimum, average) objective function value after each move, computed over all 20 repetitions.

Incorporating the cost of the flow of production material between the machines and the cost of flow across the ramp equally (*i.e.*, $\rho = 0.5$) the smallest objective function value of 1 740 220 was obtained during run number seven in Table 5.20. In the case where only the ramp cost was incorporated in the objective function, (*i.e.*, $\rho = 0$) a smallest objective function value of 2 554 060 was obtained during run number five in Table 5.20. The best improvement (14 381 500), over all runs on the 12×11 grid with $\theta = 1.0$, was obtained for run 122 in Table 5.20.

Finally, consider the problem with 22 blocks horizontally and 21 blocks vertically, and where $\theta = 1.0$. All the runs evaluated for the different combinations of variables are shown in Table 5.21, with a three dimensional representation of the smallest objective function values obtained for all 20 replications of each run shown in Figure 5.18, where the x and y–axis values mapped to the same parameter values as indicated in Tables 5.19(a) and (b). On average it took 2 hours and 48 minutes to obtain a final layout for the problem on a 22×21 grid with $\theta = 1.0$. Again, it is evident from Figure 5.18 that the choice of the tabu list length does not affect the objective function values significantly. The best objective function value of 806 504 was obtained during run 75 in Table 5.21 where $\rho = 1.0$ (in other words where no ramp cost was incorporated), and the objective function values obtained for each move during this run are presented in Figure 5.17 by means of a solid line. The crosses (stars, circles) indicate the maximum (minimum,

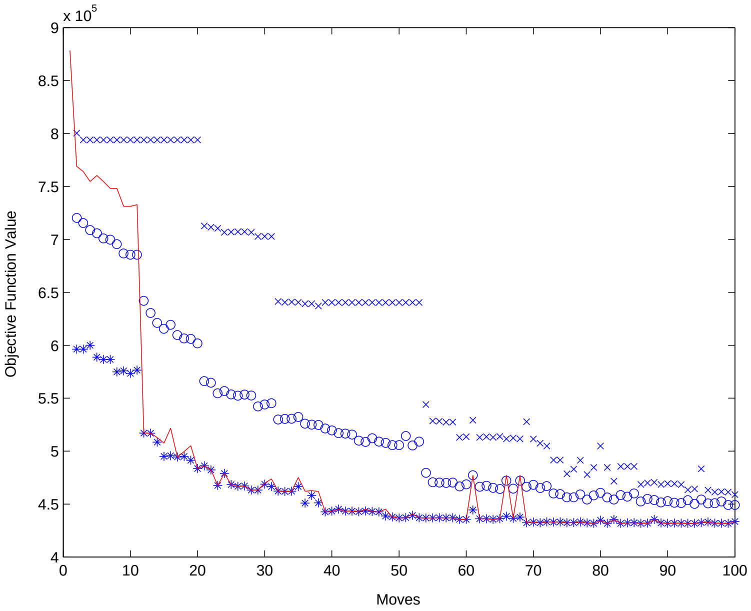

Figure 5.13: *The moves for run number* 45 *of the hybrid tabu search in Table* 5.18 *with* $\theta = 0.5$ *and a grid of* 22 × 21 *blocks. The crosses (stars, circles) indicate the maximum (minimum, average) objective function value after each move, computed over all 20 replications. The solid line show the objective function values of each move of the replication producing the best layout obtained.*

average) objective function value after each move, over all 20 replications.

Incorporating the cost of the flow of production material between the machines and the cost of flow across the ramp equally (*i.e.*, $\rho = 0.5$) the best objective function value of 1 736 500 was obtained during run 6 in Table 5.21. In the case where only the ramp cost was incorporated in the objective function and flow of production material over a distance was not incorporated (*i.e.*, $\rho = 0$), an objective function value of 2 471 110 was achieved during run 1 in Table 5.21. The best improvement over all runs on the 22 × 21 grid with $\theta = 1.0$ was obtained for run 122 in Table 5.21. For this run a total improvement of 20 300 400 was achieved, starting from a random initial layout with an objective function value of 65 255 600, where $\rho = 0$, in other words, only the ramp cost of 1 000 up the ramp and 2 000 down the ramp was incorporated (with a tabu list length of 15 moves).

The overall minimum objective function value obtained for the layout problem over all grid sizes where flow of production material and installation cost were incorporated equally and an additional ramp cost was included in the calculations of the distances between the machines, was 898 664 (run 8 in Table 5.17) with the layout presented in Figure 5.19. It was decided to use the case where $\theta = 0.5$ for implementation purposes, because it provides a more realistic solution. It was not clear which weights the managers of LWC would prefer. This solution represents an improvement of 21.98% of the current layout at LWC which has an objective function value of 1 151 859.

However, the layout in Figure 5.19 is impractical in the sense that the Base Coat Spray–booth and Planer are positioned in front of the ramp. It was therefore recommended that manual changes be made to the layout. The Base Coat Spray–booth and Planer were subsequently moved away from the ramp by the management of LWC and the Top Coat Spray–booth were moved closer to the wall to ensure easier implementation of the extractor fans. The layout

x–**value**	ρ	q
1	0	1
2	0.5	1
3	1	1
4	0	1.5
5	0.5	1.5
6	1	1.5
7	0	2
8	0.5	2
9	1	2

(a) *The x–values in Figures 5.11, 5.14, 5.16 and 5.18.*

y–**value**	**Tabu list Length**	**Ramp Cost Up**
1	5	100
2	15	100
3	30	100
4	50	100
5	75	100
6	5	500
7	15	500
8	30	500
9	50	500
10	75	500
11	5	1 000
12	15	1 000
13	30	1 000
14	50	1 000
15	75	1 000

(b) *The y–values in Figures 5.11, 5.14, 5.16 and 5.18.*

Table 5.19*: The x and y–axis values for the three dimensional Figures 5.11, 5.14, 5.16, 5.18 representing the smallest objective function values for all runs of the hybrid tabu search for different combinations of the parameters.*

obtained after manual changes were made is presented in Figure 5.20. The manual moves resulted in an increase in the objective function value of 1 139 units. This layout nevertheless corresponds to a 21.89% improvement on the layout at LWC observed on the 17th of October 2002 [131].

5.3 Chapter Summary

There is a large variety of methods to solve a facility layout problem. During this study the conventional approach and a hybrid tabu search heuristic produced feasible results that could be implemented. The results obtained by means of the conventional approach were analyzed

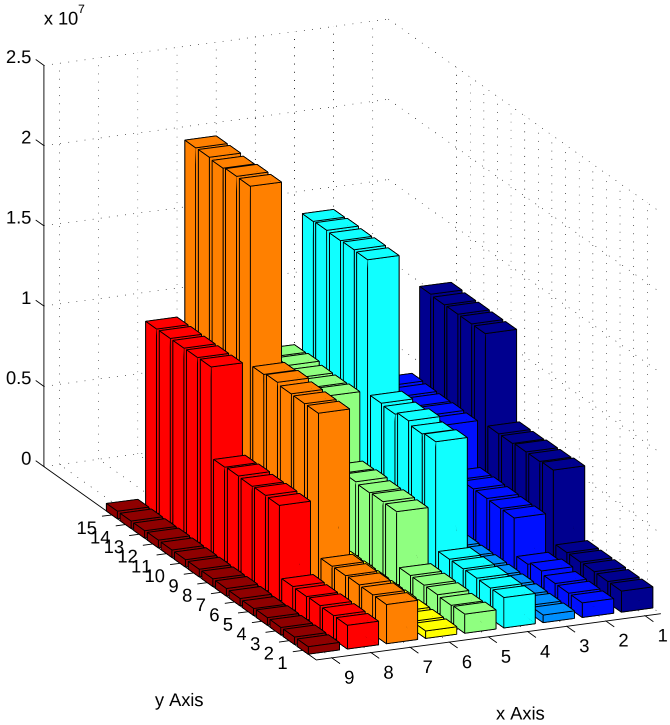

Figure 5.14: *Smallest objective function values obtained over all* 20 *replications of each run of the hybrid tabu search represented in Table 5.18, where the same parameter values map to the* x *and* y *values as explained in Tables 5.19(a) and (b).*

and inserted into the objective function of the problem producing the best result for the hybrid tabu search method. The hybrid tabu search heuristic result improved on the conventional approach result by 15.31%. This is due to a major disadvantage of the conventional method in that it is highly dependent on human intervention and is not as objective as the hybrid tabu search.

The results of this analysis were presented to LWC in November 2003. It was recommended to LWC that the layout obtained in the hybrid tabu search analysis should be implemented. A document was presented to LWC to explain the above mentioned methods in detail. The presentation was accompanied with a presentation of the decision support system that will be discussed in Chapter 7. The management of LWC was satisfied with the results obtained in the analysis and showed a positive reaction to the results, because they foresaw that an improved layout could potentially also improve upon production.

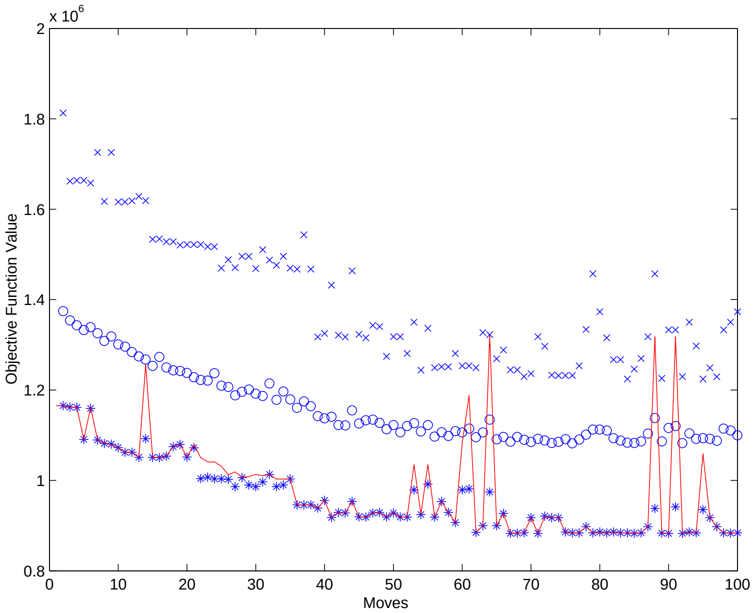

Figure 5.15: *The moves for run number 73 of the hybrid tabu search in Table 5.20 with* $\theta = 1.0$ *and a grid of* 12×11 *blocks. The crosses (stars, circles) indicate the maximum (minimum, average) objective function values after each move, computed over all 20 replications. The solid line shows the objective function value after each move of the replication producing the best layout obtained.*

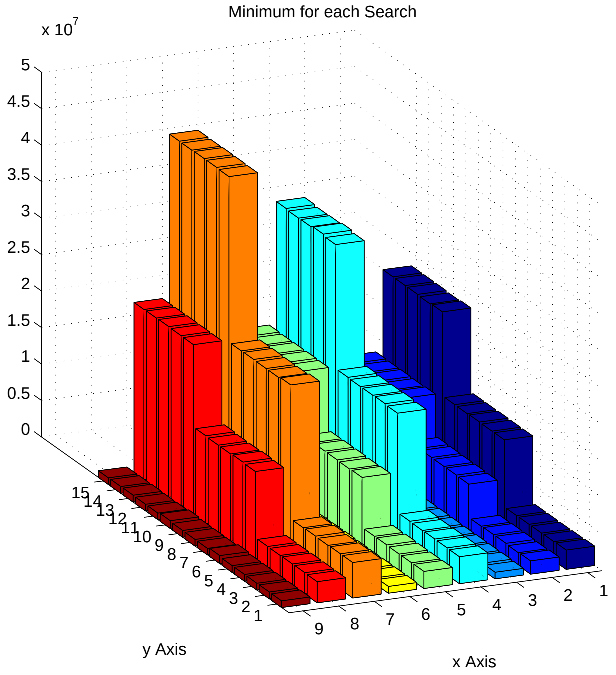

Figure 5.16: *Smallest objective function values obtained over all 20 replications of each run of the hybrid tabu represented in Table 5.20, where the parameter values map to the* x *and* y *values as explained in Tables 5.19(a) and (b).*

No	Ramp Cost Up	q	ρ	Tabu list Length	Initial Objective	Best Objective		No	Ramp Cost Up	q	ρ	Tabu list Length	Initial Objective	Best Objective
1	100	1.0	0.0	5	3 818 710	2 647 840		2	100	1	0	15	3 703 180	2 597 300
3	100	1	0	30	4 079 320	2 556 570		4	100	1	0	50	3 456 910	2 557 700
5	100	1	0	75	3 195 550	2 554 060		6	100	1	0.5	5	2 542 360	1 803 680
7	100	1	0.5	15	2 208 880	1 740 220		8	100	1	0.5	30	2 641 100	1 803 900
9	100	1	0.5	50	2 409 650	1 804 680		10	100	1	0.5	75	2 324 790	1 752 160
11	100	1	1	5	1 078 700	908 144		12	100	1	1	15	1 391 940	951 561
13	100	1	1	30	1 432 290	941 780		14	100	1	1	50	1 091 040	937 271
15	100	1	1	75	1 323 740	916 318		16	100	1.5	0	5	4 741 220	3 682 150
17	100	1.5	0	15	5 110 210	3 711 770		18	100	1.5	0	30	4 750 570	3 706 820
19	100	1.5	0	50	5 243 810	3 684 570		20	100	1.5	0	75	4 727 010	3 735 940
21	100	1.5	0.5	5	2 786 190	2 334 010		22	100	1.5	0.5	15	3 370 980	2 311 300
23	100	1.5	0.5	30	3 032 430	2 300 240		24	100	1.5	0.5	50	3 023 390	2 354 170
25	100	1.5	0.5	75	2 974 500	2 323 650		26	100	1.5	1	5	1 186 200	938 530
27	100	1.5	1	15	1 516 470	911 413		28	100	1.5	1	30	1 112 570	928 669
29	100	1.5	1	50	1 464 850	915 681		30	100	1.5	1	75	1 392 530	925 415
31	100	2	0	5	6 275 690	4 853 040		32	100	2	0	15	6 499 020	4 866 170
33	100	2	0	30	6 040 020	4 800 000		34	100	2	0	50	6 006 120	4 862 150
35	100	2	0	75	6 531 040	4 810 280		36	100	2	0.5	5	3 705 780	2 889 050
37	100	2	0.5	15	3 830 010	2 916 830		38	100	2	0.5	30	3 674 320	2 911 040
39	100	2	0.5	50	3 977 500	2 879 680		40	100	2	0.5	75	3 571 620	2 900 780
41	100	2	1	5	1 302 500	916 070		42	100	2	1	15	1 193 780	926 068
43	100	2	1	30	1 151 920	924 062		44	100	2	1	50	1 191 590	927 140
45	100	2	1	75	1 233 240	932 039		46	500	1	0	5	18 040 600	11 726 800
47	500	1	0	15	15 373 300	11 720 400		48	500	1	0	30	18 035 300	11 751 300
49	500	1	0	50	16 040 300	11 705 300		50	500	1	0	75	16 462 800	11 724 600
51	500	1	0.5	5	8 471 010	6 309 600		52	500	1	0.5	15	8 090 990	6 345 790
53	500	1	0.5	30	8 142 980	6 333 720		54	500	1	0.5	50	8 503 220	6 350 770
55	500	1	0.5	75	8 429 910	6 376 580		56	500	1	1	5	706 190	922 708
57	500	1	1	15	1 079 390	940 796		58	500	1	1	30	1 371 670	930 718
59	500	1	1	50	1 499 730	955 796		60	500	1	1	75	1 089 850	927 648
61	500	1.5	0	5	26 186 400	17 351 200		62	500	1.5	0	15	24 296 300	17 441 700
63	500	1.5	0	30	22 158 000	17 385 800		64	500	1.5	0	50	22 349 400	17 367 900
65	500	1.5	0	75	24 330 800	17 435 300		66	500	1.5	0.5	5	11 690 000	9 195 120
67	500	1.5	0.5	15	10 944 100	9 139 530		68	500	1.5	0.5	30	12 318 800	9 187 910
69	500	1.5	0.5	50	11 633 600	9 181 120		70	500	1.5	0.5	75	12 952 100	9 136 580
71	500	1.5	1	5	1 139 860	957 543		72	500	1.5	1	15	1 298 520	913 588
73	500	1.5	1	30	1 165 340	882 743		74	500	1.5	1	50	1 083 420	926 954
75	500	1.5	1	75	1 285 820	949 263		76	500	2	0	5	28 566 800	23 178 800
77	500	2	0	15	28 968 400	23 022 500		78	500	2	0	30	30 850 100	23 024 200
79	500	2	0	50	32 865 200	23 058 800		80	500	2	0	75	29 530 500	23 031 300
81	500	2	0.5	5	15 645 800	11 967 800		82	500	2	0.5	15	15 409 900	12 054 000
83	500	2	0.5	30	15 730 200	11 962 000		84	500	2	0.5	50	16 377 200	11 972 400
85	500	2	0.5	75	13 711 900	12 049 000		86	500	2	1	5	1 305 770	1 093 560
87	500	2	1	15	1 084 550	887 552		88	500	2	1	30	1 161 300	900 383
89	500	2	1	50	1 315 000	932 870		90	500	2	1	75	1 120 060	1 055 260
91	1 000	1	0	5	29 051 200	23 244 700		92	1 000	1	0	15	37 232 600	23 135 200
93	1 000	1	0	30	37 397 300	23 221 300		94	1 000	1	0	50	32 258 500	23 226 000
95	1 000	1	0	75	30 498 300	23 228 700		96	1 000	1	0.5	5	16 861 300	12 108 500
97	1 000	1	0.5	15	15 662 700	12 040 300		98	1 000	1	0.5	30	19 082 100	12 083 900
99	1 000	1	0.5	50	17 683 400	12 052 500		100	1 000	1	0.5	75	16 591 100	12 095 200
101	1 000	1	1	5	1 553 670	978 812		102	1 000	1	1	15	1 343 070	930 535
103	1 000	1	1	30	1 254 650	928 200		104	1 000	1	1	50	1 515 030	918 490
105	1 000	1	1	75	1 220 130	917 406		106	1 000	1.5	0	5	44 460 800	34 429 000
107	1 000	1.5	0	15	47 651 800	34 665 300		108	1 000	1.5	0	30	43 596 200	34 470 400
109	1 000	1.5	0	50	41 592 900	34 433 000		110	1 000	1.5	0	75	41 646 400	34 561 600
111	1 000	1.5	0.5	5	23 174 300	17 703 400		112	1 000	1.5	0.5	15	19 388 300	17 754 200
113	1 000	1.5	0.5	30	21 308 400	17 734 300		114	1 000	1.5	0.5	50	23 199 700	17 703 600
115	1 000	1.5	0.5	75	23 835 900	17 733 800		116	1 000	1.5	1	5	1 187 650	936 786
117	1 000	1.5	1	15	1 694 060	926 970		118	1 000	1.5	1	30	1 268 040	1 133 820
119	1 000	1.5	1	50	1 220 130	917 406		120	1 000	1.5	1	75	1 576 760	958 851
121	1 000	2	0	5	56 780 100	45 715 500		122	1 000	2	0	15	60 143 500	45 762 000
123	1 000	2	0	30	56 551 100	45 774 900		124	1 000	2	0	50	54 400 800	45 726 000
125	1 000	2	0	75	53 625 300	45 744 200		126	1 000	2	0.5	5	30 556 500	23 337 100
127	1 000	2	0.5	15	29 952 300	23 348 200		128	1 000	2	0.5	30	32 606 600	23 389 100
129	1 000	2	0.5	50	30 949 400	23 353 200		130	1 000	2	0.5	75	32 925 500	23 328 800
131	1 000	2	1	5	1 286 190	892 045		132	1 000	2	1	15	1 286 190	892 045
133	1 000	2	1	30	1 281 820	935 789		134	1 000	2	1	50	1 214 610	916 047
135	1 000	2	1	75	1 295 990	905 346								

Table 5.20: *Objective function values obtained for the* 135 *runs of the hybrid tabu search in which* $\theta = 1.0$ *on a grid of* 12 *blocks horizontally and* 11 *blocks vertically.*

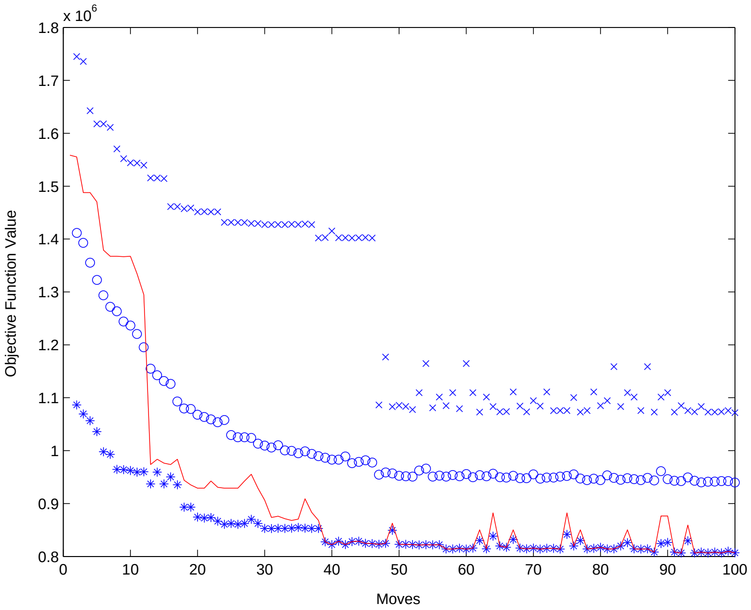

Figure 5.17: *The moves for run number 75 of the hybrid tabu search in Table 5.21 with* $\theta = 1.0$ *and a grid of* 22×21 *blocks. The crosses (stars, circles) indicate the maximum (minimum, average) objective function values after each move, computed over for all 20 replications. The solid line shows the objective function value after each move of the replication producing the best layout obtained.*

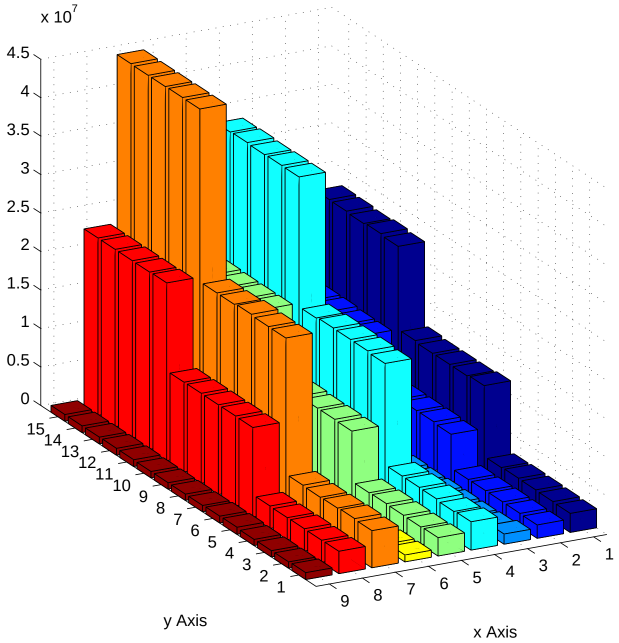

Figure 5.18: *Smallest objective function values obtained over all 20 replications of each run of the hybrid tabu search represented in Table 5.21, where the parameter values map to the* x *and* y *values as explained in Tables 5.19(a) and (b).*

No	Ramp Cost Up	q	ρ	Tabu list Length	Initial Objective	Best Objective		No	Ramp Cost Up	q	ρ	Tabu list Length	Initial Objective	Best Objective
1	100	1	0	5	3 374 850	2 471 110		2	100	1	0	15	3 278 540	2 542 910
3	100	1	0	30	3 842 940	2 595 640		4	100	1	0	50	3 716 280	2 638 200
5	100	1	0	75	3 576 930	2 561 180		6	100	1	0.5	5	2 332 790	1 736 500
7	100	1	0.5	15	2 722 160	1 772 770		8	100	1	0.5	30	2 669 480	1 804 480
9	100	1	0.5	50	2 603 040	1 782 670		10	100	1	0.5	75	2 418 600	1 783 930
11	100	1	1	5	1 635 730	1 318 120		12	100	1	1	15	1 630 040	968 233
13	100	1	1	30	1 570 320	886 226		14	100	1	1	50	1 605 120	910 005
15	100	1	1	75	1 452 730	904 440		16	100	1.5	0	5	4 791 210	3 688 760
17	100	1.5	0	15	4 776 750	3 558 500		18	100	1.5	0	30	5 417 800	3 727 140
19	100	1.5	0	50	4 863 740	3 738 820		20	100	1.5	0	75	4 942 130	3 748 100
21	100	1.5	0.5	5	3 415 580	2 394 230		22	100	1.5	0.5	15	2 702 350	2 313 060
23	100	1.5	0.5	30	3 555 600	2 347 030		24	100	1.5	0.5	50	3 679 470	2 387 430
25	100	1.5	0.5	75	3 217 670	2 345 550		26	100	1.5	1	5	1 378 180	899 118
27	100	1.5	1	15	1 200 840	898 272		28	100	1.5	1	30	1 060 160	876 987
29	100	1.5	1	50	1 240 910	1 016 880		30	100	1.5	1	75	1 405 460	885 920
31	100	2	0	5	6 180 070	4 819 080		32	100	2	0	15	5 920 750	4 912 780
33	100	2	0	30	6 257 080	4 829 770		34	100	2	0	50	6 691 310	4 768 370
35	100	2	0	75	6 986 350	4 860 810		36	100	2	0.5	5	3 537 400	2 904 840
37	100	2	0.5	15	4 167 420	2 881 050		38	100	2	0.5	30	4 068 810	2 902 870
39	100	2	0.5	50	3 694 170	2 871 720		40	100	2	0.5	75	3 826 350	2 916 100
41	100	2	1	5	1 160 090	885 740		42	100	2	1	15	1 699 210	825 987
43	100	2	1	30	1 815 590	815 819		44	100	2	1	50	1 213 830	814 918
45	100	2	1	75	1 124 150	914 161		46	500	1	0	5	15 871 800	11 742 000
47	500	1	0	15	15 719 600	11 559 100		48	500	1	0	30	18 095 600	11 557 200
49	500	1	0	50	16 214 300	11 538 200		50	500	1	0	75	17 027 900	11 712 800
51	500	1	0.5	5	8 880 110	6 176 290		52	500	1	0.5	15	9 876 820	6 327 380
53	500	1	0.5	30	8 877 800	6 322 180		54	500	1	0.5	50	9 200 140	6 337 750
55	500	1	0.5	75	8 868 170	6 332 380		56	500	1	1	5	1 376 030	816 222
57	500	1	1	15	1 333 910	925 512		58	500	1	1	30	1 723 740	820 295
59	500	1	1	50	1 262 140	814 323		60	500	1	1	75	1 195 420	818 612
61	500	1.5	0	5	22 889 100	16 917 200		62	500	1.5	0	15	25 064 200	17 081 400
63	500	1.5	0	30	21 836 500	17 088 900		64	500	1.5	0	50	22 461 200	17 114 800
65	500	1.5	0	75	23 186 300	16 955 700		66	500	1.5	0.5	5	12 011 900	8 891 800
67	500	1.5	0.5	15	12 721 300	8 953 610		68	500	1.5	0.5	30	11 999 200	8 933 850
69	500	1.5	0.5	50	12 400 600	9 052 730		70	500	1.5	0.5	75	10 966 200	9 160 150
71	500	1.5	1	5	1 335 180	810 682		72	500	1.5	1	15	1 455 280	815 930
73	500	1.5	1	30	1 519 470	809 708		74	500	1.5	1	50	1 382 850	813 201
75	500	1.5	1	75	1 558 560	806 504		76	500	2	0	5	26 936 100	22 515 500
77	500	2	0	15	30 508 200	22 525 000		78	500	2	0	30	30 949 900	22 666 700
79	500	2	0	50	28 601 000	22 490 300		80	500	2	0	75	26 390 100	22 494 900
81	500	2	0.5	5	15 480 500	11 650 100		82	500	2	0.5	15	14 067 700	11 678 400
83	500	2	0.5	30	16 046 300	11 668 700		84	500	2	0.5	50	15 792 600	11 680 700
85	500	2	0.5	75	16 181 700	11 661 200		86	500	2	1	5	1 200 280	894 902
87	500	2	1	15	1 461 050	808 334		88	500	2	1	30	1 368 260	816 672
89	500	2	1	50	1 256 270	822 296		90	500	2	1	75	1 310 180	819 154
91	1 000	1	0	5	32 257 500	22 487 400		92	1 000	1	0	15	32 239 700	22 684 700
93	1 000	1	0	30	27 558 900	22 523 200		94	1 000	1	0	50	35 811 900	22 666 100
95	1 000	1	0	75	33 908 300	22 712 800		96	1 000	1	0.5	5	16 119 800	11 716 200
97	1 000	1	0.5	15	16 794 800	11 741 300		98	1 000	1	0.5	30	17 190 900	11 903 300
99	1 000	1	0.5	50	17 059 200	11 896 300		100	1 000	1	0.5	75	17 207 700	11 923 600
101	1 000	1	1	5	1 224 430	888 932		102	1 000	1	1	15	1 461 700	889 899
103	1 000	1	1	30	1 200 430	900 433		104	1 000	1	1	50	1 453 070	883 731
105	1 000	1	1	75	1 536 290	870 682		106	1 000	1.5	0	5	47 254 900	33 811 900
107	1 000	1.5	0	15	45 543 100	33 831 400		108	1 000	1.5	0	30	47 134 100	33 774 400
109	1 000	1.5	0	50	46 805 400	33 873 700		110	1 000	1.5	0	75	51 339 500	33 779 200
111	1 000	1.5	0.5	5	23 810 100	17 409 700		112	1 000	1.5	0.5	15	24 130 400	17 417 500
113	1 000	1.5	0.5	30	24 252 500	17 433 200		114	1 000	1.5	0.5	50	23 991 800	17 500 500
115	1 000	1.5	0.5	75	25 263 300	17 433 000		116	1 000	1.5	1	5	1 619 850	888 752
117	1 000	1.5	1	15	1 299 830	916 336		118	1 000	1.5	1	30	1 306 220	885 002
119	1 000	1.5	1	50	1 524 220	903 299		120	1 000	1.5	1	75	1 788 160	917 927
121	1 000	2	0	5	58 724 800	44 941 200		122	1 000	2	0	15	65 255 600	44 955 200
123	1 000	2	0	30	63 923 300	44 919 200		124	1 000	2	0	50	64 727 000	44 911 900
125	1 000	2	0	75	60 709 000	44 956 000		126	1 000	2	0.5	5	31 560 800	23 090 200
127	1 000	2	0.5	15	31 325 700	23 034 900		128	1 000	2	0.5	30	33 362 600	23 045 300
129	1 000	2	0.5	50	32 947 600	23 043 900		130	1 000	2	0.5	75	30 219 800	23 054 700
131	1 000	2	1	5	1 232 740	884 129		132	1 000	2	1	15	1 479 530	899 083
133	1 000	2	1	30	1 688 810	877 853		134	1 000	2	1	50	1 229 970	864 193
135	1 000	2	1	75	1 201 170	885 378								

Table 5.21: *Objective function values obtained for all 135 runs of the hybrid tabu search in which $\theta = 1.0$ on a grid of 22 blocks horizontally and 21 blocks vertically.*

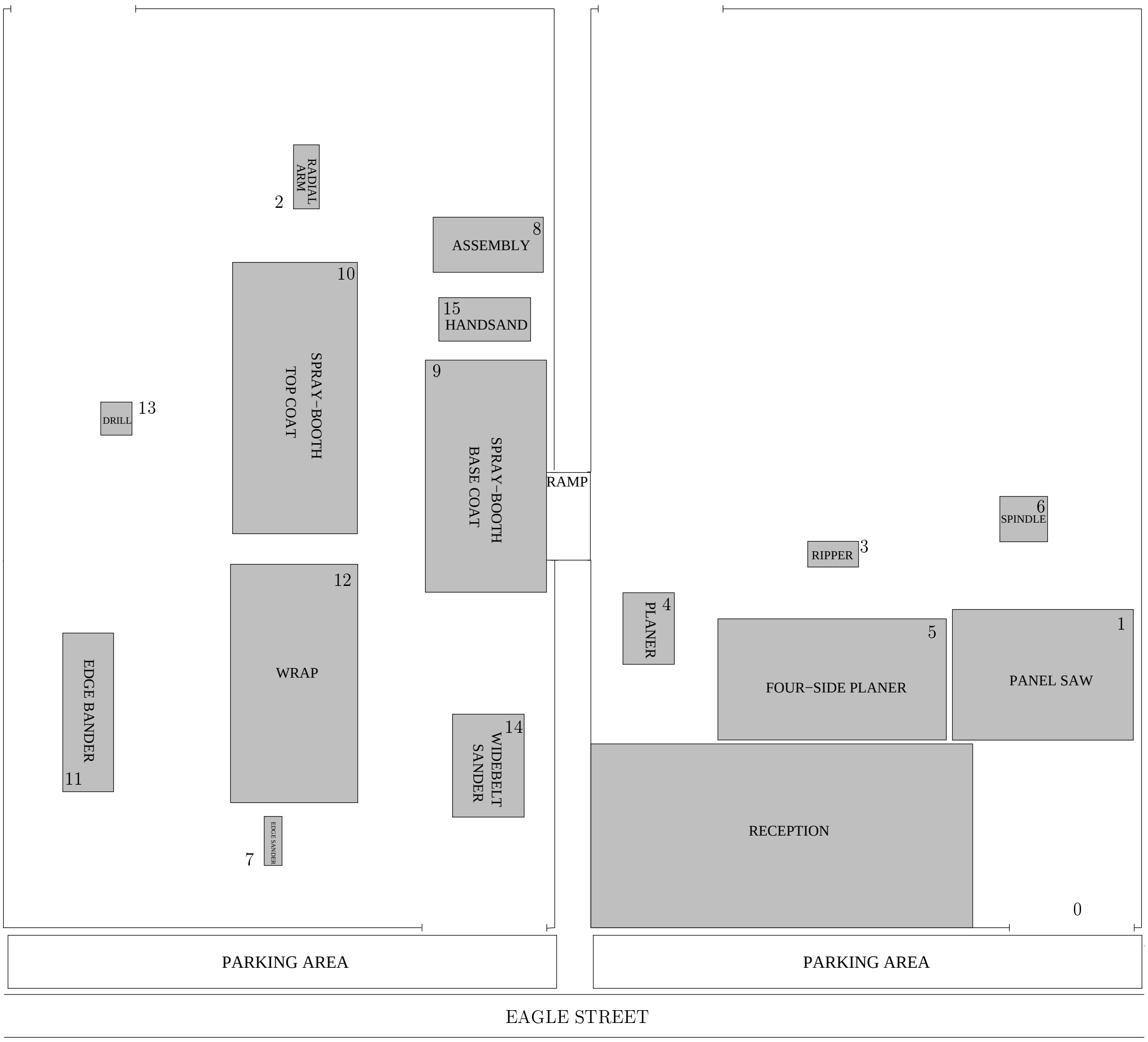

Figure 5.19: *The layout with the smallest objective function value (898 664) obtained for the layout problem at LWC, with* $\theta = 0.5$ *and* $\rho = 0.5$.

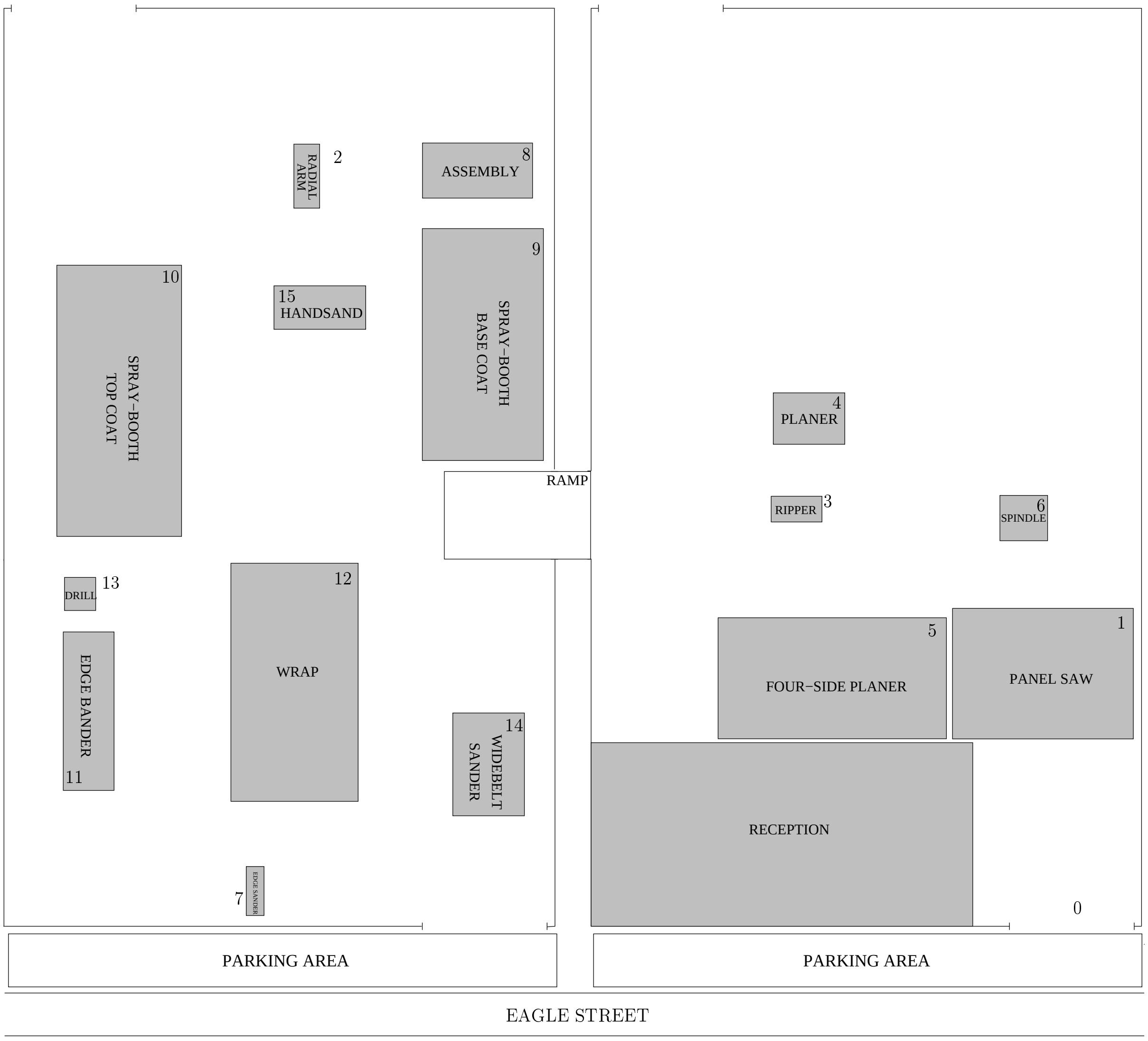

Figure 5.20: *Layout obtained after manual changes were made by the LWC management of the layout in Figure 5.19. The large gap at the top of the right hand side of the factory can be used to store all the raw material.*

Chapter 6

The Scheduling Problem at Loubser Wood Components

In this chapter the methodology of §3.2 is applied to the specific scheduling problem of Loubser Wood Components (LWC), as described in §4.5. LWC is an example of a job–shop manufacturing facility, because it manufactures a large variety of products with different processing sequences. This chapter opens with a discussion of the data analysis conducted to facilitate the scheduling method, followed in §6.2 by a discussion of the implementation challenges of the LWC modeling problem. This is followed by a description of the application of a heuristic scheduling method in §6.3 in an attempt to resolve the scheduling problem at LWC, as well as a comparison between the heuristic method and the current manual scheduling performed at LWC.

6.1 Data Analysis

In order to schedule tasks on machines, one of the core data elements required is the processing times of the machines. In the case of LWC the processing times on the machines are dependent on the order sizes. Considering the physical purposes of the machines, a number of different independent variables (physical measurements) were used to describe the processing times of the machines with the aid of regression models. The independent variables used to measure the processing times for the machines are presented in Table 6.1. The *cut length* of an order is the sum of the physical lengths of cuts made to obtain the component sizes of the order. *Running metres* is a measurement used by LWC for the length of edging that has to be attached to an order, in other words, the sum of the edges that need to be edged, either with solid wooden edges or veneer edging.

Data were collected on different occasions during the progression of this thesis, mainly with the aid of a stopwatch. The processing times collected at each machine, as well as the values of the independent variables used to estimate the processing times, are presented in Appendix D. In regression analysis the aim is to find a function that minimizes the error in the estimate of the dependent variable (processing time in this case) with respect to the data available. The curve thus obtained may only be used for values of the independent variables in the same range as those of the data collected, in order to obtain valid estimates of the processing times [measured in seconds]. The problem, therefore, is how to predict the processing times when the independent variables do not fall within the ranges of the data collected. Due to the lack of

No	Machine	Independent variable	Unit
1	Panel Saw	Cut Length	m
2	Radial Arm	Width	m
3	Ripper	Length	m
4	Planer	Length	m
5	Four–side Planer	Length	m
6	Spindle	Length	m
7	Edge Sander	Length	m
8	Assembly Station	Surface area	m^2
9	Base Coat Spray–booth	Surface area	m^2
10	Top Coat Spray–booth	Surface area	m^2
11	Edge Bander	Running metres	m
12	Wrapping Unit	Surface area	m^2
13	Drill	Number of holes	
14	Widebelt Sander	Surface area	m^2
15	Handsand Area	Surface area	m^2

Table 6.1: *The independent variables used for describing the machine processing times.*

data over the whole spectrum of possible data values it was assumed that the processing time behaves the same for larger values as in the regression curves obtained for smaller values. This assumption may only be good if the regression curves are concave or linear, in order to ensure that the estimated processing times for higher values, are not unrealistically high.

For regression curve fits, errors are typically assessed using a so–called *standard error* estimate and *correlation coefficient*. These estimates are not ideal, but they do give some indication of the quality of a regression curve with respect to the observed data. The standard error of the estimate is defined as

$$S = \sqrt{\frac{\sum_{i=1}^{n_q}(y_i - f(x_i))^2}{n_q - N_p}},$$

where $f(x_i)$ denotes the value of the dependent variable calculated from the regression model, where (x_i, y_i), $i = 1, \ldots, n_q$ denote the data points, and where N_p is the number of parameters in the particular model (so that the denominator is the number of degrees of freedom). The standard error of the estimate quantifies the spread of the data points around the regression curve. As the quality of the regression model increases, the standard error approaches zero [94].

Another measure of the accuracy of the regression model is the correlation coefficient. To explain the meaning of this measure, we return to the data points and define the *standard deviation*, which quantifies the spread of the data around the mean ($\overline{y}$), as

$$S_t = \sqrt{\sum_{i=1}^{n_q}(\overline{y} - y_i)^2},$$

where the mean of the data points is simply given by

$$\overline{y} = \frac{1}{n_q}\sum_{i=1}^{n_q} y_i.$$

The quantity S_t measures the spread around the mean of the data values as opposed to the spread around the regression model. S_t is therefore a measure of the uncertainty of the dependent variable y prior to regression. Also define the deviation from the regression curve as

$$S_r = \sqrt{\sum_{i=1}^{n_q} (y_i - f(x_i))^2}\,.$$

Note the similarity of this expression to the standard error of the estimate given above. This quantity likewise measures the spread of the points around the regression function, but does not take the number of degrees of freedom into account. Thus, the improvement (or error reduction) due to describing the data in terms of a regression model may be quantified by subtracting the two quantities. Because the magnitude of the quantity is dependent on the scale of the data, this difference is usually normalized to yield

$$r = \sqrt{\frac{S_t - S_r}{S_t}},$$

which is defined as the correlation coefficient. As the regression model describes the data more accurately, the correlation coefficient approaches unity. For a perfect fit, the standard error of the estimate is $S_r = 0$ and the correlation coefficient is $r = 1$.

6.1.1 Processing Time Estimates

The regression curves used to determine estimates for the machine processing times were based on the physical measurements (independent variables) of orders and were obtained by means of CurveExpert Version 1.37 for Microsoft Windows. The program uses the technique of least squares in an attempt at minimizing S_r. The best regression curves obtained are presented in Table 6.2, along with the standard error and correlation coeficient for each machine.

The regression curves obtained are presented graphically in Figure 6.1, superimposed onto measured data. A *growth curve*[1] was used to obtain the best fit for the data measured on the Panel Saw (Figure 6.1(a) and Table 6.2(1)). The fit was not particularly good, with an r value of 0.72, which implies that with this regression curve an accurate estimate is obtained only 72% of the time. However, the standard error is almost 5 minutes, which is not particularly high when viewed in the practical context of the problem.

In the case of the Radial Arm Saw (Figure 6.1(b) and Table 6.2(2)) a better estimate was obtained with a linear fit than with a growth curve. A correlation coefficient of $r = 0.83$ and a smaller standard error than with the Panel Saw was obtained. It is important to note that in this case fewer data points were used for the prediction, which may create the impression of a more accurate fit. The number of data points or measurements obtained for each machine are presented in Table 6.3.

A linear fit was obtained for the Ripper (Figure 6.1(c) and Table 6.2(3)) with a correlation coefficient of 0.95, and a standard error of almost 5.5 minutes, which is worse than the error of the Radial Arm. However, considering the practical context of the problem, 5.5 minutes is not expected to make a significant difference.

In the case of the Planer (Figure 6.1(d) and Table 6.2(4)) a growth curve produced the best estimated curve to the data, with a relatively high correlation coefficient of 0.92.

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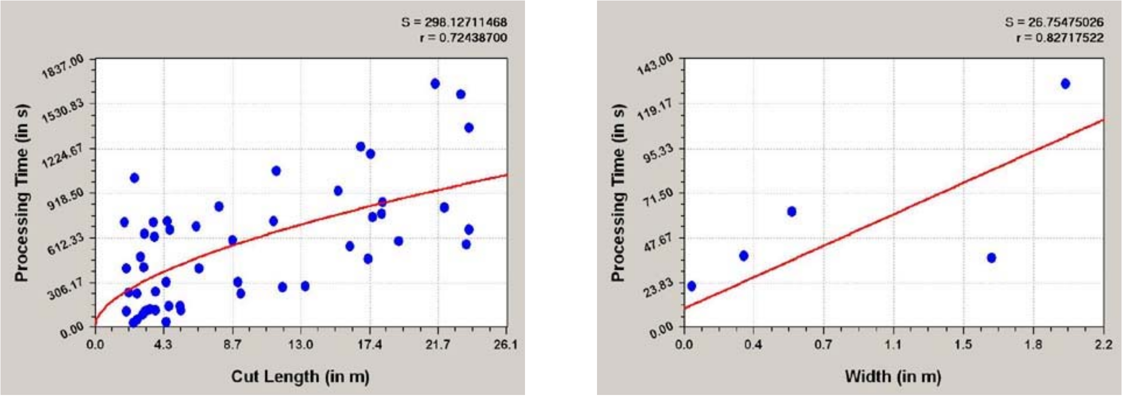
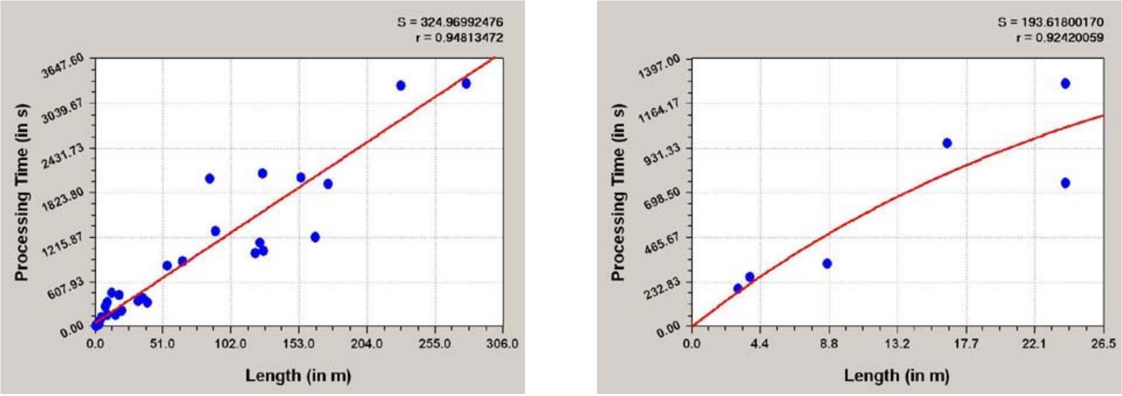
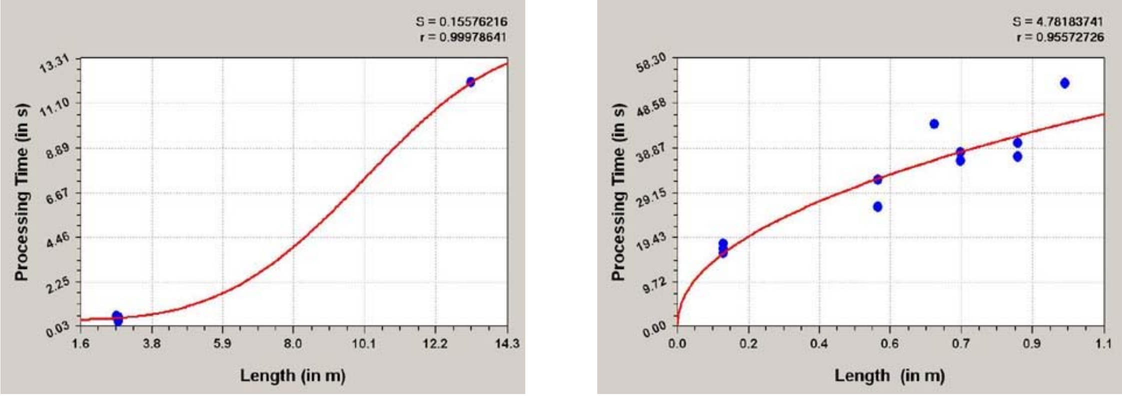
[1] A growth curve is characterized by a monotonic growth from some fixed point to an asymptote. A sigmoidal curve is also referred to as a growth curve, where the curve starts at a fixed point and increases its growth rate monotonically to reach an inflection point.



(a) *Processing time at the Panel Saw.* (b) *Processing time at the Radial Arm Saw.*



(c) *Processing time at the Ripper.* (d) *Processing time at the Planer.*



(e) *Processing time at the Spindle.* (f) *Processing time at the Edge Sander.*

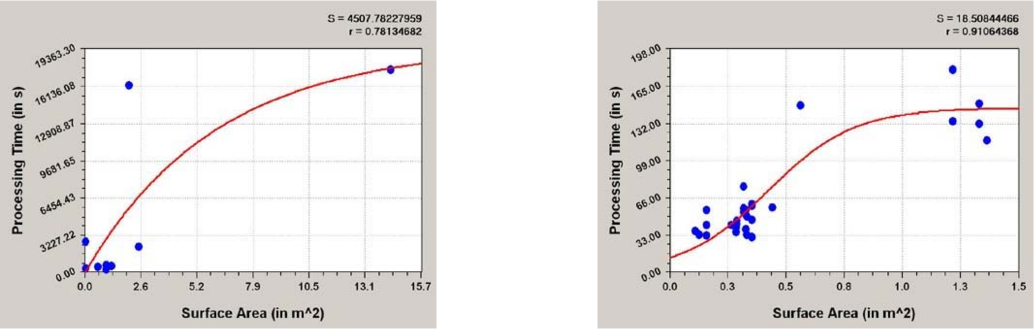
Figure 6.1: *The regression curves obtained when estimating the processing times [measured in seconds] of the processing machines at LWC. The regression equations are given in Table 6.2.*

No	Type of curve	Regression curve, $y = f(x)$	Parameter values	S_r [in s]	r
1	Growth	$y = \frac{ab+cx^d}{b+x^d}$	$a = 22.08$ $b = 1298844.80$ $c = 1.98 \times 10^8$ $d = 0.58$	298.13	0.72
2	Linear	$y = a + bx$	$a = 10.26$ $b = 46.13$	26.75	0.83
3	Linear	$y = a + bx$	$a = 56.88$ $b = 12.07$	324.97	0.95
4	Growth	$y = a(1 - e^{-bx})$	$a = 1813.60$ $b = 0.035$	193.62	0.92
5	Linear	$y = a + bx$	$a = 0$ $b = 12.508$	0	1
6	Growth	$y = a - be^{cx^d}$	$a = 14.24$ $b = 13.87$ $c = 1.74 \times 10^{-4}$ $d = 3.59$	0.155	1
7	Growth	$y = \frac{ab+cx^d}{b+x^d}$	$a = 0.67$ $b = 8804369.60$ $c = 3.79 \times 10^{-8}$ $d = 0.49$	4.78	0.96
8	Growth	$y = a(1 - e^{-bx})$	$a = 19616.06$ $b = 0.16$	4507.78	0.78
9	Growth	$y = \frac{a}{1+be^{-cx}}$	$a = 145.72$ $b = 9.97$ $c = 5.42$	18.51	0.91
10	Linear	$y = a + bx$	$a = 0$ $b = 222.24$	1336.95	0.92
11	Linear	$y = a + bx$	$a = 567.39$ $b = 28.57$	800.43	0.81
12	Linear	$y = a + bx$	$a = 0$ $b = 1.86$	0.89	0.99
13	Linear	$y = a + bx$	$a = 0$ $b = 144$	0	1
14	Growth	$y = \frac{ab+cx^d}{b+x^d}$	$a = 17.37$ $b = -354104.68$ $c = -55850989.00$ $d = 0.53$	440.88	0.71
15	Growth	$y = a(1 - e^{-bx})$	$a = 6458.85$ $b = 0.09$	1003.85	0.85

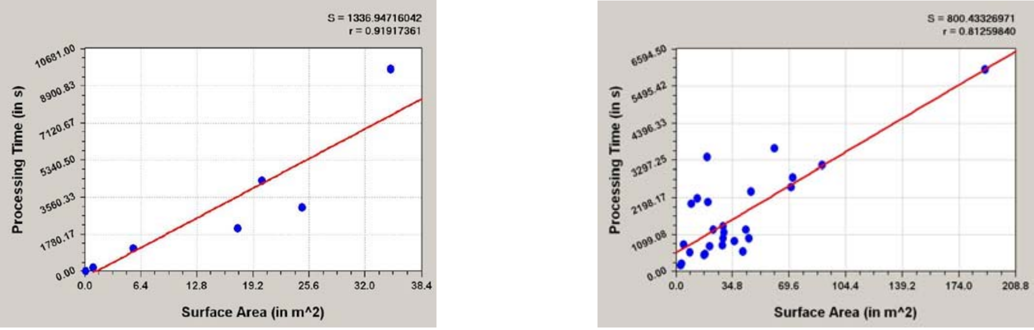
Table 6.2: *The regression curves obtained for processing times along with the standard error and correlation coefficient for each machine. The machines are listed and numbered in correspondence with the numbers in Table 6.1.*

Due to the different types of orders that were processed by LWC during the period of data capture, as well as the large amount of raw wood that was in inventory, only one data point could be captured for the Four–side Planer (Table 6.2(5)). A linear fit was therefore used to obtain an estimated processing time. The correlation coefficient was 1.00 for this fit, due to the lack of multiple data points.

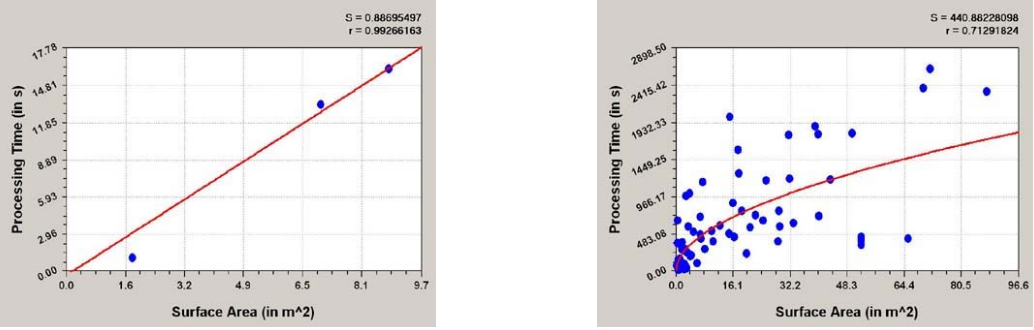
A very good fit was obtained for the Spindle (Figure 6.1(e) and Table 6.2(6)) by using a growth curve, although only 6 measurements were used to determine the estimated curve. The



(g) *Processing time at the Assembly Station.* (h) *Processing time at the Base Coat Spray–booth.*

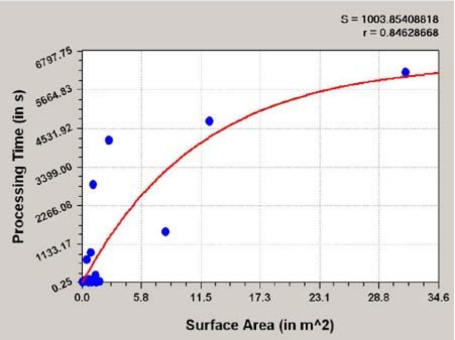


(i) *Processing time at the Top Coat Spray–booth.* (j) *Processing time at the Edge Bander.*



(k) *Processing time at the Wrapping Unit.* (l) *Processing time at the Widebelt Sander*

Figure 6.1 (continued): *The regression curves obtained when estimating the processing times [measured in seconds] of the processing machines at LWC. The regression equations are given in Table 6.2.*



(m) *Processing time at the Handsand Area.*

Figure 6.1 (continued): *The regression curves obtained when estimating the processing times [measured in seconds] of the processing machines at LWC. The regression equations are given in Table 6.2.*

regression yielded a correlation coefficient of 1.

The processing times of the Edge Sander (Figure 6.1(f) and Table 6.2(7)) could also be estimated with the aid of a growth curve. A correlation coefficient of 0.96 was obtained, which indicates that the curve predicts the processing time accurately for approximately 96% of the data points.

No	**Machine**	**Number of data points**
1	Panel Saw	51
2	Radial Arm	5
3	Ripper	32
4	Planer	6
5	Four–side Planer	1
6	Spindle	6
7	Edge Sander	13
8	Assembly Station	9
9	Base Coat Spray–booth	29
10	Top Coat Spray–booth	8
11	Edge Bander	26
12	Wrapping Unit	3
13	Drill	1
14	Widebelt Sander	79
15	Handsand Area	21

Table 6.3: *The number of data points obtained from measurements at each machine on the LWC factory floor.*

Moving on to the regression curve for the processing time of the Assembly station (Figure 6.1(g) and Table 6.2(8)), a growth curve with a correlation coefficient of 0.78 was obtained. The corresponding standard error was 1.25 hours, which is relatively large. This is due to a human factor that could not be incorporated into the measuring of the data. Some workers take longer than others to assemble the same size and type of order.

A correlation coefficient of 0.91 and a standard error of 18.51 were obtained for the growth curve fitted to the data collected at the Base Coat Spay–booth (Figure 6.1(h) and Table 6.2(9)), while a linear regression curve was fitted to the eight data points collected at the Top Coat Spray–booth (Figure 6.1(i) and Table 6.2(10)). In this case an error of approximately 22 minutes was obtained, which is also a relatively large error.

A large standard error of approximately 13 minutes was obtained with the linear regression curve fitted to the data collected at the Edge Bander (Figure 6.1(j) and Table 6.2(11)). This may be due to the different setup and processing times for orders with veneer edging and solid wooden edging. The veneer high capacity edging is done considerably faster than the solid wood edging.

Only 3 measurements could be collected for the Wrapping Unit (Figure 6.1(k) and Table 6.2(12)). A linear regression fit with a very good correlation coefficient of 0.99 and a standard error of approximately 1 minute was obtained from these data points.

Due to the different types of orders that were processed by LWC during the period of data capture only one data point could be captured for the Drill. A linear fit was therefore used to obtain the estimated processing time (Table 6.2(13)).

The best regression fit to the data collected on the Widebelt Sander (Figure 6.1(l) and Table 6.2(14)) was a growth function. A correlation coefficient of 0.71 was obtained, which is rather low. As mentioned in Chapter 4, the Widebelt Sander has different functions, which may have caused the low correlation coefficient.

A large standard error of approximately 17 minutes and a low correlation coefficient of 0.85 were obtained for the growth curve fitted to the data collected at the Handsand Area (Figure 6.1(m) and Table 6.2(15)). The main cause of this is the human factor involved when different numbers of workers are sanding at different times, as well as the small hand sanding machine which is sometimes used.

Using the limited data collected, the regression curves described above were used to predict the processing times on the machines at LWC, given certain order sizes. The cut length and running metres of an order also had to be predicted — this was also achieved with the aid of regression.

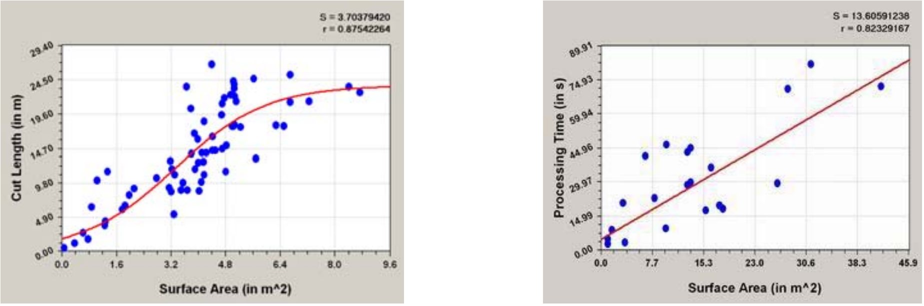
The surface area [measured in m^2] of a particular order was used as the unit of the independent variable in estimating the cutting length [measured in metres] of that order. A growth curve of the form

$$y = f(x) = \frac{a}{1 + be^{-cx}}$$

with $a = 23.71, b = 11.67$ and $c = 0.75$ fitted the data relatively accurately, with a standard error of $S = 3.70$ m and a correlation coefficient of $r = 0.88$ when 66 data points were used. A linear regression curve,

$$y = f(x) = a + bx$$

with $a = 4.80$ and $b = 1.72$ was used to estimate the running metres when the surface area [in m^2] was used as an independent variable. A standard error of $S = 13.6$ m and a correlation coefficient of 0.82 was obtained, which was relatively large. However, using another physical measurement as an independent variable did not produce a more accurate fit. The curves obtained for the cutting length and running metres are presented in Figure 6.2.



(a) *Fit for the cutting length.* (b) *Fit for the running metres.*

Figure 6.2: *The regression curves obtained in estimating the cutting length and running metre [in m].*

6.2 Case Study Implementation Challenges

The processing schedule for machines at a facility should be updated with the arrival of new jobs (orders) at the facility. In the case of the LWC production facility, the schedule is updated daily during a production meeting, at the start of each business day. When the models in this thesis were implemented at the LWC facility, in cases where jobs were not finished during the previous day, the remaining tasks of these jobs were viewed as separate jobs during the next (and consecutive) business days, and were therefore scheduled along with the new job arrivals. This is currently standard practice at LWC.

As mentioned in Chapter 4, LWC consists of two factory floors connected by means of a ramp with an incline. To incorporate this feature into the scheduling problem an additional processing time of 5 or 20 minutes (respectively for different problem instances) were added to a task on a machine on the top half of the factory floor when it is sequenced before a task on the lower half of the factory floor. It was assumed that there was no additional effort in time when moving material from the lower half of the factory to the upper half of the factory. The assumption was made that moving manufacturing material up the ramp is not more time consuming than moving manufacturing material between two machines on the same floor.

In order to simulate the current situation at LWC three dummy workstations or machines were incorporated into the scheduling problem. The first two stations were included to incorporate the time spent (a full or half a working day) by the LWC management to draw up a cutting plan for those orders that have to be cut on the Panel Saw as part of their processing sequence. Secondly, an additional workstation was included for the orders that have to go to an external Veneer Factory for a period of three days. Due to the fact that multiple jobs could be sent to the external Veneer Factory at the same time, the processing time between tasks on this dummy machine in the scheduling problem was taken as 1 second, but the processing time between this machine and the next machine in the processing sequence of the particular job was taken as three working days.

LWC manufactures a large variety of products, as mentioned in §4.4. Each of these products have different machine processing sequences. For documentation purposes each machine or workstation was numbered as shown in Table 6.4.

The machine processing sequences for the different types of products are presented in Table 6.5, using the numbers in Table 6.4. LWC also manufactures *ad hoc* products, for example cupboards or counters. The only *ad hoc* product for which the processing order was known,

No	Machine	No	Machine
1	Panel Saw	2	Radial Arm
3	Ripper	4	Planer
5	Four–side Planer	6	Spindle
7	Edge Sander	8	Assembly Station
9	Base Coat Spray–booth	10	Top Coat Spray–booth
11	Edge Bander	12	Wrapping Unit
13	Drill	14	Widebelt Sander
15	Handsand Area	16	Veneer Factory
17	Draw Cutting plan (1 day)	18	Draw Cutting plan ($\frac{1}{2}$ day)

Table 6.4: *The number associated with each machine throughout this thesis.*

is the so–called poster box. The processing sequences of all other *ad hoc* products were not available and therefore it was assumed that they were processed on machines 1 and 18, because most of these *ad hoc* orders had to be cut first. The other machines in those sequences could not be identified.

The job types, arrival and dispatch dates of all the jobs accepted in the last six months of 2002 are presented in Tables E.1–E.7 of Appendix E.

6.3 Tabu Search Implementation at LWC

In §3.2.1 two exact scheduling methods were described to solve the job–shop scheduling problem optimally by minimizing the total makespan of the jobs. Both methods solve a mixed integer linear programming model presented by Adams, *et al.* [2] with the aid of the branch–and–bound method. However, as mentioned in §3.2.1.2 the worst case complexity of the branch–and–bound method is exponential in the number of binary variables and constraints. Considering that some days 30 new jobs arrive at the LWC facility, which add up to a total of 210 new tasks on average (assuming a job has 7 tasks, on average), this situation results in a problem which is currently too large to solve within 16 hours. LWC must perform scheduling each day and therefore it is impractical if a solution cannot be obtained within 16 hours (seeing that the schedule might be changed on a daily basis). For this reason only the heuristic tabu search method has been implemented for the LWC scheduling problem. The particular tabu search heuristic method in question was developed by Nowicki & Smutnicki [148], as discussed in §3.2.2.

Recall that the graph $G(\pi) = (\mathcal{T}, \mathcal{A} \cup \mathcal{E}(\pi))$ consists of n nodes representing the tasks in the scheduling problem, where $\mathcal{A}$ is the set of conjunctive arcs, as defined in §2.3.2, and where

$$\mathcal{E}(\pi) = \cup_{k=1}^{m} \cup_{i=1}^{m_k - 1} \{(\pi_k(i), \pi_k(i+1))\}$$

represents the processing sequence of tasks on machines. Also, the graph $G(\pi)$ represents a feasible schedule if it is acyclic. In the LWC problem it may happen that two consecutive tasks of the same job are processed on the same machine (see order types 8 and 9 in Table 6.5, for example). In such cases $\mathcal{A} \cap \mathcal{E}(\pi) \neq \emptyset$, which may cause problems during implementation due to the fact that the changes in the task order on a machine, when trying to avoid cycles, may result in a change of the task order of a job. It was therefore decided that in cases where two consecutive tasks of the same order are processed on the same machine, the two tasks would be viewed as one task with a longer processing time, so as to decrease the complexity of the problem.

No	Description of the Component	Machine Processing Sequence
1	Contract Calibrate Sand	$\{14\}$
2	Contract Cut	$\{18, 1\}$
3	Contract Veneer Sand	$\{14\}$
4	Veneer Over Edge	$\{17, 1, 3, 14, 2, 15, 11, 14, 16, 1, 14, 15, 9, 14, 15, 10, 12\}$
5	Contract Spray Lacquer Top and Base Coat	$\{9, 15, 10\}$
6	Contract Edging	$\{11\}$
7	Board Components	$\{17, 1, 11, 14, 9, 14, 9, 14, 15, 10, 12\}$
8	Shaker Doors	$\{17, 1, 14, 6, 1, 6, 1, 14, 8, 14, 14, 15, 9, 15, 10, 13, 12\}$
9	Contract Calibrate and Veneer Sand	$\{14, 14\}$
10	Contract Cut and Edge	$\{18, 1, 11\}$
11	Contract Plane all Round(PAR)	$\{4\}$
12	Contract Spray: Stain Top Coat	$\{10\}$
13	Contract Spray: Base Coat	$\{9\}$
14	Components on Edge	$\{17, 1, 16, 1, 11, 14, 12\}$
15	Contract Cut, Edge and Groove	$\{18, 1, 11, 6\}$
16	Contract Cut and Calibrate Sand	$\{18, 1, 14\}$
17	Contract Spray: Base Coat and Route	$\{9, 6\}$
18	Contract Cut and Spray	$\{18, 1, 10\}$
19	Contract Cut, Edge and Calibrate Sand	$\{18, 1, 11, 14\}$
20	Contract Spray: Top and Base Coat and Edge Cut	$\{17, 1, 11, 9, 15, 10, \}$
21	Contract Edging and Calibrate Sand	$\{11, 14\}$
22	Contract PAR, Rip and Groove	$\{4, 3, 6\}$
23	Contract PAR, Calibrate and Veneer Sand	$\{4, 14, 14\}$
24	Contract Spray: Top and Base Coat	$\{9, 15, 10\}$
25	Contract Cut and Assembly	$\{18, 1, 8\}$
26	Contract Cut, Veneer Sand and Edging	$\{18, 1, 14, 11\}$
27	Contract PAR and Edging	$\{18, 1, 14, 11\}$
28	Contract Spray: Lacquer Top and Base Coat and Calibrate and Veneer Sand	$\{14, 9, 15, 14, 10\}$
29	Contract Spray: Top and Base Coat and Edging	$\{11, 9, 15, 10\}$
30	Contract Spray: Top and Base Coat, Calibrate and Veneer Sand	$\{14, 9, 15, 14, 10\}$
31	Contract Groove	$\{6\}$
32	Contract Cut and Route	$\{18, 1, 8\}$
33	Unique Product: Poster Boxes	$\{18, 1, 6, 1, 8, 15, 9, 7, 15, 9, 12\}$

Table 6.5: *A summary of the machine processing sequences of different components manufactured over a period of six months.*

The objective of the tabu search method is to minimize the makespan of the schedule. Considering a particular day, the input to the scheduling model is the machine processing sequence of jobs starting on that particular day and incompleted jobs from the previous day. A solution to the problem is given in the form of starting times for the tasks on the different machines for that day. The scheduling process is repeated for each working day under the assumption that no new jobs will be added the next day, because it is not known which jobs will arrive in the next day. A number of different tabu search runs were preformed using different parameter value combinations. Tabu list lengths of $f_{\max} = 5,\ 15,\ 30$ and 50 were implemented respectively and the search was terminated after 3 000 iterations. The list $\mathcal{L}$ was assumed to have a maximum length of $\mathcal{L}_{\max} = 5$ or 25 nodes. These two values were chosen to cater for a short and long list respectively. In the case where a node in the list $\mathcal{L}$ at position ℓ was used during backtracking, the maximum number of iterations was readjusted to be $3\,000 - 400 \times (\mathcal{L}_{\max} - \ell)$ iterations. This was performed to ensure that with each backtrack the tabu search could complete less moves than before to reduce the processing time. An additional stopping criterion was implemented to test for cycles of length, $1 \leq \delta \leq \delta_{\max}$, with $\delta_{\max} \in \{25, 50, 75, 100\}$, during the search process, testing for the start of a cycle in the search process as far back as $\eta = c \times \delta_{\max}$ iterations, where $c \in \{10, 20\}$. This was especially important due to the backtracking performed by using nodes saved in the backtrack list $\mathcal{L}$. The tabu search heuristics implemented in a C++ program was tested on the Fisher & Thompson [74] benchmark problem consisting of 6 processors and 6 jobs with 6 tasks for each job, and the same results as indicated by Nowicki & Smutnicki [148] were obtained.

During the search process an initial schedule was determined using the shortest processing time priority dispatch rule. Each run was performed on the data collected at LWC for the six months spanning, 7th of June 2002 to 18th of December 2002. The data used for the scheduling problem consisted of the starting dates and dispatch dates of jobs that entered the factory. The actual starting and resulting dispatch dates of the orders along with the LWC dispatch dates of the orders are presented in Tables E.1–E.7 in Appendix E for the six months separately.

Since the details of jobs that commenced before the 7th of June 2002 were unavailable, and because a number of these jobs would have been processed during the period 7th to 30th of June 2002, the processing times of jobs during this period could not be seen as a true representation of reality. Therefore, this period is typically referred to as a warm–up period. Jobs that were completed after the 18th of December 2002 were also excluded from the runs since these jobs, in reality, would be processed together with jobs that commenced after the 18th of December 2002, for which no data were available. The period after the 18th of December 2002 is typically referred to as the cool–down period. The data for the period before the 1st of July 2002 were included into the runs, but not into the calculation of the objective function value to cater for the warm–up and cool–down periods.

An objective function had to be derived to compare the global solutions of the tabu scheduling runs to the scheduling that was performed at LWC between the warm–up and cool–down periods. The net flow time F_j of job j may be defined as the length of the time interval between the starting time (s_j) and the completion time (C_j) of job j, *i.e.*,

$$F_j = C_j - s_j.$$

The objective function used for the comparison between the tabu scheduling runs and the actual scheduling that was done at LWC was the total net flow time $\mathcal{G} = \sum_{\forall j} F_j$ [measured in days]. This objective function gives an indication of the number of “net flow” days saved as a result of improved scheduling within the six months spanning the different jobs. The different runs and their objective function values are presented in Table 6.6 and 6.7 with ramp costs of 5 minutes and 20 minutes respectively. The variation in the cycle lengths as stopping criteria did not make any difference in the objective function values obtained.

Tabu List Length($f_{\max}$)	**Backtrack ($\mathcal{L}_{\max}$)**	**Total Net Flow Time [Days] (LWC)**	**Total Net Flow Time [Days]**	**% Improvement**
5	5	8 354	2 771	66.84%
15	5	8 354	2 785	66.67%
30	5	8 354	2 756	67.02%
50	5	8 354	2 763	66.94%
5	25	8 354	2 755	67.03%
15	25	8 354	2 785	66.67%
30	25	8 354	2 772	66.83%
50	25	8 354	2 772	66.83%

Table 6.6: *The different variable and objective function values for various runs at a ramp cost of 5 minutes. LWC actually achieved a total net flow time of the jobs of* 8 354 *days.*

The best objective function value obtained with the assumption of a ramp cost of 5 minutes was obtained during a run with a tabu list length of 5 and a backtrack list length of 25. This run exhibited a 67.03% improvement on the actual (manual) scheduling done at LWC. The starting and dispatch days of this best solution obtained are compared to the LWC starting and dispatch dates in Table F.2 in Appendix F. In the last columns of these tables the percentages improvement in the net flow time per job are displayed. The average percentage improvement of the net flow time per job was 36.66%.

Tabu List Length($f_{\max}$)	**Backtrack ($\mathcal{L}_{\max}$)**	**Total Net Flow Time [Days] (LWC)**	**Total Net Flow Time [Days]**	**% Improvement**
5	5	8 354	3 418	58.96%
15	5	8 354	3 376	59.46%
30	5	8 354	3 380	59.41%
50	5	8 354	3 378	59.41%
5	25	8 354	3 387	59.33%
15	25	8 354	3 411	59.04%
30	25	8 354	3 405	59.04%
50	25	8 354	3 423	58.89%

Table 6.7: *The different variable and objective function values for various runs at a ramp cost of 20 minutes. LWC actually achieved a sum of the total net flow time of the jobs of* 8 354 *days.*

The best objective function value obtained with the assumption of a ramp cost of 20 minutes was obtained during a run with a tabu list length of 15 and a backtrack list length of 5. This run exhibited a 59.46% improvement on the actual (manual) scheduling done at LWC. The starting and dispatch days of this best solution obtained are compared to the LWC starting and dispatch dates in Table F.2 of Appendix F. In the last columns of these tables the percentages improvement in the net flow time per job are displayed. The average percentage improvement of the net flow time per job was 17.48%.

6.4 Chapter Summary

There is a large variety of methods available that may be used to solve job–shop scheduling problems (approximately or exactly). Considering time constraints when schedules are constructed it is recommended that a heuristic method is used rather than an exact method, for realistically sized problem instances.

The tabu search method developed by Nowicki & Smutnicki [148] was implemented and adjusted to suit the practical nature of the LWC scheduling problem. An overall improvement of more than 50% in the total net flow time was achieved, compared to the results of the actual (manual) method used at LWC. However, more data points may and should be used in the future, so as to obtain better estimated processing times, especially for the Radial Arm Saw, Edge Bander, Assembly Station and Handsand Area.

It is recommended that the data of all the jobs conducted at LWC be kept and that time sheets are filled in by project managers to ensure that when the tabu search model is implemented it keeps on producing results simulating the reality in the manufacturing facility. At the time of the delivery of this thesis the solutions obtained in the job–shop scheduling part have not yet been delivered to LWC.

Chapter 7

The LWC Decision Support System

The main deliverables to LWC with respect to the research conducted in this thesis were two decision support systems (DSS), one for the layout problem and one for the scheduling problem at LWC. In this chapter the use of both these DSSs are discussed.

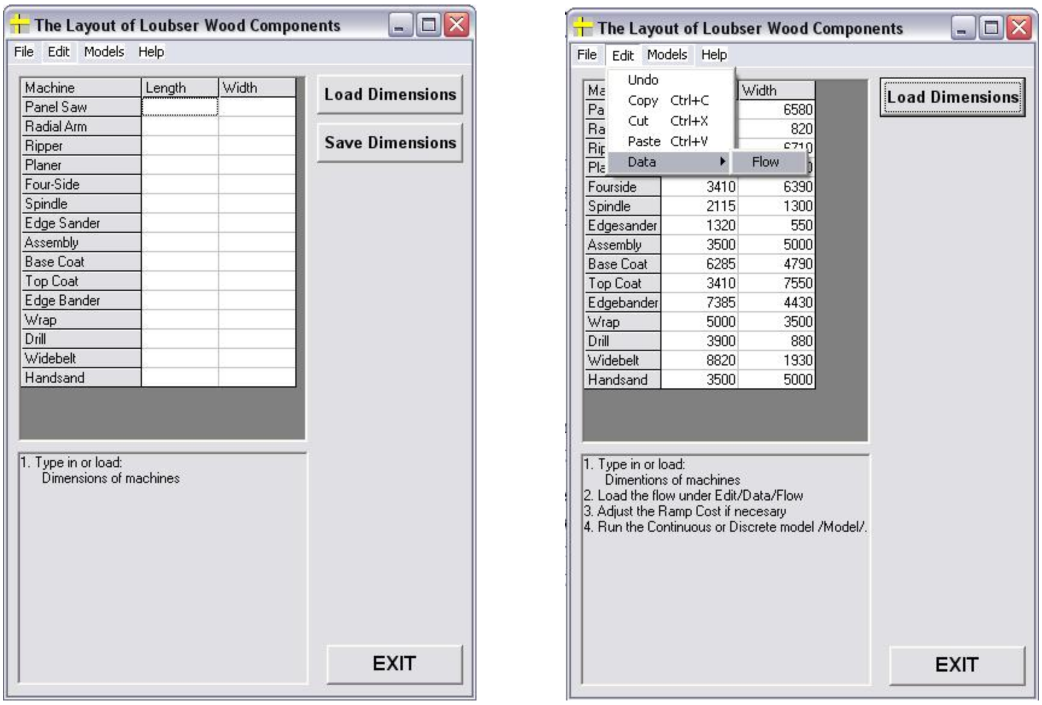
7.1 The DSS for the Layout Problem

The DSS for the layout problem was developed within a Microsoft Visual Basic support shell. The user is prompted to provide input values for the applicable parameters, such as θ and ρ, as well as the dimensions of the machines and layout area. The DSS makes provision for the two exact models, namely the discrete and continuous layout models, as well as for the tabu search method for the discrete problem.

The main screen prompts the user for the specific dimensions of the machines, as shown in Figure 7.1(a). The machine dimensions are only expected to change when new machine are bought or old ones are replaced. Therefore it would be inefficient to re–enter all the dimensions every time the program is used. The machine dimensions may hence be saved in memory by selecting the **save dimensions** button in the top right hand corner of the main window, shown in Figure 7.1(a) to ease their input, and may be loaded by means of the **load dimensions** button (above the **save dimensions** button) in the main window as shown in Figure 7.1(a).

After implementation of the DSS, the flow volumes between the machines should be updated monthly. For the results in Chapter 5 of this thesis the flow volumes between the machines were loaded as obtained during the 6 month period from July 2002 until December 2002. This data may be updated by selecting the *Data/Flow menu* under the *Edit menu* shown in Figure 7.1(b). In the resulting flow window shown in Figure 7.2, the standard product types are listed on the right hand side of the window. The flow volumes of the product types are shown in m^2 per six months and should be updated regularly. The **compute** button at the bottom of the window may be used to compute the different flow volumes between the machines in m^2 per six months by using the standard machine sequences for the particular set of products. The **save & exit** button may be used to save the different flow volumes into a matrix similar to the one on the left hand side of Figure 7.2. This matrix is used in calculations at a later stage.

The next step is to select one of the three different models that may be used in the DSS, by selecting the appropriate option under the *Models menu* in Figure 7.1. The usages of these three models are described in the following three subsections.



Machine	Length	Width
Panel Saw		
Radial Arm		
Ripper		
Planer		
Four-Side		
Spindle		
Edge Sander		
Assembly		
Base Coat		
Top Coat		
Edge Bander		
Wrap		
Drill		
Widebelt		
Handsand		

1. Type in or load:
Dimensions of machines

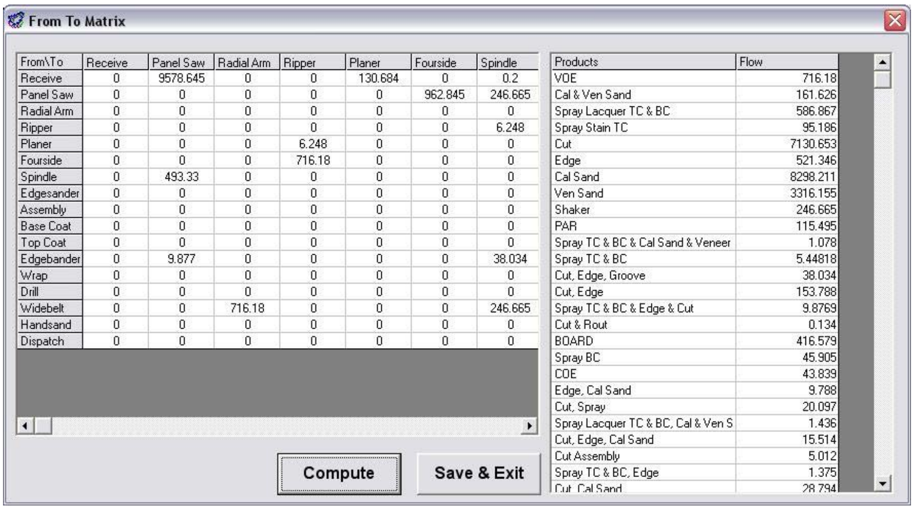
Ma		Width
Pa		6580
Ra		820
Rip		[illegible]
Pla		
Fourside	3410	6390
Spindle	2115	1300
Edgesander	1320	550
Assembly	3500	5000
Base Coat	6285	4790
Top Coat	3410	7550
Edgebander	7385	4430
Wrap	5000	3500
Drill	3900	880
Widebelt	8820	1930
Handsand	3500	5000

1. Type in or load:
Dimentions of machines
2. Load the flow under Edit/Data/Flow
3. Adjust the Ramp Cost if necesary
4. Run the Continuous or Discrete model /Model/.

(a) *The main window of the Layout DSS.*

(b) *Selection of the flow window used to import the new flow volumes between machines. In the bottom left hand side the steps that should be taken are logged.*

Figure 7.1: *The main window of the Layout DSS and the selection of the flow window to import new flow volumes between machines.*



From\To	Receive	Panel Saw	Radial Arm	Ripper	Planer	Fourside	Spindle
Receive	0	9578.645	0	0	130.684	0	0.2
Panel Saw	0	0	0	0	0	962.845	246.665
Radial Arm	0	0	0	0	0	0	0
Ripper	0	0	0	0	0	0	6.248
Planer	0	0	0	6.248	0	0	0
Fourside	0	0	0	716.18	0	0	0
Spindle	0	493.33	0	0	0	0	0
Edgesander	0	0	0	0	0	0	0
Assembly	0	0	0	0	0	0	0
Base Coat	0	0	0	0	0	0	0
Top Coat	0	0	0	0	0	0	0
Edgebander	0	9.877	0	0	0	0	38.034
Wrap	0	0	0	0	0	0	0
Drill	0	0	0	0	0	0	0
Widebelt	0	0	716.18	0	0	0	246.665
Handsand	0	0	0	0	0	0	0
Dispatch	0	0	0	0	0	0	0

Products	Flow
VOE	716.18
Cal & Ven Sand	161.626
Spray Lacquer TC & BC	586.867
Spray Stain TC	95.186
Cut	7130.653
Edge	521.346
Cal Sand	8298.211
Ven Sand	3316.155
Shaker	246.665
PAR	115.495
Spray TC & BC & Cal Sand & Veneer	1.078
Spray TC & BC	5.44818
Cut, Edge, Groove	38.034
Cut, Edge	153.788
Spray TC & BC & Edge & Cut	9.8769
Cut & Rout	0.134
BOARD	416.579
Spray BC	45.905
COE	43.839
Edge, Cal Sand	9.788
Cut, Spray	20.097
Spray Lacquer TC & BC, Cal & Ven S	1.436
Cut, Edge, Cal Sand	15.514
Cut Assembly	5.012
Spray TC & BC, Edge	1.375
Cut, Cal Sand	28.794

Figure 7.2: *The flow window used to update flow volumes between machines.*

7.1.1 The Discrete Exact Model

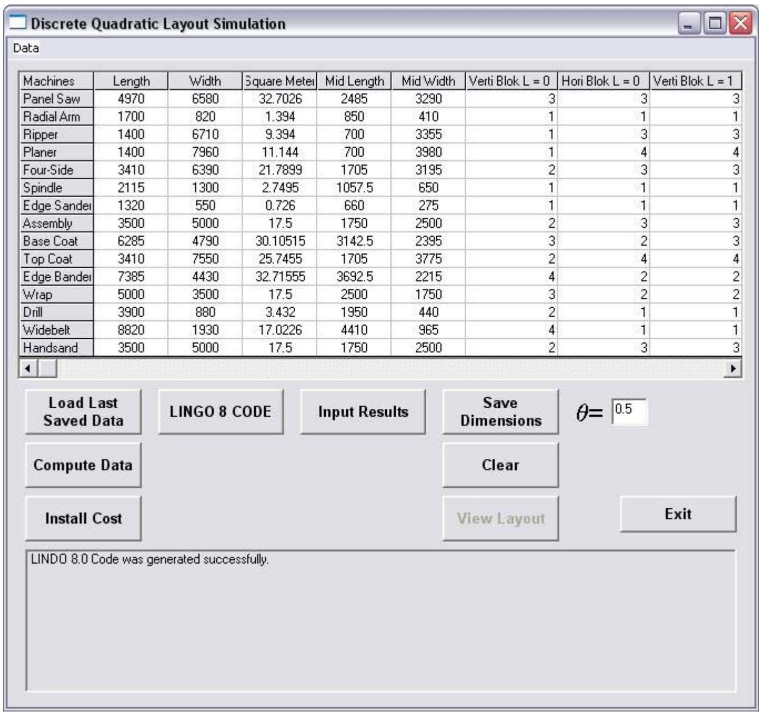
It should be noted that both the exact models can only be applied to very small problem instances, due to the long computational times involved in their solution methods. The DSS generates code as input for the **Lingo 8.0** optimization package and the results obtained by this package are then automatically inserted back into the DSS.

The discrete exact model may be selected by means of the *Discrete Quadratic/Exact menu* under the *Models menu*, to obtain the window shown in Figure 7.3. The first step is to load the saved machine dimensions into the table by clicking on the **Load Last Saved Data** button. This action generates the first five columns of the table. The selection of the **Save Dimensions** button, saves the name, length, width, mid length and mid width of each machine in the table. The blocks used in the discrete model may be calculated by selecting the **Compute Data** button that becomes available upon loading of the data. The number of grid–points in the horizontal and vertical directions are then computed automatically. Due to the fact that the facility should comprise two sides of equal width the number of points in the horizontal direction should be even. The **Clear** button clears the whole table after which the data have to be re–entered and computed again. Clicking on the **Install Cost** button opens a window showing the hard coded installation costs of the machines. A value for the parameter θ, which is used in the objective function, should also be provided. This may be achieved by entering a value in the window provided for θ, as shown in the right hand side of Figure 7.3. The distances between the machines may be updated by selecting the *Data/Distance menu*, as shown in Figure 7.4. The ramp cost value, as well as the value of ρ and the percentage of the ramp cost down, may be specified here. By clicking the **Compute** button the distances between all possible grid–points are calculated. This information are saved in matrix format, to be inserted into the model, by clicking on the **Exit** button. Finally, back at the screen in Figure 7.3 the **Lingo 8.0 code** button must be selected, upon which **Lingo** code is generated in a file in the root directory of the system, called `layout.txt`. This file should be opened in **Lingo 8.0** and the resulting **Lingo** output should be saved in a file with extension `*.lgr`. This file is then used as input into the DSS by selecting the **Input Results** button. The **View Layout** button may be selected to visually present the layout to the DSS user. Due to the size of the LWC problem, it could not be solved within a feasible time span and therefore no screen shot of the layout can be presented.

7.1.2 The Continuous Exact Model

The user also has the option to select the continuous model to solve the layout problem optimally. This may be done by selecting the *Continuous Linear* option under the *Models menu*. In the continuous linear modeling window the user has the option to specify how many floors the facility has, the cost of three phase cable per metre, the physical dimensions of the facility and the respective installation costs per machine, as presented in Figure 7.5.

After all of the above mentioned information has been entered the user may generate the model by selecting the **Compute Lingo code** button. A **Lingo 8.0** file, called `ContiLin.lg4` will then be created. The user may open and run this file in **Lingo 8.0** to obtain a solution. The user may then input the solution obtained via **Lingo 8.0** into the Microsoft Visual Basic program by selecting the **Input data from *.lgr** button, as presented in Figure 7.5, to view a graphical display of the layout. Again, due to the size of the LWC layout problem, it cannot be displayed in a screen shot, because the problem could not be solved within feasible time constraints.

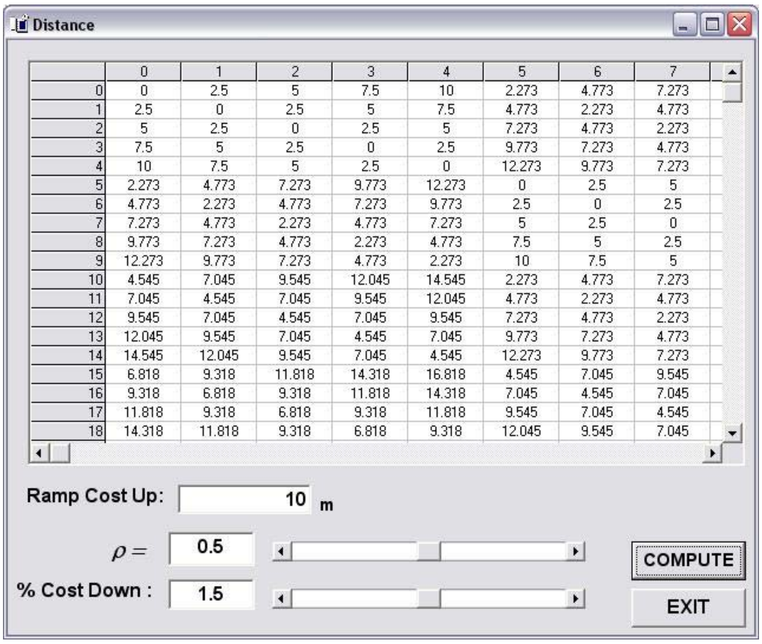


Machines	Length	Width	Square Meter	Mid Length	Mid Width	Verti Blok L = 0	Hori Blok L = 0	Verti Blok L = 1
Panel Saw	4970	6580	32.7026	2485	3290	3	3	3
Radial Arm	1700	820	1.394	850	410	1	1	1
Ripper	1400	6710	9.394	700	3355	1	3	3
Planer	1400	7960	11.144	700	3980	1	4	4
Four-Side	3410	6390	21.7899	1705	3195	2	3	3
Spindle	2115	1300	2.7495	1057.5	650	1	1	1
Edge Sander	1320	550	0.726	660	275	1	1	1
Assembly	3500	5000	17.5	1750	2500	2	3	3
Base Coat	6285	4790	30.10515	3142.5	2395	3	2	3
Top Coat	3410	7550	25.7455	1705	3775	2	4	4
Edge Bander	7385	4430	32.71555	3692.5	2215	4	2	2
Wrap	5000	3500	17.5	2500	1750	3	2	2
Drill	3900	880	3.432	1950	440	2	1	1
Widebelt	8820	1930	17.0226	4410	965	4	1	1
Handsand	3500	5000	17.5	1750	2500	2	3	3

$\theta=$ 0.5

LINDO 8.0 Code was generated successfully.

Figure 7.3: *The window used to specify the parameters required by the discrete exact model.*



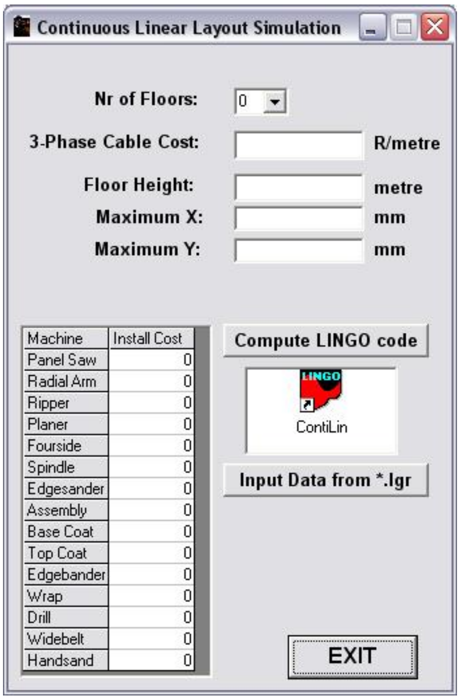
	0	1	2	3	4	5	6	7
0	0	2.5	5	7.5	10	2.273	4.773	7.273
1	2.5	0	2.5	5	7.5	4.773	2.273	4.773
2	5	2.5	0	2.5	5	7.273	4.773	2.273
3	7.5	5	2.5	0	2.5	9.773	7.273	4.773
4	10	7.5	5	2.5	0	12.273	9.773	7.273
5	2.273	4.773	7.273	9.773	12.273	0	2.5	5
6	4.773	2.273	4.773	7.273	9.773	2.5	0	2.5
7	7.273	4.773	2.273	4.773	7.273	5	2.5	0
8	9.773	7.273	4.773	2.273	4.773	7.5	5	2.5
9	12.273	9.773	7.273	4.773	2.273	10	7.5	5
10	4.545	7.045	9.545	12.045	14.545	2.273	4.773	7.273
11	7.045	4.545	7.045	9.545	12.045	4.773	2.273	4.773
12	9.545	7.045	4.545	7.045	9.545	7.273	4.773	2.273
13	12.045	9.545	7.045	4.545	7.045	9.773	7.273	4.773
14	14.545	12.045	9.545	7.045	4.545	12.273	9.773	7.273
15	6.818	9.318	11.818	14.318	16.818	4.545	7.045	9.545
16	9.318	6.818	9.318	11.818	14.318	7.045	4.545	7.045
17	11.818	9.318	6.818	9.318	11.818	9.545	7.045	4.545
18	14.318	11.818	9.318	6.818	9.318	12.045	9.545	7.045

Ramp Cost Up: 10 m

$\rho =$ 0.5

% Cost Down : 1.5

Figure 7.4: *The window used to specify the distances between the grid–points.*



Nr of Floors: 0

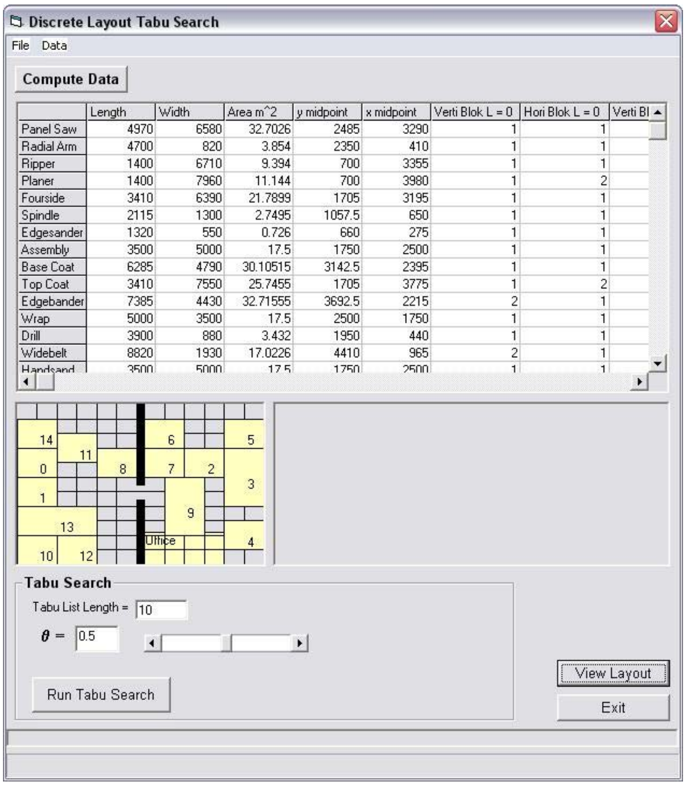
Machine	Install Cost
Panel Saw	0
Radial Arm	0
Ripper	0
Planer	0
Fourside	0
Spindle	0
Edgesander	0
Assembly	0
Base Coat	0
Top Coat	0
Edgebander	0
Wrap	0
Drill	0
Widebelt	0
Handsand	0

Figure 7.5: *The window used for specifying the parameters required by the exact continuous linear model.*

7.1.3 The Tabu Search Heuristic Model

The final option the user has is to opt for the heuristic tabu search method to obtain a good solution for the discrete quadratic model for the layout problem. This may be achieved by selecting *Discrete Quadratic/Heuristic/Tabu Search* from the *Models menu*, which opens the window displayed in Figure 7.6.

First, the number of blocks that each of the machines may potentially occupy must be determined. Selecting the **Compute Data** button in the top left hand side of the window, the user is prompted to enter the required number of horizontal and vertical grid lines. The program then determines the number of blocks that each machine may occupy and displays it as in Figure 7.6. Before the tabu search method is executed, the installation cost as well as the distances between the machines should be generated and saved. This may be done by selecting the respective options from the *Data menu*. On selection of the *Data/Installation cost menu* a window containing a table with the installation costs of each machine on each possible position (grid–point) in the facility, is displayed, exactly the same as in the Discrete Exact model window in Figure 7.7. In the case where the *Data/Distance menu* is selected, the user is asked to enter the ramp cost, ρ (measured in metres) and the percentage of the ramp cost that is incurred to transport a unit load of production material down the ramp. These values are required to compute the distances between each grid–point, taking into account the ramp cost. After all the necessary information has been computed the user may exit this window and the information is saved. The tabu list length, as well as the value of θ, should be adjusted at this stage. After the selection of the **Run Tabu Search** button, the user will be prompted to specify the file name and destination where the results should be saved. The DSS then attempts to solve the layout problem iteratively with the aid of the tabu search method. At termination of the method the initial and final objective function values, as well as the total time it took for the tabu search

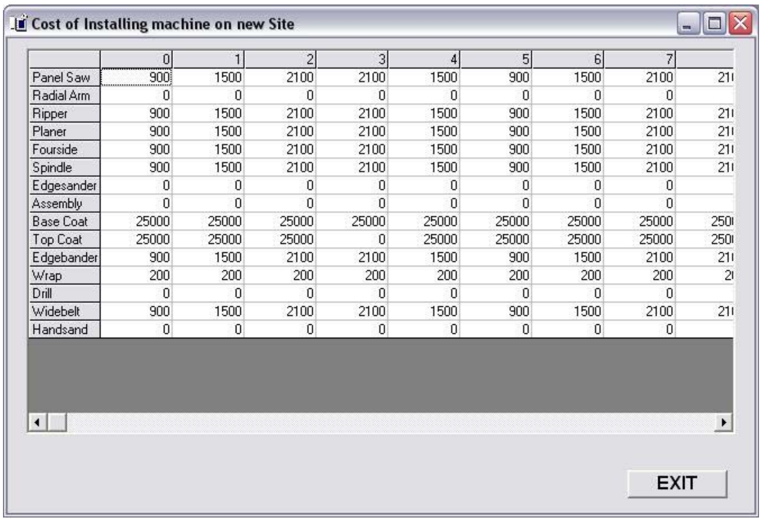


	Length	Width	Area m^2	y midpoint	x midpoint	Verti Blok L = 0	Hori Blok L = 0	Verti Bl
Panel Saw	4970	6580	32.7026	2485	3290	1	1	
Radial Arm	4700	820	3.854	2350	410	1	1	
Ripper	1400	6710	9.394	700	3355	1	1	
Planer	1400	7960	11.144	700	3980	1	2	
Fourside	3410	6390	21.7899	1705	3195	1	1	
Spindle	2115	1300	2.7495	1057.5	650	1	1	
Edgesander	1320	550	0.726	660	275	1	1	
Assembly	3500	5000	17.5	1750	2500	1	1	
Base Coat	6285	4790	30.10515	3142.5	2395	1	1	
Top Coat	3410	7550	25.7455	1705	3775	1	2	
Edgebander	7385	4430	32.71555	3692.5	2215	2	1	
Wrap	5000	3500	17.5	2500	1750	1	1	
Drill	3900	880	3.432	1950	440	1	1	
Widebelt	8820	1930	17.0226	4410	965	2	1	
Handsand	3500	5000	17.5	1750	2500	1	1	

Tabu List Length = 10

θ = 0.5

Figure 7.6: *The output window which assists the user of the DSS with solving the discrete quadratic model by means of the tabu search method.*



	0	1	2	3	4	5	6	7	
Panel Saw	900	1500	2100	2100	1500	900	1500	2100	21
Radial Arm	0	0	0	0	0	0	0	0	
Ripper	900	1500	2100	2100	1500	900	1500	2100	21
Planer	900	1500	2100	2100	1500	900	1500	2100	21
Fourside	900	1500	2100	2100	1500	900	1500	2100	21
Spindle	900	1500	2100	2100	1500	900	1500	2100	21
Edgesander	0	0	0	0	0	0	0	0	
Assembly	0	0	0	0	0	0	0	0	
Base Coat	25000	25000	25000	25000	25000	25000	25000	25000	250
Top Coat	25000	25000	25000	0	25000	25000	25000	25000	250
Edgebander	900	1500	2100	2100	1500	900	1500	2100	21
Wrap	200	200	200	200	200	200	200	200	2
Drill	0	0	0	0	0	0	0	0	
Widebelt	900	1500	2100	2100	1500	900	1500	2100	21
Handsand	0	0	0	0	0	0	0	0	

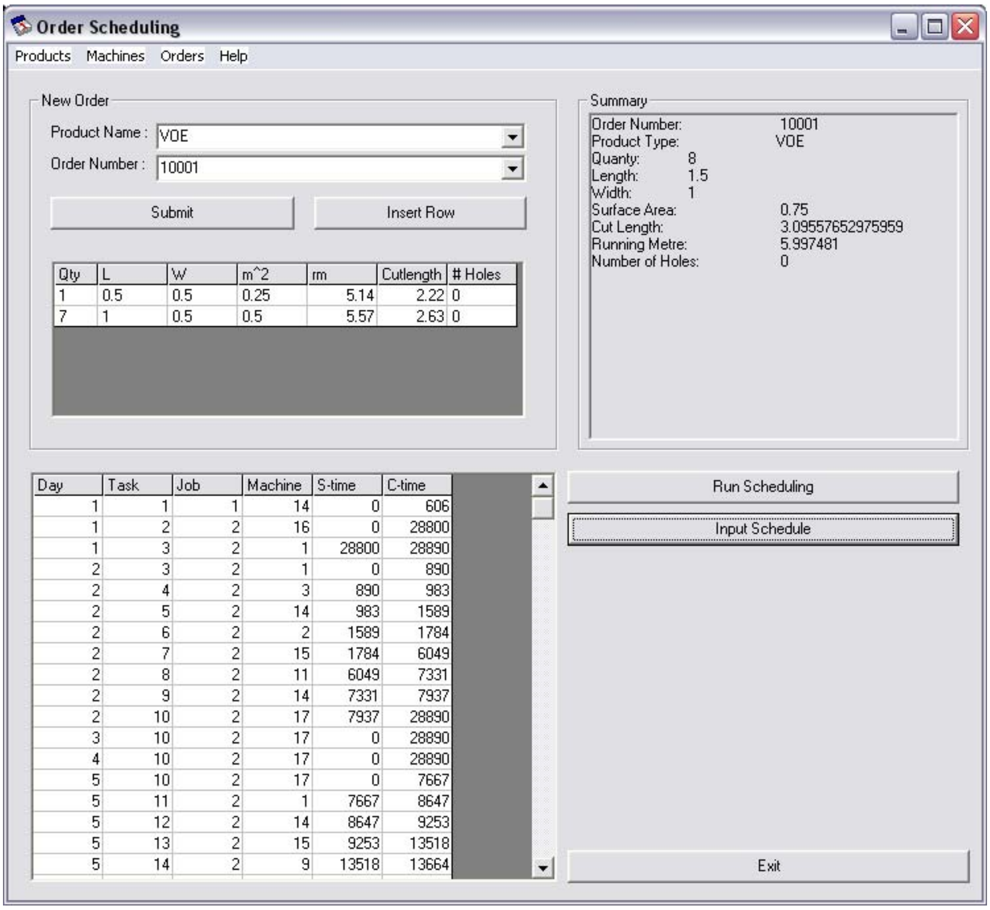
Figure 7.7: *The window used to specify the installation costs for all the grid–points.*

to obtain the best solution, are displayed in the middle left hand side of the window. Finally, clicking on the **View Layout** button, a graphical representation of the layout is displayed, as shown in Figure 7.6.

7.2 The DSS for the Scheduling Problem

A DSS for the scheduling problem was developed within a Microsoft Visual Basic support shell. The DSS makes use of the heuristic Tabu Search method, as discussed in Chapter 6, with a tabu list length of 15 and a backtracking list length of $\mathcal{L}_{\max} = 5$, with a cost of 20 minutes associated with moving material down the ramp.

The user has the option to, when necessary, specify additional machines as well as an estimated function of the processing times associated with it, by selecting the *Insert New* option from the *Machines menu* in the main screen of the DSS, shown in Figure 7.8. The window presented in Figure 7.9(a) gives the user the option to specify the name of the machine, the independent variable, and processing time estimation curve. The estimation curve is specified by selecting the curve type and specifying the underlying parameter values. The text box at the bottom of the screen (containing the word 'days') provides the user with the option to define dummy machines with fixed processing times (for example, to accommodate the external veneer factory). When the **Insert** button is clicked, the details of the new machine are saved to a text file, called `LWCMachine.txt` in the root directory of the system.



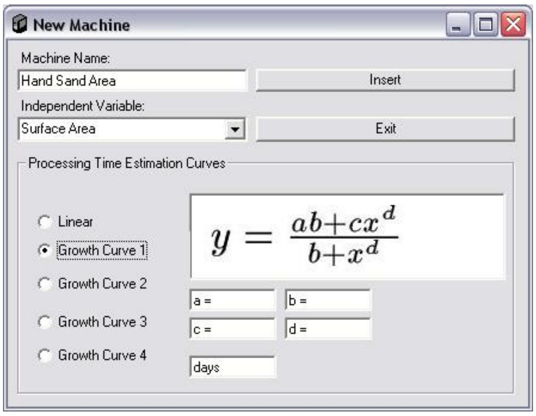
Product Name : VOE
Order Number : 10001

Qty	L	W	m^2	rm	Cutlength	# Holes
1	0.5	0.5	0.25	5.14	2.22	0
7	1	0.5	0.5	5.57	2.63	0

Order Number: 10001
Product Type: VOE
Quanty: 8
Length: 1.5
Width: 1
Surface Area: 0.75
Cut Length: 3.09557652975959
Running Metre: 5.997481
Number of Holes: 0

Day	Task	Job	Machine	S-time	C-time
1	1	1	14	0	606
1	2	2	16	0	28800
1	3	2	1	28800	28890
2	3	2	1	0	890
2	4	2	3	890	983
2	5	2	14	983	1589
2	6	2	2	1589	1784
2	7	2	15	1784	6049
2	8	2	11	6049	7331
2	9	2	14	7331	7937
2	10	2	17	7937	28890
3	10	2	17	0	28890
4	10	2	17	0	28890
5	10	2	17	0	7667
5	11	2	1	7667	8647
5	12	2	14	8647	9253
5	13	2	15	9253	13518
5	14	2	9	13518	13664

Figure 7.8: *The main DSS window in which newly arrived jobs may be entered daily.*



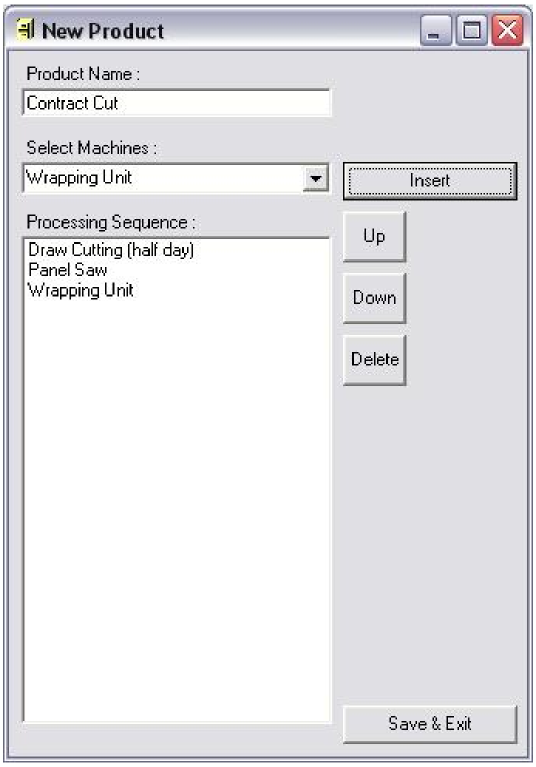
Machine Name: Hand Sand Area

Independent Variable: Surface Area

● Growth Curve 1

$$y = \frac{ab+cx^d}{b+x^d}$$

(a) *The DSS window in which new machines may be inserted.*



Product Name : Contract Cut

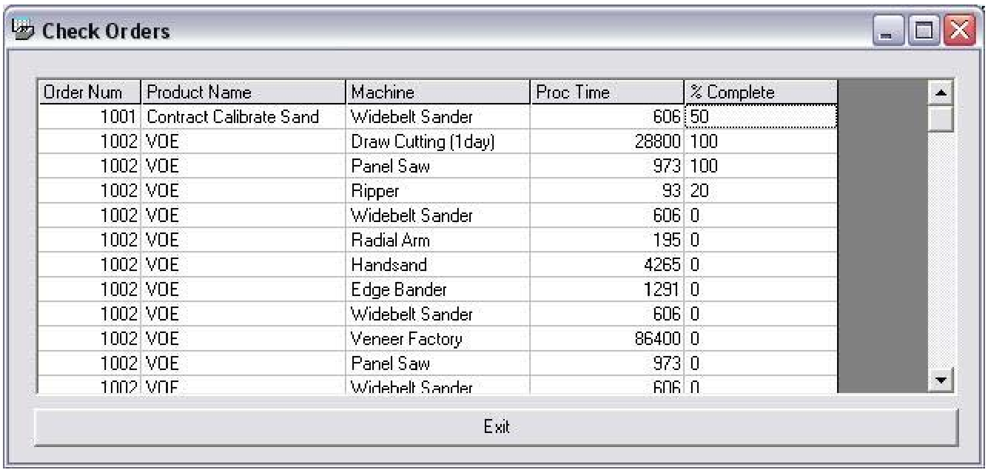
Select Machines : Wrapping Unit

Processing Sequence :
Draw Cutting (half day)
Panel Saw
Wrapping Unit

(b) *The DSS window in which new products may be inserted.*

Figure 7.9: *The DSS window in which new machines may be inserted and the window in which new products may be inserted.*

The user of the DSS has the option to specify a new product to be manufactured, by selecting the *Insert New* option from the *Products menu*. The window presented in Figure 7.9(b) gives the user the option to specify the machine processing sequence and the name of the new product. The product name may be typed into the *Machine Name* text box at the top of the window. The processing sequence may be set up by repeatedly selecting a machine from the drop down machine list menu from the *Select Machines* window in Figure 7.9(b). The user may then insert this machine into the processing sequence by clicking on the **Insert** button. When a machine is inserted it appears in the list in the middle of the screen. The **Up**, **Down** and **Delete** buttons may be used to move a selected machine in the processing sequence, or remove it respectively. The machine processing sequence is saved to a text file, called `LWCSequences.txt` in the root directory of the system. The user may exit this window by either clicking on the **Save & Exit** button in which case the machine sequence of the product will be saved, or by selecting the red cross in the top right hand corner of the screen in which case the machine processing sequence will not be saved.



Order Num	Product Name	Machine	Proc Time	% Complete
1001	Contract Calibrate Sand	Widebelt Sander	606	50
1002	VOE	Draw Cutting (1day)	28800	100
1002	VOE	Panel Saw	973	100
1002	VOE	Ripper	93	20
1002	VOE	Widebelt Sander	606	0
1002	VOE	Radial Arm	195	0
1002	VOE	Handsand	4265	0
1002	VOE	Edge Bander	1291	0
1002	VOE	Widebelt Sander	606	0
1002	VOE	Veneer Factory	86400	0
1002	VOE	Panel Saw	973	0
1002	VOE	Widebelt Sander	606	0

Figure 7.10: *The check orders window where processed orders are updated daily.*

Each day, newly arrived jobs should be inserted from the main screen of the DSS, as displayed in Figure 7.8. The finished tasks from the previous working day should be updated by selecting the *Check Orders* option from the *Orders menu*. This will open a window containing a table with all the currently processed orders, as displayed in Figure 7.10. The user has the option to adjust the processing times of the tasks by completing the last column with a percentage completed for each task. The processing times will be adjusted automatically when the user closes the window. New orders may be added in the main screen by selecting the product name and inserting or selecting an order number from the drop down menu in the *New Order area.* An order may consist of more than one item, or board, and therefore multiple lines may be added by selecting the **Insert Row** button. Each new job is saved to a file in the root directory of the system called `LWCOrders.txt` when the **Submit** button is clicked. These orders are combined with the remaining tasks of previously submitted orders and the DSS produces a file called `LWCSched.txt`, to be used as input to a tabu search implementation, when the **Run Schedule** button is clicked. The tabu search heuristic is a C++ based program and runs in the DOS environment. This will produce an output file for each of the subsequent 31 working days containing the tasks that will be scheduled on those days, assuming that no other orders are received during these 31 days.

The **Input Schedule** button inputs the text files produced during the scheduling process and generates new text files that may be printed. This button also populates the table at the bottom left hand corner of the main screen in Figure 7.8 with the processing day, starting and completion times of the different orders that need to be processed. A text file containing the contents of this table is generated. These text files may then be printed through a Notepad environment, for example and may then be handed out to the head worker of each machine, as well as to the process scheduling manager who may monitor the production process.

7.3 Future Improvements

Both layout and scheduling decision support systems were designed for the LWC facility, but may be upgraded to be used at a more general manufacturing facility. The installation costs would typically change over time and in an upgraded version of the DSS there should be the option to change these costs. Currently the layout DSSs do not allow new machines to be added to the facility, which may be built into the system. To ensure that both the layout and scheduling DSSs are used optimally it is important to ensure that the head worker of each machine keeps track of the processing times and flow through his machine in order to change the estimated processing times on the DSS manually. This ensures that the DSS schedule remains feasible and realistic. Currently the user does not have the option to change the parameters of the tabu search method, but this may be added into an upgrade of the system.

Currently LWC makes use of a Gantt chart representation in their production planning, as mentioned in Chapter 4. These Gantt charts are typically produced on a monthly basis and shown on the white board in the facility. This Gantt chart is currently updated daily and this is also expected to happen in future. The scheduling DSS, designed for LWC produces a printout of the starting times of the jobs and their respective tasks and this may be transformed manually by the production manager into a visual Gantt chart representation. A feature that may also be added to the DSS is a Gantt Chart representation facility for all the active jobs on the factory floor.

7.4 Chapter Summary

In this chapter two DSSs to be implemented at LWC production site were introduced. The DSSs make use of the tabu search heuristic to solve the layout and scheduling problem at the LWC production facility approximately. In §7.1 the DSS to assist LWC management with the layout problem was discussed in detail. The use of the scheduling DSS was discussed in §7.2.

The chapter closed in §7.3 with some suggestions with respect to additional future improvements to the DSSs. The key to the optimal usage of the DSSs in practice is to ensure that the information is always kept up to date.

Chapter 8

Conclusions

This chapter consists of two sections. In the first section (§8.1) a brief summary is provided of the work contained in this thesis. In the second section (§8.2) possible improvements and refinements of the work contained in this thesis, as well as future work, are outlined.

8.1 Thesis Summary

This thesis consists of eight chapters (including this final chapter) and opened with a general introduction to layout and scheduling problems at manufacturing facilities. A number of general questions regarding layout and production scheduling problems were outlined, and the general characteristics of both these problems were covered in the first half of Chapter 1. In the second half of the introductory chapter the problems at the Loubser Wood Components (LWC) manufacturing facility were stated informally, and a number of objectives were stated for this thesis.

Chapter 2 opened with a discussion on basic complexity theory. Extensive research was conducted since the 1950s on both the layout and production scheduling problems respectively, as summarized in §2.2 and §2.3. In §2.2 the different types of layout problems that occur in the literature were discussed, as well as a newly developed classification notation for layout problems. In general, scheduling problems in literature conform to a specific notation, as outlined in §2.3. Some representation methods of schedules were discussed and a number of different types of schedules were summarized.

More detailed theoretical descriptions of each of the methodologies that were actually attempted or applied to either the layout problem or the job–shop scheduling problem at LWC were given in §3.1 and §3.2 respectively, satisfying Objective I and II mentioned in §1.3. The practical implementations of these methods were discussed in Chapters 5 and 6 respectively, after the LWC problems and their prior situation before this study were described in some detail in Chapter 4. In §4.2 the current machine layout in the LWC factory was also discussed in conjunction with the detailed functionality of each machine. Furthermore, each product produced at the factory has a different processing sequence as was discussed extensively in §4.4.

In Chapter 5 a conventional method of solving layout problems at production facilities was applied to the LWC problem and compared to the results when the hybrid heuristic tabu search method, proposed by Bazaraa [21] and described in §3.1.2.1(i), is applied to the LWC discrete layout problem. The hybrid heuristic tabu search method proved to bring about a benefit of approximately 15% over the conventional method when applied to the LWC layout problem. The tabu search method also produced a benefit of approximately 22% over the layout at LWC prior to this study. Two exact mathematical programming problems were also formulated, one for the discrete layout problem and one for the continuous layout problem, but neither of these methods could be applied due to the complexity of their solution procedures. The hybrid tabu search method and the exact methods were included in a decision support system (DSS) as discussed in Chapter 7. This DSS makes it possible for the user to evaluate a change in layout of his/her factory, without having to affect of changes physically. The development of the DSS achieves Objective III mentioned in §1.3.

The theoretical methodologies for solving job–shop scheduling problems were discussed in Chapter 3 and applied to the LWC job–shop scheduling problem in Chapter 6. Due to the size of the problem none of the exact scheduling methods could be applied to the LWC job–shop scheduling problem. In order to apply the tabu search method of Nowicki & Smutnicki [148], an extensive data analysis was performed to estimate the processing times of machines, (see §6.1). The best tabu search solution obtained for the scheduling problem based on LWC data from 1 June 2002 to 18 December 2005, brought about an improvement of approximately 50% on the current scheduling practices at the LWC factory in terms of the total net flow time of all the jobs in this period. The tabu search method was incorporated into a DSS to aid in the daily scheduling meeting held at the LWC facility, as presented in Chapter 7. The development of the DSS achieves Objective IV raised in §1.3.

8.2 Possible Future Work

In this thesis the tabu search heuristic was applied to both the layout and scheduling problems at LWC. Another possible methodology that may be applied to the scheduling problem is the class of priority dispatch heuristics. However, priority dispatch heuristics are typically highly problem dependent [98], and therefore further study is recommended with respect to implementation of this class of heuristic methods for possible implementation at LWC. Other possible methodologies that may also be investigated in terms of feasibility are the shifting bottleneck and simulated annealing heuristics.

Both the layout and scheduling DSS presented in this thesis were designed specifically for the LWC facility, but may be generalized for use at a more general manufacturing facility by means of an upgrade. The DSSs may also be upgraded to cater for the changes in installation costs of machines that would typically change over time, due to inflation. Currently the layout DSS does not allow new machines to be added to the facility, but such a feature may certainly be incorporated into the system. To ensure that both the layout and scheduling DSSs are used optimally it is important to ensure that the head worker of each machine keeps track of the processing times and flow of production materials through his/her machine in order to manually update or improve the estimated processing times used in the DSSs. It is recommended that LWC also design a form and attach it to the job card of each order to be kept at every machine and updated for each machine on which it is processed. If LWC were to acquire statistically significant amounts of data in such a fashion, these data may be used to determine better machine processing time estimation functions. Currently the user does not have the option to change the parameters of the tabu search method employed by the DSSs, but such a feature may certainly be incorporated in an upgrade of the system. Another feature that may potentially be added to the DSS is a Gantt chart facility for all the active jobs on the factory floor. The user may then look at the DSS to ensure that projects are progressing as expected, where currently the LWC management makes use of a handdrawn Gantt chart on a large white board inside the factory, so that all the workers can monitor their progress.

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Appendix A

Lingo Programs

This appendix is devoted to provide the reader access to the **Lingo 8.0** and **Lindo 6.0** programs used for solving the example problems in Chapter 3 (see Examples 3.6, 3.7 and 3.9). These programs were executed on a personal computer with one 2.6 GHz Pentium 4 central processing unit, 512 Mb random access memory and a Windows XP operating system.

A.1 The Set–Covering Approach for Solving Facility Layout Problems

The following **Lingo 8.0** program was developed to solve Example 3.6 which is an example of a facility layout problem (described in Examples 3.1–3.4) by using the set–covering approach as described in §3.1.2.1(i).

```
MODEL:
!Define the sets;
SETS:
    MACHINE/1..6/;          !There are 6 Machines;
    LOCATION/1..18/;        !The number of gridpoints;
    BLOKKE/1..28/;          !Number of blocks;
    !ORIENTATE(MACHINE): O; !The Orientation of the machine;
    MXL(MACHINE, LOCATION): X, COST; !X is the assignment of the positions to
                                      machines and COST is the installation
                                      cost of the machines;
    !FLOWTODISP(MACHINE): FTD;       !The set for flow to dispatch;
    !FLOWFROMRECI(MACHINE): FFR;     !The set for flow from receive;
    LXL(LOCATION, LOCATION): DIST;   !The distances between the different
     locations;
    MXM(MACHINE, MACHINE): FROMTO, EYE, F, G;   !The flow between machines;
    !MXLXB(MXL, BLOKKE): TOEL;       !The feasible moves;
    LXB(LOCATION, BLOKKE): A;        !The blocks occupied if specific machines
     are at specific positions;
ENDSETS
DATA:
FROMTO= 0 0 1500 0 0 300
1000 0 300 0 0 0
```

```
300 0 0 1500 0 0
0 0 0 0 0 1500
0 300 0 0 0 0
0 0 0 0 0 0
;
DIST =0 4 8 12 16 20 5 9 13 17 21 25 10 14 18 22 26 30
4 0 4 8 12 16 9 5 9 13 17 21 14 10 14 18 22 26
8 4 0 4 8 12 13 9 5 9 13 17 18 14 10 14 18 22
12 8 4 0 4 8 17 13 9 5 9 13 22 18 14 10 14 18
16 12 8 4 0 4 21 17 13 9 5 9 26 22 18 14 10 14
20 16 12 8 4 0 25 21 17 13 9 5 30 26 22 18 14 10
5 9 13 17 21 25 0 4 8 12 16 20 5 9 13 17 21 25
9 5 9 13 17 21 4 0 4 8 12 16 9 5 9 13 17 21
13 9 5 9 13 17 8 4 0 4 8 12 13 9 5 9 13 17
17 13 9 5 9 13 12 8 4 0 4 8 17 13 9 5 9 13
21 17 13 9 5 9 16 12 8 4 0 4 21 17 13 9 5 9
25 21 17 13 9 5 20 16 12 8 4 0 25 21 17 13 9 5
10 14 18 22 26 30 5 9 13 17 21 25 0 4 8 12 16 20
14 10 14 18 22 26 9 5 9 13 17 21 4 0 4 8 12 16
18 14 10 14 18 22 13 9 5 9 13 17 8 4 0 4 8 12
22 18 14 10 14 18 17 13 9 5 9 13 12 8 4 0 4 8
26 22 18 14 10 14 21 17 13 9 5 9 16 12 8 4 0 4
30 26 22 18 14 10 25 21 17 13 9 5 20 16 12 8 4 0
;
COST = 3878 2235 2857 4565 2084 9815 5077 6237 6237 2176 2234 4663 9470 6897
347 2205 6139 7961
9162 7265 2227 5907 7316 1305 8908 5761 9550 3836 7112 495 2592 691 4628 6713
1567 8419
8761 8415 9865 2685 44 6894 9085 176 2486 4111 1597 787 4764 4809 6996 125 2924
9694
2749 1893 7705 9403 9951 1801 5378 9579 1136 7755 267 3087 2603 1682 8624 5149
4687 2437
3169 8305 3606 8978 6570 5598 827 2180 1961 2547 1721 7206 5973 3645 7852 1234
5029 991
4367 1069 7715 1946 222 9682 7535 597 6439 8386 3195 6279 3881 1670 7526 4441
685 5409
;
A =
1 1 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 1 1 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 1 1 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 1 1 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 1 1 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 1 1 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 1 1 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0
```

```
0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 1 1 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 1 1 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 1 1 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 1 1 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 1 1 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 1 1 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 1 1
;
ENDDATA

!Each machine must be assigned to one location;
@FOR(MACHINE(B):
        @SUM(LOCATION(J):X(B,J))=1);
!Each location J can be occupied by only one machine;
@FOR(LOCATION(J):
        @SUM(MACHINE(B):X(B,J))<=1);

!Constraints to ensure that a machine is in a feasible location;
!@FOR(MXL(I,J):X(I,J) <= ((1-O(I))*TOEL(I,J,1)+ O(I)*TOEL(I,J,2)));
@FOR(BLOKKE(B):
@SUM(LOCATION(K):A(K,B)*
@SUM(MACHINE(I):X(I,K))) <= 1);
! The objective function;
 MIN = 0.5*@SUM(MXL(I,J):@SUM(MXL(K,H):FROMTO(I,K)*DIST(J,H)*X(I,J)*X(K,H)))+
 0.5* @SUM(MXL(I,L):COST(I,L)*X(I,L));

!All the X variables are binary;
@FOR(MXL:@BIN(X));
END
```

A.2 The MILP Approach for Solving Facility Layout Problems

The **Lingo 8.0** program below was developed to solve an example of a facility layout problem (described in Examples 3.1–3.4) by using the MILP approach as described in §3.1.2.1(ii) and implemented in Example 3.7.

```
MODEL:

SETS:
MACHINE/1..6/ : O, ALPHA, BETA, L, W, X, Y, FF;
MXM(MACHINE, MACHINE): F, Cc, E1, E2, RR, LL, AA, BB, TOTAL;
ENDSETS

DATA:
ALPHA = 8 7 7 6 5 4; !The length of the machines;
BETA = 9 9 7 7 6 5;  !The width of the machines;
Cc =  0 0 1500 0 0 300 !The flow between the machines;
```

```
      1000 0 300 0 0 0
      300 0 0 1500 0 0
0 0 0 0 0 1500
0 300 0 0 0 0
0 0 0 0 0 0;
FF = 7628 3495 1866 6137 9779 2277;
F =  0 0 1 0 0 1
1 0 1 0 0 0
1 0 0 1 0 0
0 0 0 0 0 1
0 1 0 0 0 0
0 0 0 0 0 0;
ENDDATA
!Machine Orientation;
@FOR(MACHINE(I):L(I) = ALPHA(I)*O(I)+BETA(I)*(1-O(I)));
@FOR(MACHINE(J):W(J) = ALPHA(J) + BETA(J) - L(J));
!Machine overlapping constraints;
@FOR(MXM(I,J)|J#GT#I: X(I)-X(J)+10000*(E1(I,J)+E2(I,J))>=(L(I)+L(J))/2);
@FOR(MXM(I,J)|J#GT#I: X(I)-X(J)+10000*(1-E1(I,J)+E2(I,J))>=(L(I)+L(J))/2);
@FOR(MXM(I,J)|J#GT#I: Y(I)-Y(J)+10000*(1+E1(I,J)-E2(I,J))>=(W(I)+W(J))/2);
@FOR(MXM(I,J)|J#GT#I: Y(I)-Y(J)+10000*(2-E1(I,J)-E2(I,J))>=(W(I)+W(J))/2);
!Distance constraints;
@FOR(MXM(I,J)|F(I,J) #EQ# 1 : RR(I,J) - LL(I,J) = X(I) - X(J));
@FOR(MXM(I,J)|F(I,J) #EQ# 1 : AA(I,J) - BB(I,J) = Y(I) - Y(J));
@FOR(MXM(I,J)|F(I,J) #EQ# 1 : TOTAL(I,J) = RR(I,J) + LL(I,J) + AA(I,J) + BB(I,J));
!Additional layout constraints;
@FOR(MACHINE(I): X(I)>= L(I)/2);
@FOR(MACHINE(I): Y(I)>= W(I)/2);
@FOR(MACHINE(I): X(I) + L(I)/2 <= 28);
@FOR(MACHINE(I): Y(I) + W(I)/2 <= 20);

!Objective Function;
MIN = @SUM(MXM(I,J)|F(I,J) #EQ# 1: Cc(I,J) * TOTAL(I,J)) + @SUM(MACHINE(I): FF(I));

!Binary Constraints;
@FOR(MXM:@BIN(E1));
@FOR(MXM:@BIN(E2));
@FOR(MACHINE:@BIN(O));
END
```

A.3 The Branch–and–Bound Approach for Solving Job–shop Scheduling Problems

The **Lindo 6.0** program below was developed to solve an example of a scheduling problem, described in Example 3.9 by using the branch–and–bound approach as described in §3.2.1.1.

```
Min s_end
subject to
s_end - s21 >= 2
s21 - s11 >= 1
s_end - s32 >= 2
s32 - s22 >= 1
s22 - s12 >= 3
s_end - s33 >= 1
s33 - s23 >= 1
s23 - s13 >= 2
-s32 + s11 + 50 y3211 <= 49
s11 - s32 + 50 y3211 >= 2
-s32 + s23 + 50 y3223 >= 49
s23 - s32 + 50 y3223 >= 2
-s23 + s11 + 50 y2311 >= 49
s11 - s23 + 50 y2311 >= 1
-s12 + s33 + 50 y1233 >= 49
s33 - s12 + 50 y1233 >= 3
-s21 + s22 + 50 y2122 >= 49
s22 - s21 + 50 y2122 >= 2
-s22 + s13 + 50 y2213 >= 48
s13 - s22 + 50 y2213 >= 1
-s13 + s21 + 50 y1321 >= 48
s21 - s13 + 50 y1321 >= 2
s11 >= 0
s21 >= 0
s12 >= 0
s22 >= 0
s32 >= 0
s13 >= 0
s23 >= 0
s33 >= 0
END
INT y3211
INT y3223
INT y2311
INT y1233
INT y2122
INT y2213
INT y1321
```

Appendix B

Longest Path Algorithm

In this appendix a longest path algorithm is presented. This algorithm may be used to calculate the makespan of a schedule, which is the length of the longest path from the dummy task T_{start} to the dummy task T_{end}. See §2.3.2 for more details about the makespan of a schedule.

Algorithm 3 Longest Path

```
Input: Connected, weighted, directed graph $G(\mathcal{D}^*)$, and a vertex $T_{im} \in V(G(\mathcal{D}^*))$.
Output: Longest path from $T_{im}$ to every other vertex in $G(\mathcal{D}^*)$.
1: Initially all arcs and vertices are unmarked. Let $D(T_{kj})$ be the longest path length from vertex $T_{im}$ to vertex $T_{kj}$. Initialize $D(T_{im}) \leftarrow 0$ and mark vertex $T_{im}$. For all vertices $T_{j\ell}$ that have only vertex $T_{im}$ as predecessor, set $D(T_{j\ell}) \leftarrow p_{im}$ and mark the vertex $T_{j\ell}$ and arc $(T_{im}, T_{j\ell})$.
2: If all the vertices are marked, then stop; otherwise, for every vertex $T_{j\ell}$ that has only marked vertices as predecessors, set $D(T_{j\ell}) \leftarrow \max\{D(T_{hk}) + p_{hk}\}$ over all possible immediate predecessors $T_{hk}$ of $T_{j\ell}$. Mark vertex $T_{j\ell}$ as well as the arc $(T_{hk}, T_{j\ell})$ for which the preceding maximum is determined.
3: Repeat step (2).
```

Appendix C

Parameter Values for the LWC Layout Problem

In this appendix the sets $S_i(k)$ of blocks occupied by each machine i when positioned at grid–point k on the LWC factory floor, are provided in Table C.1 for the grid with 12 horizontal and 11 vertical blocks, for the grid with 22 horizontal and 21 vertical blocks (see the file `SikGrid2221.xls` on the accompanying CD). These sets are used within the quadratic set–covering approach (discussed in §3.1.2.1(i)), which incorporated different machine sizes for a discrete facility layout problem. This method reduces the number of candidate locations per machine by only using the feasible locations given in the sets $S_i(k)$, for each machine. The data in these sets are used in §5.2.1(i) and §5.2.2. In §5.2.1(i) the quadratic set–covering approach is used, with the aid of the branch–and–bound method, in an attempt to obtain the optimal solution to the LWC discrete facility layout problem. Whereas, in §5.2.2 a hybrid tabu search method was applied to the quadratic set–covering problem, in order to improve the LWC discrete facility layout.

	Machines								
Grid–points	1	2	3	4	5	6	7	8	9
0	{1, 2, 7, 8}	{1, 2, 7, 8}	{1, 2, 7, 8}	∅	{1, 2, 7, 8}	{1, 2, 7, 8}	{1, 2, 7, 8}	{1, 2, 7, 8}	{1, 2, 7, 8}
1	{2, 3, 8, 9}	{2, 3, 8, 9}	{2, 3, 8, 9}	{1, 2, 3, 4, 7, 8, 9, 10}	{2, 3, 8, 9}	{2, 3, 8, 9}	{2, 3, 8, 9}	{2, 3, 8, 9}	{2, 3, 8, 9}
2	{3, 4, 9, 10}	{3, 4, 9, 10}	{3, 4, 9, 10}	{2, 3, 4, 5, 8, 9, 10, 11}	{3, 4, 9, 10}	{3, 4, 9, 10}	{3, 4, 9, 10}	{3, 4, 9, 10}	{3, 4, 9, 10}
3	{4, 5, 10, 11}	{4, 5, 10, 11}	{4, 5, 10, 11}	{3, 4, 5, 6, 9, 10, 11, 12}	{4, 5, 10, 11}	{4, 5, 10, 11}	{4, 5, 10, 11}	{4, 5, 10, 11}	{4, 5, 10, 11}
4	{5, 6, 11, 12}	{5, 6, 11, 12}	{5, 6, 11, 12}	∅	{5, 6, 11, 12}	{5, 6, 11, 12}	{5, 6, 11, 12}	{5, 6, 11, 12}	{5, 6, 11, 12}
5	{7, 8, 13, 14}	{7, 8, 13, 14}	{7, 8, 13, 14}	∅	{7, 8, 13, 14}	{7, 8, 13, 14}	{7, 8, 13, 14}	{7, 8, 13, 14}	{7, 8, 13, 14}
6	{8, 9, 14, 15}	{8, 9, 14, 15}	{8, 9, 14, 15}	{7, 8, 9, 10, 13, 14, 15, 16}	{8, 9, 14, 15}	{8, 9, 14, 15}	{8, 9, 14, 15}	{8, 9, 14, 15}	{8, 9, 14, 15}
7	{9, 10, 15, 16}	{9, 10, 15, 16}	{9, 10, 15, 16}	{8, 9, 10, 11, 14, 15, 16, 17}	{9, 10, 15, 16}	{9, 10, 15, 16}	{9, 10, 15, 16}	{9, 10, 15, 16}	{9, 10, 15, 16}
8	{10, 11, 16, 17}	{10, 11, 16, 17}	{10, 11, 16, 17}	{9, 10, 11, 12, 15, 16, 17, 18}	{10, 11, 16, 17}	{10, 11, 16, 17}	{10, 11, 16, 17}	{10, 11, 16, 17}	{10, 11, 16, 17}
9	{11, 12, 17, 18}	{11, 12, 17, 18}	{11, 12, 17, 18}	∅	{11, 12, 17, 18}	{11, 12, 17, 18}	{11, 12, 17, 18}	{11, 12, 17, 18}	{11, 12, 17, 18}
10	{13, 14, 19, 20}	{13, 14, 19, 20}	{13, 14, 19, 20}	∅	{13, 14, 19, 20}	{13, 14, 19, 20}	{13, 14, 19, 20}	{13, 14, 19, 20}	{13, 14, 19, 20}
11	{14, 15, 20, 21}	{14, 15, 20, 21}	{14, 15, 20, 21}	{13, 14, 15, 16, 19, 20, 21, 22}	{14, 15, 20, 21}	{14, 15, 20, 21}	{14, 15, 20, 21}	{14, 15, 20, 21}	{14, 15, 20, 21}
12	{15, 16, 21, 22}	{15, 16, 21, 22}	{15, 16, 21, 22}	{14, 15, 16, 17, 20, 21, 22, 23}	{15, 16, 21, 22}	{15, 16, 21, 22}	{15, 16, 21, 22}	{15, 16, 21, 22}	{15, 16, 21, 22}
13	{16, 17, 22, 23}	{16, 17, 22, 23}	{16, 17, 22, 23}	{15, 16, 17, 18, 21, 22, 23, 24}	{16, 17, 22, 23}	{16, 17, 22, 23}	{16, 17, 22, 23}	{16, 17, 22, 23}	{16, 17, 22, 23}
14	{17, 18, 23, 24}	{17, 18, 23, 24}	{17, 18, 23, 24}	∅	{17, 18, 23, 24}	{17, 18, 23, 24}	{17, 18, 23, 24}	{17, 18, 23, 24}	{17, 18, 23, 24}
15	{19, 20, 25, 26}	{19, 20, 25, 26}	{19, 20, 25, 26}	∅	{19, 20, 25, 26}	{19, 20, 25, 26}	{19, 20, 25, 26}	{19, 20, 25, 26}	{19, 20, 25, 26}
16	{20, 21, 26, 27}	{20, 21, 26, 27}	{20, 21, 26, 27}	{19, 20, 21, 22, 25, 26, 27, 28}	{20, 21, 26, 27}	{20, 21, 26, 27}	{20, 21, 26, 27}	{20, 21, 26, 27}	{20, 21, 26, 27}
17	{21, 22, 27, 28}	{21, 22, 27, 28}	{21, 22, 27, 28}	{20, 21, 22, 23, 26, 27, 28, 29}	{21, 22, 27, 28}	{21, 22, 27, 28}	{21, 22, 27, 28}	{21, 22, 27, 28}	{21, 22, 27, 28}
18	{22, 23, 28, 29}	{22, 23, 28, 29}	{22, 23, 28, 29}	{21, 22, 23, 24, 27, 28, 29, 30}	{22, 23, 28, 29}	{22, 23, 28, 29}	{22, 23, 28, 29}	{22, 23, 28, 29}	{22, 23, 28, 29}
19	{23, 24, 29, 30}	{23, 24, 29, 30}	{23, 24, 29, 30}	∅	{23, 24, 29, 30}	{23, 24, 29, 30}	{23, 24, 29, 30}	{23, 24, 29, 30}	{23, 24, 29, 30}
20	{25, 26, 31, 32}	{25, 26, 31, 32}	{25, 26, 31, 32}	∅	{25, 26, 31, 32}	{25, 26, 31, 32}	{25, 26, 31, 32}	{25, 26, 31, 32}	{25, 26, 31, 32}
21	{26, 27, 32, 33}	{26, 27, 32, 33}	{26, 27, 32, 33}	{25, 26, 27, 28, 31, 32, 33, 34}	{26, 27, 32, 33}	{26, 27, 32, 33}	{26, 27, 32, 33}	{26, 27, 32, 33}	{26, 27, 32, 33}
22	{27, 28, 33, 34}	{27, 28, 33, 34}	{27, 28, 33, 34}	{26, 27, 28, 29, 32, 33, 34, 35}	{27, 28, 33, 34}	{27, 28, 33, 34}	{27, 28, 33, 34}	{27, 28, 33, 34}	{27, 28, 33, 34}
23	{28, 29, 34, 35}	{28, 29, 34, 35}	{28, 29, 34, 35}	{27, 28, 29, 30, 33, 34, 35, 36}	{28, 29, 34, 35}	{28, 29, 34, 35}	{28, 29, 34, 35}	{28, 29, 34, 35}	{28, 29, 34, 35}
24	{29, 30, 35, 36}	{29, 30, 35, 36}	{29, 30, 35, 36}	∅	{29, 30, 35, 36}	{29, 30, 35, 36}	{29, 30, 35, 36}	{29, 30, 35, 36}	{29, 30, 35, 36}
25	{31, 32, 37, 38}	{31, 32, 37, 38}	{31, 32, 37, 38}	∅	{31, 32, 37, 38}	{31, 32, 37, 38}	{31, 32, 37, 38}	{31, 32, 37, 38}	{31, 32, 37, 38}
26	{32, 33, 38, 39}	{32, 33, 38, 39}	{32, 33, 38, 39}	{31, 32, 33, 34, 37, 38, 39, 40}	{32, 33, 38, 39}	{32, 33, 38, 39}	{32, 33, 38, 39}	{32, 33, 38, 39}	{32, 33, 38, 39}
27	{33, 34, 39, 40}	{33, 34, 39, 40}	{33, 34, 39, 40}	{32, 33, 34, 35, 38, 39, 40, 41}	{33, 34, 39, 40}	{33, 34, 39, 40}	{33, 34, 39, 40}	{33, 34, 39, 40}	{33, 34, 39, 40}
28	{34, 35, 40, 41}	{34, 35, 40, 41}	{34, 35, 40, 41}	{33, 34, 35, 36, 39, 40, 41, 42}	{34, 35, 40, 41}	{34, 35, 40, 41}	{34, 35, 40, 41}	{34, 35, 40, 41}	{34, 35, 40, 41}
29	{35, 36, 41, 42}	{35, 36, 41, 42}	{35, 36, 41, 42}	∅	{35, 36, 41, 42}	{35, 36, 41, 42}	{35, 36, 41, 42}	{35, 36, 41, 42}	{35, 36, 41, 42}
30	{37, 38, 43, 44}	{37, 38, 43, 44}	{37, 38, 43, 44}	∅	{37, 38, 43, 44}	{37, 38, 43, 44}	{37, 38, 43, 44}	{37, 38, 43, 44}	{37, 38, 43, 44}
31	{38, 39, 44, 45}	{38, 39, 44, 45}	{38, 39, 44, 45}	{37, 38, 39, 40, 43, 44, 45, 46}	{38, 39, 44, 45}	{38, 39, 44, 45}	{38, 39, 44, 45}	{38, 39, 44, 45}	{38, 39, 44, 45}
32	{39, 40, 45, 46}	{39, 40, 45, 46}	{39, 40, 45, 46}	{38, 39, 40, 41, 44, 45, 46, 47}	{39, 40, 45, 46}	{39, 40, 45, 46}	{39, 40, 45, 46}	{39, 40, 45, 46}	{39, 40, 45, 46}
33	{40, 41, 46, 47}	{40, 41, 46, 47}	{40, 41, 46, 47}	{39, 40, 41, 42, 45, 46, 47, 48}	{40, 41, 46, 47}	{40, 41, 46, 47}	{40, 41, 46, 47}	{40, 41, 46, 47}	{40, 41, 46, 47}
34	{41, 42, 47, 48}	{41, 42, 47, 48}	{41, 42, 47, 48}	∅	{41, 42, 47, 48}	{41, 42, 47, 48}	{41, 42, 47, 48}	{41, 42, 47, 48}	{41, 42, 47, 48}
35	{43, 44, 49, 50}	{43, 44, 49, 50}	{43, 44, 49, 50}	∅	{43, 44, 49, 50}	{43, 44, 49, 50}	{43, 44, 49, 50}	{43, 44, 49, 50}	{43, 44, 49, 50}
36	{44, 45, 50, 51}	{44, 45, 50, 51}	{44, 45, 50, 51}	{43, 44, 45, 46, 49, 50, 51, 52}	{44, 45, 50, 51}	{44, 45, 50, 51}	{44, 45, 50, 51}	{44, 45, 50, 51}	{44, 45, 50, 51}
37	{45, 46, 51, 52}	{45, 46, 51, 52}	{45, 46, 51, 52}	{44, 45, 46, 47, 50, 51, 52, 53}	{45, 46, 51, 52}	{45, 46, 51, 52}	{45, 46, 51, 52}	{45, 46, 51, 52}	{45, 46, 51, 52}
38	{46, 47, 52, 53}	{46, 47, 52, 53}	{46, 47, 52, 53}	{45, 46, 47, 48, 51, 52, 53, 54}	{46, 47, 52, 53}	{46, 47, 52, 53}	{46, 47, 52, 53}	{46, 47, 52, 53}	{46, 47, 52, 53}
39	{47, 48, 53, 54}	{47, 48, 53, 54}	{47, 48, 53, 54}	∅	{47, 48, 53, 54}	{47, 48, 53, 54}	{47, 48, 53, 54}	{47, 48, 53, 54}	{47, 48, 53, 54}
40	{49, 50, 55, 56}	{49, 50, 55, 56}	{49, 50, 55, 56}	∅	{49, 50, 55, 56}	{49, 50, 55, 56}	{49, 50, 55, 56}	{49, 50, 55, 56}	{49, 50, 55, 56}
41	{50, 51, 56, 57}	{50, 51, 56, 57}	{50, 51, 56, 57}	{49, 50, 51, 52, 55, 56, 57, 58}	{50, 51, 56, 57}	{50, 51, 56, 57}	{50, 51, 56, 57}	{50, 51, 56, 57}	{50, 51, 56, 57}
42	{51, 52, 57, 58}	{51, 52, 57, 58}	{51, 52, 57, 58}	{50, 51, 52, 53, 56, 57, 58, 59}	{51, 52, 57, 58}	{51, 52, 57, 58}	{51, 52, 57, 58}	{51, 52, 57, 58}	{51, 52, 57, 58}
43	{52, 53, 58, 59}	{52, 53, 58, 59}	{52, 53, 58, 59}	{51, 52, 53, 54, 57, 58, 59, 60}	{52, 53, 58, 59}	{52, 53, 58, 59}	{52, 53, 58, 59}	{52, 53, 58, 59}	{52, 53, 58, 59}
44	{53, 54, 59, 60}	{53, 54, 59, 60}	{53, 54, 59, 60}	∅	{53, 54, 59, 60}	{53, 54, 59, 60}	{53, 54, 59, 60}	{53, 54, 59, 60}	{53, 54, 59, 60}
45	{55, 56, 61, 62}	{55, 56, 61, 62}	{55, 56, 61, 62}	∅	{55, 56, 61, 62}	{55, 56, 61, 62}	{55, 56, 61, 62}	{55, 56, 61, 62}	{55, 56, 61, 62}
46	{56, 57, 62, 63}	{56, 57, 62, 63}	{56, 57, 62, 63}	{55, 56, 57, 58, 61, 62, 63, 64}	{56, 57, 62, 63}	{56, 57, 62, 63}	{56, 57, 62, 63}	{56, 57, 62, 63}	{56, 57, 62, 63}
47	{57, 58, 63, 64}	{57, 58, 63, 64}	{57, 58, 63, 64}	{56, 57, 58, 59, 62, 63, 64, 65}	{57, 58, 63, 64}	{57, 58, 63, 64}	{57, 58, 63, 64}	{57, 58, 63, 64}	{57, 58, 63, 64}
48	{58, 59, 64, 65}	{58, 59, 64, 65}	{58, 59, 64, 65}	{57, 58, 59, 60, 63, 64, 65, 66}	{58, 59, 64, 65}	{58, 59, 64, 65}	{58, 59, 64, 65}	{58, 59, 64, 65}	{58, 59, 64, 65}
49	{59, 60, 65, 66}	{59, 60, 65, 66}	{59, 60, 65, 66}	∅	{59, 60, 65, 66}	{59, 60, 65, 66}	{59, 60, 65, 66}	{59, 60, 65, 66}	{59, 60, 65, 66}
50	{67, 68, 73, 74}	{67, 68, 73, 74}	{67, 68, 73, 74}	∅	{67, 68, 73, 74}	{67, 68, 73, 74}	{67, 68, 73, 74}	{67, 68, 73, 74}	{67, 68, 73, 74}
51	{68, 69, 74, 75}	{68, 69, 74, 75}	{68, 69, 74, 75}	{67, 68, 69, 70, 73, 74, 75, 76}	{68, 69, 74, 75}	{68, 69, 74, 75}	{68, 69, 74, 75}	{68, 69, 74, 75}	{68, 69, 74, 75}
52	{69, 70, 75, 76}	{69, 70, 75, 76}	{69, 70, 75, 76}	{68, 69, 70, 71, 74, 75, 76, 77}	{69, 70, 75, 76}	{69, 70, 75, 76}	{69, 70, 75, 76}	{69, 70, 75, 76}	{69, 70, 75, 76}
53	{70, 71, 76, 77}	{70, 71, 76, 77}	{70, 71, 76, 77}	{69, 70, 71, 72, 75, 76, 77, 78}	{70, 71, 76, 77}	{70, 71, 76, 77}	{70, 71, 76, 77}	{70, 71, 76, 77}	{70, 71, 76, 77}
54	{71, 72, 77, 78}	{71, 72, 77, 78}	{71, 72, 77, 78}	∅	{71, 72, 77, 78}	{71, 72, 77, 78}	{71, 72, 77, 78}	{71, 72, 77, 78}	{71, 72, 77, 78}
55	{73, 74, 79, 80}	{73, 74, 79, 80}	{73, 74, 79, 80}	∅	{73, 74, 79, 80}	{73, 74, 79, 80}	{73, 74, 79, 80}	{73, 74, 79, 80}	{73, 74, 79, 80}
56	{74, 75, 80, 81}	{74, 75, 80, 81}	{74, 75, 80, 81}	{73, 74, 75, 76, 79, 80, 81, 82}	{74, 75, 80, 81}	{74, 75, 80, 81}	{74, 75, 80, 81}	{74, 75, 80, 81}	{74, 75, 80, 81}
57	{75, 76, 81, 82}	{75, 76, 81, 82}	{75, 76, 81, 82}	{74, 75, 76, 77, 80, 81, 82, 83}	{75, 76, 81, 82}	{75, 76, 81, 82}	{75, 76, 81, 82}	{75, 76, 81, 82}	{75, 76, 81, 82}
58	{76, 77, 82, 83}	{76, 77, 82, 83}	{76, 77, 82, 83}	{75, 76, 77, 78, 81, 82, 83, 84}	{76, 77, 82, 83}	{76, 77, 82, 83}	{76, 77, 82, 83}	{76, 77, 82, 83}	{76, 77, 82, 83}
59	{77, 78, 83, 84}	{77, 78, 83, 84}	{77, 78, 83, 84}	∅	{77, 78, 83, 84}	{77, 78, 83, 84}	{77, 78, 83, 84}	{77, 78, 83, 84}	{77, 78, 83, 84}
60	{79, 80, 85, 86}	{79, 80, 85, 86}	{79, 80, 85, 86}	∅	{79, 80, 85, 86}	{79, 80, 85, 86}	{79, 80, 85, 86}	{79, 80, 85, 86}	{79, 80, 85, 86}
61	{80, 81, 86, 87}	{80, 81, 86, 87}	{80, 81, 86, 87}	{79, 80, 81, 82, 85, 86, 87, 88}	{80, 81, 86, 87}	{80, 81, 86, 87}	{80, 81, 86, 87}	{80, 81, 86, 87}	{80, 81, 86, 87}
62	{81, 82, 87, 88}	{81, 82, 87, 88}	{81, 82, 87, 88}	{80, 81, 82, 83, 86, 87, 88, 89}	{81, 82, 87, 88}	{81, 82, 87, 88}	{81, 82, 87, 88}	{81, 82, 87, 88}	{81, 82, 87, 88}
63	{82, 83, 88, 89}	{82, 83, 88, 89}	{82, 83, 88, 89}	{81, 82, 83, 84, 87, 88, 89, 90}	{82, 83, 88, 89}	{82, 83, 88, 89}	{82, 83, 88, 89}	{82, 83, 88, 89}	{82, 83, 88, 89}
64	{83, 84, 89, 90}	{83, 84, 89, 90}	{83, 84, 89, 90}	∅	{83, 84, 89, 90}	{83, 84, 89, 90}	{83, 84, 89, 90}	{83, 84, 89, 90}	{83, 84, 89, 90}
65	{85, 86, 91, 92}	{85, 86, 91, 92}	{85, 86, 91, 92}	∅	{85, 86, 91, 92}	{85, 86, 91, 92}	{85, 86, 91, 92}	{85, 86, 91, 92}	{85, 86, 91, 92}
66	{86, 87, 92, 93}	{86, 87, 92, 93}	{86, 87, 92, 93}	{85, 86, 87, 88, 91, 92, 93, 94}	{86, 87, 92, 93}	{86, 87, 92, 93}	{86, 87, 92, 93}	{86, 87, 92, 93}	{86, 87, 92, 93}
67	{87, 88, 93, 94}	{87, 88, 93, 94}	{87, 88, 93, 94}	{86, 87, 88, 89, 92, 93, 94, 95}	{87, 88, 93, 94}	{87, 88, 93, 94}	{87, 88, 93, 94}	{87, 88, 93, 94}	{87, 88, 93, 94}
68	{88, 89, 94, 95}	{88, 89, 94, 95}	{88, 89, 94, 95}	{87, 88, 89, 90, 93, 94, 95, 96}	{88, 89, 94, 95}	{88, 89, 94, 95}	{88, 89, 94, 95}	{88, 89, 94, 95}	{88, 89, 94, 95}
69	{89, 90, 95, 96}	{89, 90, 95, 96}	{89, 90, 95, 96}	∅	{89, 90, 95, 96}	{89, 90, 95, 96}	{89, 90, 95, 96}	{89, 90, 95, 96}	{89, 90, 95, 96}
70	{91, 92, 97, 98}	{91, 92, 97, 98}	{91, 92, 97, 98}	∅	{91, 92, 97, 98}	{91, 92, 97, 98}	{91, 92, 97, 98}	{91, 92, 97, 98}	{91, 92, 97, 98}
71	{92, 93, 98, 99}	{92, 93, 98, 99}	{92, 93, 98, 99}	{91, 92, 93, 94, 97, 98, 99, 100}	{92, 93, 98, 99}	{92, 93, 98, 99}	{92, 93, 98, 99}	{92, 93, 98, 99}	{92, 93, 98, 99}
72	{93, 94, 99, 100}	{93, 94, 99, 100}	{93, 94, 99, 100}	{92, 93, 94, 95, 98, 99, 100, 101}	{93, 94, 99, 100}	{93, 94, 99, 100}	{93, 94, 99, 100}	{93, 94, 99, 100}	{93, 94, 99, 100}
73	{94, 95, 100, 101}	{94, 95, 100, 101}	{94, 95, 100, 101}	{93, 94, 95, 96, 99, 100, 101, 102}	{94, 95, 100, 101}	{94, 95, 100, 101}	{94, 95, 100, 101}	{94, 95, 100, 101}	{94, 95, 100, 101}
74	{95, 96, 101, 102}	{95, 96, 101, 102}	{95, 96, 101, 102}	∅	{95, 96, 101, 102}	{95, 96, 101, 102}	{95, 96, 101, 102}	{95, 96, 101, 102}	{95, 96, 101, 102}
75	{97, 98, 103, 104}	{97, 98, 103, 104}	{97, 98, 103, 104}	∅	{97, 98, 103, 104}	{97, 98, 103, 104}	{97, 98, 103, 104}	{97, 98, 103, 104}	{97, 98, 103, 104}
76	{98, 99, 104, 105}	{98, 99, 104, 105}	{98, 99, 104, 105}	{97, 98, 99, 100, 103, 104, 105, 106}	{98, 99, 104, 105}	{98, 99, 104, 105}	{98, 99, 104, 105}	{98, 99, 104, 105}	{98, 99, 104, 105}
77	{99, 100, 105, 106}	{99, 100, 105, 106}	{99, 100, 105, 106}	{98, 99, 100, 101, 104, 105, 106, 107}	{99, 100, 105, 106}	{99, 100, 105, 106}	{99, 100, 105, 106}	{99, 100, 105, 106}	{99, 100, 105, 106}
78	{100, 101, 106, 107}	{100, 101, 106, 107}	{100, 101, 106, 107}	{99, 100, 101, 102, 105, 106, 107, 108}	{100, 101, 106, 107}	{100, 101, 106, 107}	{100, 101, 106, 107}	{100, 101, 106, 107}	{100, 101, 106, 107}
79	{101, 102, 107, 108}	{101, 102, 107, 108}	{101, 102, 107, 108}	∅	{101, 102, 107, 108}	{101, 102, 107, 108}	{101, 102, 107, 108}	{101, 102, 107, 108}	{101, 102, 107, 108}
80	{103, 104, 109, 110}	{103, 104, 109, 110}	{103, 104, 109, 110}	∅	{103, 104, 109, 110}	{103, 104, 109, 110}	{103, 104, 109, 110}	{103, 104, 109, 110}	{103, 104, 109, 110}
81	{104, 105, 110, 111}	{104, 105, 110, 111}	{104, 105, 110, 111}	{103, 104, 105, 106, 109, 110, 111, 112}	{104, 105, 110, 111}	{104, 105, 110, 111}	{104, 105, 110, 111}	{104, 105, 110, 111}	{104, 105, 110, 111}
82	{105, 106, 111, 112}	{105, 106, 111, 112}	{105, 106, 111, 112}	{104, 105, 106, 107, 110, 111, 112, 113}	{105, 106, 111, 112}	{105, 106, 111, 112}	{105, 106, 111, 112}	{105, 106, 111, 112}	{105, 106, 111, 112}
83	{106, 107, 112, 113}	{106, 107, 112, 113}	{106, 107, 112, 113}	{105, 106, 107, 108, 111, 112, 113, 114}	{106, 107, 112, 113}	{106, 107, 112, 113}	{106, 107, 112, 113}	{106, 107, 112, 113}	{106, 107, 112, 113}
84	{107, 108, 113, 114}	{107, 108, 113, 114}	{107, 108, 113, 114}	∅	{107, 108, 113, 114}	{107, 108, 113, 114}	{107, 108, 113, 114}	{107, 108, 113, 114}	{107, 108, 113, 114}
85	∅	∅	∅	∅	∅	∅	∅	∅	∅
86	∅	∅	∅	∅	∅	∅	∅	∅	∅
87	∅	∅	∅	∅	∅	∅	∅	∅	∅
88	∅	∅	∅	∅	∅	∅	∅	∅	∅
89	{113, 114, 115, 116}	{113, 114, 115, 116}	{113, 114, 115, 116}	∅	{113, 114, 115, 116}	{113, 114, 115, 116}	{113, 114, 115, 116}	{113, 114, 115, 116}	{113, 114, 115, 116}
90	{115, 116, 117, 118}	{115, 116, 117, 118}	{115, 116, 117, 118}	∅	{115, 116, 117, 118}	{115, 116, 117, 118}	{115, 116, 117, 118}	{115, 116, 117, 118}	{115, 116, 117, 118}
91	{117, 118, 119, 120}	{117, 118, 119, 120}	{117, 118, 119, 120}	∅	{117, 118, 119, 120}	{117, 118, 119, 120}	{117, 118, 119, 120}	{117, 118, 119, 120}	{117, 118, 119, 120}

Table C.1: *The sets* $S_i(k)$ *for the* 15 *machines at LWC used to solve the discrete layout problem at LWC with* 12 *horizontal blocks and* 11 *vertical blocks producing* 92 *grid–points.*

	Machines					
Grid–points	10	11	12	13	14	15
0	∅	∅	{1, 2, 7, 8}	{1, 2, 7, 8}	∅	{1, 2, 7, 8}
1	{1, 2, 3, 4, 7, 8, 9, 10}	∅	{2, 3, 8, 9}	{2, 3, 8, 9}	∅	{2, 3, 8, 9}
2	{2, 3, 4, 5, 8, 9, 10, 11}	∅	{3, 4, 9, 10}	{3, 4, 9, 10}	∅	{3, 4, 9, 10}
3	{3, 4, 5, 6, 9, 10, 11, 12}	∅	{4, 5, 10, 11}	{4, 5, 10, 11}	∅	{4, 5, 10, 11}
4	∅	∅	{5, 6, 11, 12}	{5, 6, 11, 12}	∅	{5, 6, 11, 12}
5	∅	{1, 2, 7, 8, 13, 14, 19, 20}	{7, 8, 13, 14}	{7, 8, 13, 14}	{1, 2, 7, 8, 13, 14, 19, 20}	{7, 8, 13, 14}
6	{7, 8, 9, 10, 13, 14, 15, 16}	{2, 3, 8, 9, 14, 15, 20, 21}	{8, 9, 14, 15}	{8, 9, 14, 15}	{2, 3, 8, 9, 14, 15, 20, 21}	{8, 9, 14, 15}
7	{8, 9, 10, 11, 14, 15, 16, 17}	{3, 4, 9, 10, 15, 16, 21, 22}	{9, 10, 15, 16}	{9, 10, 15, 16}	{3, 4, 9, 10, 15, 16, 21, 22}	{9, 10, 15, 16}
8	{9, 10, 11, 12, 15, 16, 17, 18}	{4, 5, 10, 11, 16, 17, 22, 23}	{10, 11, 16, 17}	{10, 11, 16, 17}	{4, 5, 10, 11, 16, 17, 22, 23}	{10, 11, 16, 17}
9	∅	{5, 6, 11, 12, 17, 18, 23, 24}	{11, 12, 17, 18}	{11, 12, 17, 18}	{5, 6, 11, 12, 17, 18, 23, 24}	{11, 12, 17, 18}
10	∅	{7, 8, 13, 14, 19, 20, 25, 26}	{13, 14, 19, 20}	{13, 14, 19, 20}	{7, 8, 13, 14, 19, 20, 25, 26}	{13, 14, 19, 20}
11	{13, 14, 15, 16, 19, 20, 21, 22}	{8, 9, 14, 15, 20, 21, 26, 27}	{14, 15, 20, 21}	{14, 15, 20, 21}	{8, 9, 14, 15, 20, 21, 26, 27}	{14, 15, 20, 21}
12	{14, 15, 16, 17, 20, 21, 22, 23}	{9, 10, 15, 16, 21, 22, 27, 28}	{15, 16, 21, 22}	{15, 16, 21, 22}	{9, 10, 15, 16, 21, 22, 27, 28}	{15, 16, 21, 22}
13	{15, 16, 17, 18, 21, 22, 23, 24}	{10, 11, 16, 17, 22, 23, 28, 29}	{16, 17, 22, 23}	{16, 17, 22, 23}	{10, 11, 16, 17, 22, 23, 28, 29}	{16, 17, 22, 23}
14	∅	{11, 12, 17, 18, 23, 24, 29, 30}	{17, 18, 23, 24}	{17, 18, 23, 24}	{11, 12, 17, 18, 23, 24, 29, 30}	{17, 18, 23, 24}
15	∅	{13, 14, 19, 20, 25, 26, 31, 32}	{19, 20, 25, 26}	{19, 20, 25, 26}	{13, 14, 19, 20, 25, 26, 31, 32}	{19, 20, 25, 26}
16	{19, 20, 21, 22, 25, 26, 27, 28}	{14, 15, 20, 21, 26, 27, 32, 33}	{20, 21, 26, 27}	{20, 21, 26, 27}	{14, 15, 20, 21, 26, 27, 32, 33}	{20, 21, 26, 27}
17	{20, 21, 22, 23, 26, 27, 28, 29}	{15, 16, 21, 22, 27, 28, 33, 34}	{21, 22, 27, 28}	{21, 22, 27, 28}	{15, 16, 21, 22, 27, 28, 33, 34}	{21, 22, 27, 28}
18	{21, 22, 23, 24, 27, 28, 29, 30}	{16, 17, 22, 23, 28, 29, 34, 35}	{22, 23, 28, 29}	{22, 23, 28, 29}	{16, 17, 22, 23, 28, 29, 34, 35}	{22, 23, 28, 29}
19	∅	{17, 18, 23, 24, 29, 30, 35, 36}	{23, 24, 29, 30}	{23, 24, 29, 30}	{17, 18, 23, 24, 29, 30, 35, 36}	{23, 24, 29, 30}
20	∅	{19, 20, 25, 26, 31, 32, 37, 38}	{25, 26, 31, 32}	{25, 26, 31, 32}	{19, 20, 25, 26, 31, 32, 37, 38}	{25, 26, 31, 32}
21	{25, 26, 27, 28, 31, 32, 33, 34}	{20, 21, 26, 27, 32, 33, 38, 39}	{26, 27, 32, 33}	{26, 27, 32, 33}	{20, 21, 26, 27, 32, 33, 38, 39}	{26, 27, 32, 33}
22	{26, 27, 28, 29, 32, 33, 34, 35}	{21, 22, 27, 28, 33, 34, 39, 40}	{27, 28, 33, 34}	{27, 28, 33, 34}	{21, 22, 27, 28, 33, 34, 39, 40}	{27, 28, 33, 34}
23	{27, 28, 29, 30, 33, 34, 35, 36}	{22, 23, 28, 29, 34, 35, 40, 41}	{28, 29, 34, 35}	{28, 29, 34, 35}	{22, 23, 28, 29, 34, 35, 40, 41}	{28, 29, 34, 35}
24	∅	{23, 24, 29, 30, 35, 3641, 42}	{29, 30, 35, 36}	{29, 30, 35, 36}	{23, 24, 29, 30, 35, 3641, 42}	{29, 30, 35, 36}
25	∅	{25, 26, 31, 32, 37, 38, 43, 44}	{31, 32, 37, 38}	{31, 32, 37, 38}	{25, 26, 31, 32, 37, 38, 43, 44}	{31, 32, 37, 38}
26	{31, 32, 33, 34, 37, 38, 39, 40}	{26, 27, 32, 33, 38, 39, 44, 45}	{32, 33, 38, 39}	{32, 33, 38, 39}	{26, 27, 32, 33, 38, 39, 44, 45}	{32, 33, 38, 39}
27	{32, 33, 34, 35, 38, 39, 40, 41}	{27, 28, 33, 34, 39, 40, 45, 46}	{33, 34, 39, 40}	{33, 34, 39, 40}	{27, 28, 33, 34, 39, 40, 45, 46}	{33, 34, 39, 40}
28	{33, 34, 35, 36, 39, 40, 41, 42}	{28, 29, 34, 35, 40, 41, 46, 47}	{34, 35, 40, 41}	{34, 35, 40, 41}	{28, 29, 34, 35, 40, 41, 46, 47}	{34, 35, 40, 41}
29	∅	{29, 30, 35, 3641, 42, 47, 48}	{35, 36, 41, 42}	{35, 36, 41, 42}	{29, 30, 35, 3641, 42, 47, 48}	{35, 36, 41, 42}
30	∅	{31, 32, 37, 38, 43, 44, 49, 50}	{37, 38, 43, 44}	{37, 38, 43, 44}	{31, 32, 37, 38, 43, 44, 49, 50}	{37, 38, 43, 44}
31	{37, 38, 39, 40, 43, 44, 45, 46}	{32, 33, 38, 39, 44, 45, 50, 51}	{38, 39, 44, 45}	{38, 39, 44, 45}	{32, 33, 38, 39, 44, 45, 50, 51}	{38, 39, 44, 45}
32	{38, 39, 40, 41, 44, 45, 46, 47}	{33, 34, 39, 40, 45, 46, 51, 52}	{39, 40, 45, 46}	{39, 40, 45, 46}	{33, 34, 39, 40, 45, 46, 51, 52}	{39, 40, 45, 46}
33	{39, 40, 41, 42, 45, 46, 47, 48}	{34, 35, 40, 41, 46, 47, 52, 53}	{40, 41, 46, 47}	{40, 41, 46, 47}	{34, 35, 40, 41, 46, 47, 52, 53}	{40, 41, 46, 47}
34	∅	{35, 36, 41, 42, 47, 48, 53, 54}	{41, 42, 47, 48}	{41, 42, 47, 48}	{35, 36, 41, 42, 47, 48, 53, 54}	{41, 42, 47, 48}
35	∅	{37, 38, 43, 44, 49, 50, 55, 56}	{43, 44, 49, 50}	{43, 44, 49, 50}	{37, 38, 43, 44, 49, 50, 55, 56}	{43, 44, 49, 50}
36	{43, 44, 45, 46, 49, 50, 51, 52}	{38, 39, 44, 45, 50, 51, 56, 57}	{44, 45, 50, 51}	{44, 45, 50, 51}	{38, 39, 44, 45, 50, 51, 56, 57}	{44, 45, 50, 51}
37	{44, 45, 46, 47, 50, 51, 52, 53}	{39, 40, 45, 46, 51, 52, 57, 58}	{45, 46, 51, 52}	{45, 46, 51, 52}	{39, 40, 45, 46, 51, 52, 57, 58}	{45, 46, 51, 52}
38	{45, 46, 47, 48, 51, 52, 53, 54}	{40, 41, 46, 47, 52, 53, 58, 59}	{46, 47, 52, 53}	{46, 47, 52, 53}	{40, 41, 46, 47, 52, 53, 58, 59}	{46, 47, 52, 53}
39	∅	{41, 42, 47, 48, 53, 54, 59, 60}	{47, 48, 53, 54}	{47, 48, 53, 54}	{41, 42, 47, 48, 53, 54, 59, 60}	{47, 48, 53, 54}
40	∅	{43, 44, 49, 50, 55, 56, 61, 62}	{49, 50, 55, 56}	{49, 50, 55, 56}	{43, 44, 49, 50, 55, 56, 61, 62}	{49, 50, 55, 56}
41	{49, 50, 51, 52, 55, 56, 57, 58}	{44, 45, 50, 51, 56, 57, 62, 63}	{50, 51, 56, 57}	{50, 51, 56, 57}	{44, 45, 50, 51, 56, 57, 62, 63}	{50, 51, 56, 57}
42	{50, 51, 52, 53, 56, 57, 58, 59}	{45, 46, 51, 52, 57, 58, 63, 64}	{51, 52, 57, 58}	{51, 52, 57, 58}	{45, 46, 51, 52, 57, 58, 63, 64}	{51, 52, 57, 58}
43	{51, 52, 53, 54, 57, 58, 59, 60}	{46, 47, 52, 53, 58, 59, 64, 65}	{52, 53, 58, 59}	{52, 53, 58, 59}	{46, 47, 52, 53, 58, 59, 64, 65}	{52, 53, 58, 59}
44	∅	{47, 48, 53, 54, 59, 60, 65, 66}	{53, 54, 59, 60}	{53, 54, 59, 60}	{47, 48, 53, 54, 59, 60, 65, 66}	{53, 54, 59, 60}
45	∅	∅	{55, 56, 61, 62}	{55, 56, 61, 62}	∅	{55, 56, 61, 62}
46	{55, 56, 57, 58, 61, 62, 63, 64}	∅	{56, 57, 62, 63}	{56, 57, 62, 63}	∅	{56, 57, 62, 63}
47	{56, 57, 58, 59, 62, 63, 64, 65}	∅	{57, 58, 63, 64}	{57, 58, 63, 64}	∅	{57, 58, 63, 64}
48	{57, 58, 59, 60, 63, 64, 65, 66}	∅	{58, 59, 64, 65}	{58, 59, 64, 65}	∅	{58, 59, 64, 65}
49	∅	∅	{59, 60, 65, 66}	{59, 60, 65, 66}	∅	{59, 60, 65, 66}
50	∅	∅	{67, 68, 73, 74}	{67, 68, 73, 74}	∅	{67, 68, 73, 74}
51	{67, 68, 69, 70, 73, 74, 75, 76}	∅	{68, 69, 74, 75}	{68, 69, 74, 75}	∅	{68, 69, 74, 75}
52	{68, 69, 70, 71, 74, 75, 76, 77}	∅	{69, 70, 75, 76}	{69, 70, 75, 76}	∅	{69, 70, 75, 76}
53	{69, 70, 71, 72, 75, 76, 77, 78}	∅	{70, 71, 76, 77}	{70, 71, 76, 77}	∅	{70, 71, 76, 77}
54	∅	∅	{71, 72, 77, 78}	{71, 72, 77, 78}	∅	{71, 72, 77, 78}
55	∅	{67, 68, 73, 74, 79, 80, 85, 86}	{73, 74, 79, 80}	{73, 74, 79, 80}	{67, 68, 73, 74, 79, 80, 85, 86}	{73, 74, 79, 80}
56	{73, 74, 75, 76, 79, 80, 81, 82}	{68, 69, 74, 75, 80, 81, 86, 87}	{74, 75, 80, 81}	{74, 75, 80, 81}	{68, 69, 74, 75, 80, 81, 86, 87}	{74, 75, 80, 81}
57	{74, 75, 76, 77, 80, 81, 82, 83}	{69, 70, 75, 76, 81, 82, 87, 88}	{75, 76, 81, 82}	{75, 76, 81, 82}	{69, 70, 75, 76, 81, 82, 87, 88}	{75, 76, 81, 82}
58	{75, 76, 77, 78, 81, 82, 83, 84}	{70, 71, 76, 77, 82, 83, 88, 89}	{76, 77, 82, 83}	{76, 77, 82, 83}	{70, 71, 76, 77, 82, 83, 88, 89}	{76, 77, 82, 83}
59	∅	{71, 72, 77, 78, 83, 84, 89, 90}	{77, 78, 83, 84}	{77, 78, 83, 84}	{71, 72, 77, 78, 83, 84, 89, 90}	{77, 78, 83, 84}
60	∅	{73, 74, 79, 80, 85, 86, 91, 92}	{79, 80, 85, 86}	{79, 80, 85, 86}	{73, 74, 79, 80, 85, 86, 91, 92}	{79, 80, 85, 86}
61	{79, 80, 81, 82, 85, 86, 87, 88}	{74, 75, 80, 81, 86, 87, 92, 93}	{80, 81, 86, 87}	{80, 81, 86, 87}	{74, 75, 80, 81, 86, 87, 92, 93}	{80, 81, 86, 87}
62	{80, 81, 82, 83, 86, 87, 88, 89}	{75, 76, 81, 82, 87, 88, 93, 94}	{81, 82, 87, 88}	{81, 82, 87, 88}	{75, 76, 81, 82, 87, 88, 93, 94}	{81, 82, 87, 88}
63	{81, 82, 83, 84, 87, 88, 89, 90}	{76, 77, 82, 83, 88, 89, 94, 95}	{82, 83, 88, 89}	{82, 83, 88, 89}	{76, 77, 82, 83, 88, 89, 94, 95}	{82, 83, 88, 89}
64	∅	{77, 78, 83, 84, 89, 90, 95, 96}	{83, 84, 89, 90}	{83, 84, 89, 90}	{77, 78, 83, 84, 89, 90, 95, 96}	{83, 84, 89, 90}
65	∅	{79, 80, 85, 86, 91, 92, 97, 98}	{85, 86, 91, 92}	{85, 86, 91, 92}	{79, 80, 85, 86, 91, 92, 97, 98}	{85, 86, 91, 92}
66	{85, 86, 87, 88, 91, 92, 93, 94}	{80, 81, 86, 87, 92, 93, 98, 99}	{86, 87, 92, 93}	{86, 87, 92, 93}	{80, 81, 86, 87, 92, 93, 98, 99}	{86, 87, 92, 93}
67	{86, 87, 88, 89, 92, 93, 94, 95}	{81, 82, 87, 88, 93, 94, 99, 100}	{87, 88, 93, 94}	{87, 88, 93, 94}	{81, 82, 87, 88, 93, 94, 99, 100}	{87, 88, 93, 94}
68	{87, 88, 89, 90, 93, 94, 95, 96}	{82, 83, 88, 89, 94, 95, 100, 101}	{88, 89, 94, 95}	{88, 89, 94, 95}	{82, 83, 88, 89, 94, 95, 100, 101}	{88, 89, 94, 95}
69	∅	{83, 84, 89, 90, 95, 96, 101, 102}	{89, 90, 95, 96}	{89, 90, 95, 96}	{83, 84, 89, 90, 95, 96, 101, 102}	{89, 90, 95, 96}
70	∅	{85, 86, 91, 92, 97, 98, 103, 104}	{91, 92, 97, 98}	{91, 92, 97, 98}	{85, 86, 91, 92, 97, 98, 103, 104}	{91, 92, 97, 98}
71	{91, 92, 93, 94, 97, 98, 99, 100}	{86, 87, 92, 93, 98, 99, 104, 105}	{92, 93, 98, 99}	{92, 93, 98, 99}	{86, 87, 92, 93, 98, 99, 104, 105}	{92, 93, 98, 99}
72	{92, 93, 94, 95, 98, 99, 100, 101}	{87, 88, 93, 94, 99, 100, 105, 106}	{93, 94, 99, 100}	{93, 94, 99, 100}	{87, 88, 93, 94, 99, 100, 105, 106}	{93, 94, 99, 100}
73	{93, 94, 95, 96, 99, 100, 101, 102}	{88, 89, 94, 95, 100, 101, 106, 107}	{94, 95, 100, 101}	{94, 95, 100, 101}	{88, 89, 94, 95, 100, 101, 106, 107}	{94, 95, 100, 101}
74	∅	{89, 90, 95, 96, 101, 102, 107, 108}	{95, 96, 101, 102}	{95, 96, 101, 102}	{89, 90, 95, 96, 101, 102, 107, 108}	{95, 96, 101, 102}
75	∅	{91, 92, 97, 98, 103, 104, 109, 110}	{97, 98, 103, 104}	{97, 98, 103, 104}	{91, 92, 97, 98, 103, 104, 109, 110}	{97, 98, 103, 104}
76	{97, 98, 99, 100, 103, 104, 105, 106}	{92, 93, 98, 99, 104, 105, 110, 111}	{98, 99, 104, 105}	{98, 99, 104, 105}	{92, 93, 98, 99, 104, 105, 110, 111}	{98, 99, 104, 105}
77	{98, 99, 100, 101, 104, 105, 106, 107}	{93, 94, 99, 100, 105, 106, 111, 112}	{99, 100, 105, 106}	{99, 100, 105, 106}	{93, 94, 99, 100, 105, 106, 111, 112}	{99, 100, 105, 106}
78	{99, 100, 101, 102, 105, 106, 107, 108}	{94, 95, 100, 101, 106, 107, 112, 113}	{100, 101, 106, 107}	{100, 101, 106, 107}	{94, 95, 100, 101, 106, 107, 112, 113}	{100, 101, 106, 107}
79	∅	{95, 96, 101, 102, 107, 108, 113, 114}	{101, 102, 107, 108}	{101, 102, 107, 108}	{95, 96, 101, 102, 107, 108, 113, 114}	{101, 102, 107, 108}
80	∅	∅	{103, 104, 109, 110}	{103, 104, 109, 110}	∅	{103, 104, 109, 110}
81	{103, 104, 105, 106, 109, 110, 111, 112}	∅	{104, 105, 110, 111}	{104, 105, 110, 111}	∅	{104, 105, 110, 111}
82	{104, 105, 106, 107, 110, 111, 112, 113}	∅	{105, 106, 111, 112}	{105, 106, 111, 112}	∅	{105, 106, 111, 112}
83	{105, 106, 107, 108, 111, 112, 113, 114}	∅	{106, 107, 112, 113}	{106, 107, 112, 113}	∅	{106, 107, 112, 113}
84	∅	{101, 102, 107, 108, 113, 114, 115, 116}	{107, 108, 113, 114}	{107, 108, 113, 114}	{101, 102, 107, 108, 113, 114, 115, 116}	{107, 108, 113, 114}
85	∅	∅	∅	∅	∅	∅
86	∅	∅	∅	∅	∅	∅
87	∅	∅	∅	∅	∅	∅
88	∅	∅	∅	∅	∅	∅
89	∅	{107, 108, 113, 114, 115, 116, 117, 118}	{113, 114, 115, 116}	{113, 114, 115, 116}	{107, 108, 113, 114, 115, 116, 117, 118}	{113, 114, 115, 116}
90	∅	{113, 114, 115, 116, 117, 118, 119, 120}	{115, 116, 117, 118}	{115, 116, 117, 118}	{113, 114, 115, 116, 117, 118, 119, 120}	{115, 116, 117, 118}
91	∅	∅	{117, 118, 119, 120}	{117, 118, 119, 120}	∅	{117, 118, 119, 120}

Table C.1 (continued): *The sets* $S_i(k)$ *for the* 15 *machines at LWC used to solve the discrete layout problem at LWC with* 12 *horizontal blocks and* 11 *vertical blocks producing* 92 *grid–points.*

Appendix D

Data Collected at LWC

In this appendix the processing times [in seconds] at each machine at LWC, collected with the aid of a stopwatch, are presented along with the respective independent variable values used to estimate the processing times by means of regression.

D.1 Panel Saw

The processing time and cut length for the 51 data points measured on the Panel Saw at LWC.

Cut Length [m]	**Processing Time [s]**	**Cut Length [m]**	**Processing Time [s]**	**Cut Length [m]**	**Processing Time [s]**
2.46	30.00	4.51	310.00	1.87	720.00
4.51	40.00	9.08	314.00	3.71	724.00
2.66	54.00	2.00	405.00	4.57	725.00
3.03	90.00	6.59	406.00	11.33	730.00
1.97	108.00	3.07	411.00	17.60	755.00
3.20	112.00	17.29	473.00	18.18	780.00
3.85	120.00	2.89	482.00	22.17	821.00
5.44	120.00	16.17	553.00	7.85	830.00
3.46	123.00	23.52	567.00	18.22	860.00
4.69	150.00	19.26	590.00	15.42	938.00
5.41	150.00	8.72	600.00	2.48	1 020.00
2.67	234.00	3.79	623.00	11.47	1 070.00
9.24	234.00	3.17	644.00	17.50	1 190.00
2.18	242.00	4.74	671.00	16.85	1 240.00
3.83	249.00	23.71	671.00	23.71	1 368.00
11.88	278.00	23.71	673.00	23.18	1 595.00
13.36	284.00	6.43	690.00	21.56	1 670.00

Table D.1: *The processing time and cut length data points used to estimate the processing time for the Panel Saw.*

D.2 Radial Arm Saw

The processing time and width for the five data points measured on the Radial Arm Saw at LWC.

Width [m]	**Processing Time [s]**
0.04	22.00
1.60	37.00
0.31	38.00
0.56	62.00
1.98	130.00

Table D.2: *The processing time and length data points used to estimate the processing time for the Radial Arm Saw.*

D.3 Ripper

The processing time and length for the 32 data points measured on the Ripper at LWC.

Length [m]	**Processing Time [s]**	**Length [m]**	**Processing Time [s]**
0.79	11.00	18.16	433.00
0.79	25.00	12.79	457.00
3.00	32.00	54.00	840.00
3.00	65.00	66.00	885.00
3.16	73.00	120.40	1 004.00
3.76	82.00	126.42	1 040.00
4.90	130.00	123.41	1 140.00
15.00	161.00	165.55	1 215.00
9.00	170.00	90.30	1 310.00
15.00	180.00	174.58	1 950.00
20.02	224.00	86.11	2 014.00
7.50	284.00	154.56	2 027.00
39.00	334.00	126.00	2 092.00
9.00	336.00	229.63	3 283.00
32.50	345.00	229.63	3 283.00
36.00	385.00	278.21	3 316.00

Table D.3: *The processing time and length data points used to estimate the processing time for the Ripper.*

D.4 Planer

The processing time and length for the six data points measured on the Planer at LWC.

Length [m]	**Processing Time [s]**
3.00	197.00
3.76	260.00
8.76	330.00
24.08	750.00
16.46	960.00
24.07	1 270.00

Table D.4: *The processing time and length data points used to estimate the processing time for the Planer.*

D.5 Four–side Planer

The processing time and length for the data point measured on the Four–side Planer at LWC.

Length [m]	**Processing Time [s]**
511.5	6 398

Table D.5: *The processing time and length data point used to estimate the processing time for the Four–side Planer.*

D.6 Spindle

The processing time and length for the six data points measured on the Spindle at LWC.

Length [m]	**Processing Time [s]**
2.70	0.50
2.70	0.58
2.75	0.32
2.75	0.38
2.75	0.52
13.29	12.13

Table D.6: *The processing time and length data points used to estimate the processing time for the Spindle.*

D.7 Edge Sander

The processing time and length for the 13 data points measured on the Edge Sander at LWC.

Length [m]	**Processing Time [s]**
0.12	16.00
0.12	16.00
0.12	17.00
0.12	18.00
0.53	26.00
0.53	32.00
0.68	44.00
0.75	36.00
0.75	38.00
0.90	37.00
0.90	37.00
0.90	40.00
1.02	53.00

Table D.7: *The processing time and length data points used to estimate the processing time for the Edge Sander.*

D.8 Assembly Station

The processing time and surface area for the nine data points measured on the Assembly Station at LWC.

Surface Area [m^2]	**Processing Time [s]**
1.00	276.00
0.04	315.00
0.63	464.00
1.26	544.00
1.00	645.00
2.52	2 252.00
0.04	2 701.00
2.05	16 187.00
14.28	17 603.00

Table D.8: *The processing time and surface area data points used to estimate the processing time for the Assembly Station.*

D.9 Base Coat Spray–booth

The processing time and surface area for the 29 data points measured on the Base Coat Spray–booth at LWC.

Surface Area [m^2]	**Processing Time [s]**	**Surface Area [m^2]**	**Processing Time [s]**	**Surface Area [m^2]**	**Processing Time [s]**
1.22	134.00	0.29	40.00	0.35	31.00
1.37	117.00	0.56	148.00	0.27	42.00
1.22	180.00	0.12	34.00	0.32	57.00
0.32	76.00	0.16	42.00	0.33	50.00
0.32	54.00	0.16	33.00	0.16	55.00
0.35	47.00	0.16	42.00	0.33	55.00
0.29	46.00	0.11	37.00	0.33	38.00
0.35	61.00	1.34	132.00	0.44	58.00
0.29	43.00	1.34	150.00	0.33	34.00
0.29	36.00	0.35	59.00		

Table D.9: *The processing time and surface area data points used to estimate the processing time for the Base Coat Spray–booth.*

D.10 Top Coat Spray–booth

The processing time and surface area for the eight data points measured on the Top Coat Spray–booth at LWC.

Surface Area [m^2]	**Processing Time [s]**
0.10	0.10
0.99	195.00
5.55	1 110.00
17.46	2 050.00
20.22	4 357.00
24.80	3 075.00
34.92	9 710.00
0.90	195.00

Table D.10: *The processing time and surface area data points used to estimate the processing time for the Top Coat Spray–booth.*

D.11 Edge Bander

The processing time and running metre for the 26 data points measured on the Edge Bander at LWC.

Running Metre [m]	Processing Time [s]	Running Metre [m]	Processing Time [s]	Running Metre [m]	Processing Time [s]
2.85	205.00	36.26	920.00	13.07	2 184.40
3.40	232.00	29.25	990.00	46.46	2 370.00
17.40	510.00	45.00	1 002.00	70.78	2 500.00
18.12	525.00	29.75	1 170.00	72.00	2 790.00
8.69	587.00	43.20	1 260.00	90.00	3 165.00
41.20	600.00	22.94	1 260.00	19.12	3 397.00
20.60	760.00	29.25	1 350.00	60.51	3 649.00
28.56	795.00	9.66	2 010.00	189.80	5 995.00
4.76	800.00	19.72	2 070.00		

Table D.11: *The processing time and running metre data points used to estimate the processing time for the Edge Bander.*

D.12 Wrapping Unit

The processing time and surface area for the three data points measured at the Wrapping Unit at LWC.

Surface Area [m^2]	Processing Time [s]
1.82	1.10
7.00	13.31
8.85	16.16

Table D.12: *The processing time and surface area data points used to estimate the processing time for the Wrapping Unit.*

D.13 Drill

The processing time and number of holes for the data point measured on the Drill at LWC.

Number of Holes	Processing Time [s]
8.00	1 153.00

Table D.13: *The processing time and number of holes data point used to estimate the processing time for the Drill.*

D.14 Widebelt Sander

The processing time and surface area for the 79 data points measured on the Widebelt Sander at LWC.

Surface Area [m^2]	Processing Time [s]	Surface Area [m^2]	Processing Time [s]	Surface Area [m^2]	Processing Time [s]	Surface Area [m^2]	Processing Time [s]
0.64	20.00	1.62	120.00	10.60	390.00	29.07	784.00
0.64	20.00	0.12	128.00	52.33	410.00	18.75	790.00
0.64	24.00	0.72	150.00	65.49	420.00	16.16	890.00
2.54	29.00	1.07	167.00	7.20	420.00	2.90	975.00
0.64	30.00	4.10	195.00	52.33	450.00	3.93	1 017.00
0.09	31.00	4.31	210.00	16.58	450.00	7.61	1 155.00
2.54	40.00	19.93	230.00	6.83	480.00	25.46	1 180.00
3.00	45.00	3.23	240.00	15.11	498.00	43.52	1 193.00
2.54	45.00	2.58	263.00	4.95	510.00	32.02	1 210.00
1.62	45.00	1.99	277.00	10.09	530.00	17.80	1 272.00
1.62	45.00	1.88	280.00	21.02	570.00	17.48	1 576.00
3.00	50.00	2.70	285.00	29.25	585.00	31.87	1 770.00
0.54	52.00	8.21	290.00	3.55	585.00	40.23	1 786.00
2.54	60.00	2.27	290.00	12.46	600.00	49.83	1 800.00
2.54	70.00	1.69	339.00	33.14	629.00	39.24	1 880.00
0.36	71.00	52.33	349.00	24.64	660.00	15.17	2 010.00
2.54	91.00	0.54	370.00	0.46	660.00	87.78	2 339.00
0.63	100.00	1.80	382.00	6.83	710.00	69.78	2 386.00
5.99	110.00	52.33	390.00	40.37	715.00	71.67	2 635.00
0.63	110.00	28.80	390.00	22.57	730.00		

Table D.14: *The processing time and surface area data points used to estimate the processing time for the Widebelt Sander.*

D.15 Handsand Area

The processing time and surface area for the 21 data points measured on the Handsand Area at LWC.

Surface Area [m^2]	Processing Time [s]	Surface Area [m^2]	Processing Time [s]	Surface Area [m^2]	Processing Time [s]
31.46	6 180.00	1.33	225.00	0.09	33.75
12.40	4 737.00	0.73	80.17	0.93	24.97
2.62	4 170.00	0.27	72.25	0.62	15.53
1.08	2 880.00	0.32	62.50	1.39	14.00
8.15	1 500.00	1.73	42.50	0.09	13.83
0.88	900.00	0.23	41.00	0.14	2.75
0.52	673.00	0.18	35.00	0.05	2.50

Table D.15: *The processing time and surface area data points used to estimate the processing time for the Handsand Area.*

Appendix E

The Jobs Processed by LWC from June 2002 to December 2002

In this appendix the job/order type, arrival and dispatch dates of all the jobs dispatched in the last 6 months of 2002 are presented in Tables E.1–E.7. This data were used in order to compare the tabu search scheduling done in §6.3 with the scheduling conducted at LWC.

Start Date	Job Type	Dispatch Date		Start Date	Job Type	Dispatch Date
7-Jun-2002	Contract Cut and Route	7-Jun-2002		10-Jun-2002	Contract Cut	28-Aug-2002
10-Jun-2002	Contract Calibrate Sand	28-Aug-2002		12-Jun-2002	Shaker Doors	2-Jul-2002
12-Jun-2002	Shaker Doors	2-Jul-2002		21-Jun-2002	Veneer Over Edge	10-Jul-2002
25-Jun-2002	Contract Calibrate Sand	17-Jul-2002		25-Jun-2002	Contract Veneer Sand	3-Jul-2002
25-Jun-2002	Contract Veneer Sand	3-Jul-2002		25-Jun-2002	Contract Calibrate Sand	2-Jul-2002
26-Jun-2002	Shaker Doors	2-Jul-2002		26-Jun-2002	Contract Veneer Sand	4-Jul-2002
26-Jun-2002	Contract Calibrate Sand	3-Jul-2002		26-Jun-2002	Contract Veneer Sand	3-Jul-2002
26-Jun-2002	Contract Veneer Sand	3-Jul-2002		27-Jun-2002	Contract Plane all Round (PAR)	1-Jul-2002
27-Jun-2002	Contract Spray: Top and Base Coat, Calibrate and Veneer Sand	1-Jul-2002		27-Jun-2002	Contract Cut	17-Jul-2002
27-Jun-2002	Veneer Over Edge	23-Jul-2002		27-Jun-2002	Contract Veneer Sand	3-Jul-2002
27-Jun-2002	Contract Calibrate Sand	3-Jul-2002		27-Jun-2002	Contract Veneer Sand	3-Jul-2002
28-Jun-2002	Contract Calibrate Sand	3-Jul-2002		29-Jun-2002	Veneer Over Edge	3-Jul-2002

Table E.1: *The job types, arrival dates and dispatch dates for jobs accepted by LWC during June 2002.*

Start Date	Job Type	Dispatch Date		Start Date	Job Type	Dispatch Date
1-Jul-2002	Shaker Doors	5-Jul-2002		1-Jul-2002	Veneer Over Edge	23-Jul-2002
1-Jul-2002	Contract Calibrate Sand	3-Jul-2002		2-Jul-2002	Contract Spray: Top and Base Coat	5-Jul-2002
2-Jul-2002	Veneer Over Edge	22-Jul-2002		2-Jul-2002	Veneer Over Edge	23-Jul-2002
2-Jul-2002	Veneer Over Edge	23-Jul-2002		2-Jul-2002	Veneer Over Edge	17-Jul-2002
2-Jul-2002	Veneer Over Edge	19-Jul-2002		2-Jul-2002	Veneer Over Edge	17-Jul-2002
2-Jul-2002	Veneer Over Edge	12-Jul-2002		2-Jul-2002	Contract Veneer Sand	10-Jul-2002
2-Jul-2002	Contract Veneer Sand	10-Jul-2002		2-Jul-2002	Contract Calibrate Sand	3-Jul-2002
2-Jul-2002	Contract Calibrate Sand	3-Jul-2002		3-Jul-2002	Contract Calibrate Sand	12-Jul-2002
3-Jul-2002	Contract Calibrate Sand	10-Jul-2002		3-Jul-2002	Contract Calibrate Sand	3-Jul-2002
3-Jul-2002	Contract Veneer Sand	3-Jul-2002		4-Jul-2002	Contract Calibrate Sand	8-Jul-2002
4-Jul-2002	Contract Calibrate Sand	10-Jul-2002		4-Jul-2002	Veneer Over Edge	18-Jul-2002
4-Jul-2002	Contract Cut and Edge	18-Jul-2002		5-Jul-2002	Veneer Over Edge	8-Jul-2002
5-Jul-2002	Veneer Over Edge	23-Jul-2002		5-Jul-2002	Contract Cut	23-Jul-2002
5-Jul-2002	Contract Calibrate and Veneer Sand	5-Jul-2002		5-Jul-2002	Contract Calibrate and Veneer Sand	5-Jul-2002
5-Jul-2002	Contract Calibrate Sand	5-Jul-2002		5-Jul-2002	Contract Edging	11-Jul-2002
5-Jul-2002	Veneer Over Edge	26-Jul-2002		5-Jul-2002	Contract Cut	5-Jul-2002
5-Jul-2002	Shaker Doors	26-Jul-2002		5-Jul-2002	Contract Veneer Sand	8-Jul-2002
5-Jul-2002	Contract Calibrate Sand	18-Jul-2002		5-Jul-2002	Contract Veneer Sand	18-Jul-2002
5-Jul-2002	Contract Veneer Sand	18-Jul-2002		5-Jul-2002	Contract Veneer Sand	10-Jul-2002

Table E.2: *The job types, arrival dates and dispatch dates for jobs accepted by LWC during July 2002.*

Start Date	**Job Type**	**Dispatch Date**		**Start Date**	**Job Type**	**Dispatch Date**
5-Jul-2002	Contract Calibrate Sand	10-Jul-2002		5-Jul-2002	Contract Calibrate Sand	10-Jul-2002
5-Jul-2002	Contract Calibrate Sand	8-Jul-2002		5-Jul-2002	Contract Calibrate Sand	8-Jul-2002
8-Jul-2002	Contract Cut	30-Jul-2002		8-Jul-2002	Contract Veneer Sand	8-Jul-2002
8-Jul-2002	Contract Cut and Edge	9-Jul-2002		8-Jul-2002	Contract Cut	10-Jul-2002
8-Jul-2002	Contract Calibrate and Veneer Sand	8-Jul-2002		8-Jul-2002	Contract Calibrate and Veneer Sand	8-Jul-2002
8-Jul-2002	Contract Calibrate Sand	8-Jul-2002		8-Jul-2002	Contract Veneer Sand	26-Jul-2002
8-Jul-2002	Contract Veneer Sand	16-Jul-2002		8-Jul-2002	Contract Veneer Sand	12-Jul-2002
8-Jul-2002	Contract Calibrate Sand	10-Jul-2002		8-Jul-2002	Contract Calibrate Sand	10-Jul-2002
8-Jul-2002	Contract Calibrate Sand	10-Jul-2002		8-Jul-2002	Contract Calibrate Sand	10-Jul-2002
9-Jul-2002	Contract Spray Lacquer Top and Base Coat	10-Jul-2002		9-Jul-2002	Contract Calibrate Sand	10-Jul-2002
9-Jul-2002	Contract Calibrate Sand	10-Jul-2002		10-Jul-2002	Contract Cut	11-Jul-2002
10-Jul-2002	Contract Calibrate Sand	18-Jul-2002		10-Jul-2002	Contract Calibrate Sand	12-Jul-2002
10-Jul-2002	Unique	5-Aug-2002		11-Jul-2002	Contract Calibrate Sand	12-Jul-2002
11-Jul-2002	Contract Veneer Sand	12-Jul-2002		11-Jul-2002	Contract Cut	12-Jul-2002
11-Jul-2002	Contract Veneer Sand	12-Jul-2002		11-Jul-2002	Contract Cut	12-Jul-2002
11-Jul-2002	Contract Spray Lacquer Top and Base Coat	17-Jul-2002		11-Jul-2002	Contract Spray: Stain Top Coat	17-Jul-2002
11-Jul-2002	Veneer Over Edge	18-Jul-2002		11-Jul-2002	Veneer Over Edge	23-Jul-2002
11-Jul-2002	Contract Cut	11-Jul-2002		11-Jul-2002	Contract Veneer Sand	11-Jul-2002
11-Jul-2002	Contract Calibrate and Veneer Sand	11-Jul-2002		11-Jul-2002	Contract Calibrate and Veneer Sand	11-Jul-2002
11-Jul-2002	Contract Calibrate Sand	16-Jul-2002		11-Jul-2002	Contract Calibrate Sand	16-Jul-2002
11-Jul-2002	Contract Calibrate Sand	16-Jul-2002		12-Jul-2002	Contract Cut and Edge	12-Jul-2002
12-Jul-2002	Contract Calibrate Sand	22-Jul-2002		12-Jul-2002	Contract Calibrate Sand	22-Jul-2002
12-Jul-2002	Contract Calibrate Sand	18-Jul-2002		12-Jul-2002	Contract Calibrate Sand	18-Jul-2002
12-Jul-2002	Contract Calibrate Sand	12-Jul-2002		15-Jul-2002	Contract Cut	15-Jul-2002
15-Jul-2002	Veneer Over Edge	23-Jul-2002		15-Jul-2002	Contract Cut, Edge and Groove	24-Jul-2002
15-Jul-2002	Contract Veneer Sand	24-Jul-2002		15-Jul-2002	Contract Cut	16-Jul-2002
15-Jul-2002	Contract Calibrate Sand	22-Jul-2002		15-Jul-2002	Contract Calibrate Sand	22-Jul-2002
15-Jul-2002	Contract Veneer Sand	23-Jul-2002		15-Jul-2002	Contract Veneer Sand	23-Jul-2002
15-Jul-2002	Contract Calibrate Sand	19-Jul-2002		15-Jul-2002	Contract Veneer Sand	19-Jul-2002
15-Jul-2002	Contract Veneer Sand	18-Jul-2002		15-Jul-2002	Contract Calibrate Sand	15-Jul-2002
15-Jul-2002	Contract Calibrate Sand	16-Jul-2002		15-Jul-2002	Contract Calibrate Sand	16-Jul-2002
15-Jul-2002	Contract Calibrate Sand	16-Jul-2002		16-Jul-2002	Contract Calibrate and Veneer Sand	16-Jul-2002
16-Jul-2002	Contract Calibrate Sand	16-Jul-2002		17-Jul-2002	Contract Calibrate and Veneer Sand	18-Jul-2002
17-Jul-2002	Contract Veneer Sand	23-Jul-2002		17-Jul-2002	Contract Calibrate Sand	19-Jul-2002
17-Jul-2002	Contract Calibrate Sand	19-Jul-2002		17-Jul-2002	Contract Calibrate Sand	6-Aug-2002
17-Jul-2002	Veneer Over Edge	12-Aug-2002		17-Jul-2002	Veneer Over Edge	8-Aug-2002
17-Jul-2002	Veneer Over Edge	8-Aug-2002		17-Jul-2002	Veneer Over Edge	16-Sep-2002
18-Jul-2002	Contract Calibrate and Veneer Sand	24-Jul-2002		18-Jul-2002	Contract Veneer Sand	19-Jul-2002
18-Jul-2002	Veneer Over Edge	23-Jul-2002		18-Jul-2002	Contract Veneer Sand	30-Jul-2002
18-Jul-2002	Contract Veneer Sand	30-Jul-2002		18-Jul-2002	Contract Veneer Sand	29-Jul-2002
18-Jul-2002	Contract Veneer Sand	23-Jul-2002		18-Jul-2002	Contract Calibrate Sand	19-Jul-2002
18-Jul-2002	Shaker Doors	18-Jul-2002		19-Jul-2002	Contract Veneer Sand	30-Jul-2002
19-Jul-2002	Contract Veneer Sand	30-Jul-2002		19-Jul-2002	Contract Calibrate Sand	29-Jul-2002
19-Jul-2002	Contract Veneer Sand	29-Jul-2002		19-Jul-2002	Contract Veneer Sand	26-Jul-2002
19-Jul-2002	Contract Veneer Sand	26-Jul-2002		19-Jul-2002	Contract Calibrate Sand	23-Jul-2002
19-Jul-2002	Contract Calibrate Sand	22-Jul-2002		19-Jul-2002	Contract Calibrate Sand	22-Jul-2002
19-Jul-2002	Contract Calibrate Sand	22-Jul-2002		19-Jul-2002	Contract Calibrate Sand	22-Jul-2002
19-Jul-2002	Contract Calibrate Sand	22-Jul-2002		19-Jul-2002	Contract Calibrate Sand	19-Jul-2002
19-Jul-2002	Contract Calibrate Sand	2-Aug-2002		20-Jul-2002	Contract Veneer Sand	2-Aug-2002
22-Jul-2002	Contract Cut	24-Jul-2002		22-Jul-2002	Contract Calibrate and Veneer Sand	22-Jul-2002
22-Jul-2002	Contract Calibrate and Veneer Sand	22-Jul-2002		22-Jul-2002	Contract Calibrate and Veneer Sand	22-Jul-2002
22-Jul-2002	Contract Veneer Sand	30-Jul-2002		22-Jul-2002	Contract Veneer Sand	30-Jul-2002
22-Jul-2002	Contract Calibrate Sand	25-Jul-2002		22-Jul-2002	Contract Calibrate Sand	23-Jul-2002
22-Jul-2002	Contract Calibrate Sand	23-Jul-2002		22-Jul-2002	Contract Calibrate Sand	22-Jul-2002
22-Jul-2002	Veneer Over Edge	8-Aug-2002		23-Jul-2002	Contract Cut	25-Jul-2002
23-Jul-2002	Contract Edging	26-Jul-2002		23-Jul-2002	Contract Edging	23-Jul-2002
23-Jul-2002	Contract Spray: Stain Top Coat	24-Jul-2002		23-Jul-2002	Contract Calibrate Sand	26-Jul-2002
23-Jul-2002	Contract Calibrate Sand	25-Jul-2002		23-Jul-2002	Contract Spray Lacquer Top and Base Coat	31-Aug-2002
23-Jul-2002	Board Components	19-Aug-2002		23-Jul-2002	Shaker Doors	19-Aug-2002
23-Jul-2002	Veneer Over Edge	19-Aug-2002		23-Jul-2002	Board Components	19-Aug-2002
23-Jul-2002	Veneer Over Edge	19-Aug-2002		23-Jul-2002	Veneer Over Edge	8-Aug-2002
23-Jul-2002	Board Components	5-Aug-2002		23-Jul-2002	Contract Cut	5-Aug-2002
23-Jul-2002	Veneer Over Edge	5-Aug-2002		24-Jul-2002	Contract Spray Lacquer Top and Base Coat	24-Jul-2002
24-Jul-2002	Contract Spray: Stain Top Coat	24-Jul-2002		24-Jul-2002	Components on Edge	24-Jul-2002
24-Jul-2002	Contract Calibrate Sand	24-Jul-2002		24-Jul-2002	Veneer Over Edge	24-Jul-2002
24-Jul-2002	Contract Veneer Sand	24-Jul-2002		24-Jul-2002	Contract Veneer Sand	30-Jul-2002
24-Jul-2002	Contract Calibrate Sand	29-Jul-2002		24-Jul-2002	Contract Veneer Sand	29-Jul-2002
24-Jul-2002	Contract Calibrate Sand	25-Jul-2002		24-Jul-2002	Contract Calibrate Sand	25-Jul-2002
24-Jul-2002	Contract Calibrate Sand	24-Jul-2002		24-Jul-2002	Contract Calibrate Sand	2-Aug-2002
25-Jul-2002	Contract Calibrate Sand	25-Jul-2002		25-Jul-2002	Contract Cut	25-Jul-2002
25-Jul-2002	Contract Calibrate and Veneer Sand	26-Jul-2002		25-Jul-2002	Contract Calibrate Sand	25-Jul-2002
25-Jul-2002	Contract Calibrate Sand	29-Jul-2002		25-Jul-2002	Contract Calibrate Sand	29-Jul-2002

Table E.2 (continued): *The job types, arrival dates and dispatch dates for jobs accepted by LWC during July 2002.*

Start Date	Job Type	Dispatch Date	Start Date	Job Type	Dispatch Date
25-Jul-2002	Contract Calibrate Sand	29-Jul-2002	25-Jul-2002	Contract Veneer Sand	29-Jul-2002
25-Jul-2002	Contract Veneer Sand	29-Jul-2002	25-Jul-2002	Contract Veneer Sand	29-Jul-2002
25-Jul-2002	Contract Veneer Sand	26-Aug-2002	25-Jul-2002	Contract Calibrate Sand	7-Aug-2002
25-Jul-2002	Contract Calibrate Sand	7-Aug-2002	25-Jul-2002	Shaker Doors	8-Aug-2002
25-Jul-2002	Contract Cut	2-Aug-2002	25-Jul-2002	Contract Calibrate Sand	2-Aug-2002
26-Jul-2002	Contract Calibrate Sand	29-Jul-2002	26-Jul-2002	Contract Calibrate Sand	29-Jul-2002
26-Jul-2002	Contract Veneer Sand	26-Jul-2002	26-Jul-2002	Veneer Over Edge	6-Aug-2002
26-Jul-2002	Contract Spray Lacquer Top and Base Coat	31-Jul-2002	28-Jul-2002	Poster Box	6-Aug-2002
29-Jul-2002	Contract Spray: Top and Base Coat and Edge Cut	2-Aug-2002	29-Jul-2002	Contract Cut	2-Aug-2002
29-Jul-2002	Contract Calibrate Sand	31-Jul-2002	30-Jul-2002	Contract Calibrate Sand	30-Jul-2002
30-Jul-2002	Contract Veneer Sand	30-Jul-2002	30-Jul-2002	Veneer Over Edge	26-Aug-2002
30-Jul-2002	Shaker Doors	26-Aug-2002	30-Jul-2002	Contract Calibrate Sand	19-Aug-2002
30-Jul-2002	Contract Calibrate Sand	16-Aug-2002	30-Jul-2002	Contract Veneer Sand	7-Aug-2002
30-Jul-2002	Contract Calibrate Sand	7-Aug-2002	30-Jul-2002	Contract Calibrate Sand	8-Aug-2002
30-Jul-2002	Veneer Over Edge	13-Aug-2002	31-Jul-2002	Contract Spray Lacquer Top and Base Coat	31-Jul-2002
31-Jul-2002	Contract Spray: Stain Top Coat	31-Jul-2002	31-Jul-2002	Contract Cut	31-Jul-2002
31-Jul-2002	Contract Edging	31-Jul-2002	31-Jul-2002	Contract Calibrate Sand	31-Jul-2002
31-Jul-2002	Veneer Over Edge	26-Aug-2002	31-Jul-2002	Contract Calibrate Sand	6-Aug-2002
31-Jul-2002	Contract Calibrate Sand	2-Aug-2002	31-Jul-2002	Contract Cut	15-Aug-2002
31-Jul-2002	Unique	8-Aug-2002			

Table E.2 (continued): *The job types, arrival dates and dispatch dates for jobs accepted by LWC during July 2002.*

Start Date	Job Type	Dispatch Date	Start Date	Job Type	Dispatch Date
1-Aug-2002	Contract Calibrate and Veneer Sand	1-Aug-2002	1-Aug-2002	Shaker Doors	23-Aug-2002
1-Aug-2002	Contract Calibrate Sand	7-Aug-2002	1-Aug-2002	Contract Calibrate Sand	2-Aug-2002
1-Aug-2002	Contract Calibrate Sand	2-Aug-2002	1-Aug-2002	Contract Veneer Sand	2-Aug-2002
1-Aug-2002	Contract Cut, Edge and Groove	2-Aug-2002	1-Aug-2002	Contract Cut	2-Aug-2002
1-Aug-2002	Contract Veneer Sand	2-Aug-2002	1-Aug-2002	Contract Edging	2-Aug-2002
1-Aug-2002	Contract Veneer Sand	2-Aug-2002	1-Aug-2002	Contract Cut, Edge and Groove	2-Aug-2002
2-Aug-2002	Contract Edging	28-Aug-2002	2-Aug-2002	Veneer Over Edge	26-Aug-2002
2-Aug-2002	Veneer Over Edge	26-Aug-2002	2-Aug-2002	Shaker Doors	26-Aug-2002
2-Aug-2002	Contract Calibrate Sand	21-Aug-2002	2-Aug-2002	Contract Veneer Sand	20-Aug-2002
2-Aug-2002	Contract Calibrate Sand	19-Aug-2002	2-Aug-2002	Contract Calibrate Sand	19-Aug-2002
2-Aug-2002	Contract Calibrate Sand	14-Aug-2002	2-Aug-2002	Contract Veneer Sand	8-Aug-2002
2-Aug-2002	Contract Veneer Sand	8-Aug-2002	2-Aug-2002	Contract Veneer Sand	8-Aug-2002
2-Aug-2002	Contract Calibrate Sand	7-Aug-2002	2-Aug-2002	Contract Spray Lacquer Top and Base Coat	15-Aug-2002
2-Aug-2002	Contract Spray Lacquer Top and Base Coat	15-Aug-2002	2-Aug-2002	Contract Spray Lacquer Top and Base Coat	15-Aug-2002
2-Aug-2002	Contract Spray Lacquer Top and Base Coat	15-Aug-2002	2-Aug-2002	Contract Spray Lacquer Top and Base Coat	8-Aug-2002
2-Aug-2002	Contract Spray Lacquer Top and Base Coat	11-Sep-2002	5-Aug-2002	Contract Calibrate Sand	16-Aug-2002
5-Aug-2002	Contract Calibrate Sand	7-Aug-2002	5-Aug-2002	Contract Calibrate Sand	7-Aug-2002
5-Aug-2002	Contract Calibrate Sand	7-Aug-2002	5-Aug-2002	Contract Calibrate Sand	14-Aug-2002
5-Aug-2002	Contract Calibrate Sand	14-Aug-2002	5-Aug-2002	Contract Calibrate Sand	14-Aug-2002
5-Aug-2002	Contract Calibrate Sand	8-Aug-2002	5-Aug-2002	Contract Calibrate Sand	7-Aug-2002
5-Aug-2002	Contract Cut	8-Aug-2002	5-Aug-2002	Contract Cut	8-Aug-2002
5-Aug-2002	Contract Calibrate Sand	5-Aug-2002	5-Aug-2002	Contract Veneer Sand	5-Aug-2002
6-Aug-2002	Contract Calibrate Sand	14-Aug-2002	6-Aug-2002	Contract Calibrate Sand	14-Aug-2002
6-Aug-2002	Contract Calibrate Sand	6-Aug-2002	6-Aug-2002	Contract Calibrate Sand	6-Aug-2002
6-Aug-2002	Shaker Doors	16-Aug-2002	6-Aug-2002	Unique	13-Aug-2002
6-Aug-2002	Contract Calibrate Sand	6-Aug-2002	6-Aug-2002	Contract Calibrate Sand	6-Aug-2002
6-Aug-2002	Contract Veneer Sand	6-Aug-2002	7-Aug-2002	Contract Calibrate Sand	16-Aug-2002
7-Aug-2002	Contract Calibrate Sand	14-Aug-2002	7-Aug-2002	Contract Veneer Sand	14-Aug-2002
7-Aug-2002	Contract Calibrate Sand	14-Aug-2002	7-Aug-2002	Contract Calibrate Sand	14-Aug-2002
7-Aug-2002	Contract Calibrate Sand	13-Aug-2002	7-Aug-2002	Contract Calibrate Sand	8-Aug-2002
7-Aug-2002	Contract Veneer Sand	8-Aug-2002	7-Aug-2002	Contract Veneer Sand	8-Aug-2002
7-Aug-2002	Contract Veneer Sand	8-Aug-2002	7-Aug-2002	Contract Veneer Sand	8-Aug-2002
7-Aug-2002	Contract Veneer Sand	8-Aug-2002	7-Aug-2002	Contract Calibrate Sand	13-Aug-2002
7-Aug-2002	Unique	16-Aug-2002	8-Aug-2002	Veneer Over Edge	31-Aug-2002
8-Aug-2002	Contract Calibrate Sand	31-Aug-2002	8-Aug-2002	Contract Veneer Sand	31-Aug-2002
8-Aug-2002	Contract Calibrate Sand	29-Aug-2002	8-Aug-2002	Contract Calibrate Sand	20-Aug-2002
8-Aug-2002	Contract Veneer Sand	20-Aug-2002	8-Aug-2002	Contract Calibrate Sand	16-Aug-2002
8-Aug-2002	Contract Calibrate Sand	14-Aug-2002	10-Aug-2002	Contract Calibrate Sand	14-Aug-2002
12-Aug-2002	Unique	26-Aug-2002	12-Aug-2002	Veneer Over Edge	26-Aug-2002
12-Aug-2002	Contract Veneer Sand	20-Aug-2002	12-Aug-2002	Contract Veneer Sand	16-Aug-2002

Table E.3: *The job types, arrival dates and dispatch dates for jobs accepted by LWC during August 2002.*

Start Date	Job Type	Dispatch Date	Start Date	Job Type	Dispatch Date
12-Aug-2002	Unique	15-Aug-2002	12-Aug-2002	Contract Calibrate Sand	13-Aug-2002
12-Aug-2002	Contract Edging	12-Aug-2002	12-Aug-2002	Veneer Over Edge	2-Sep-2002
12-Aug-2002	Veneer Over Edge	2-Sep-2002	13-Aug-2002	Board Components	30-Aug-2002
13-Aug-2002	Board Components	29-Aug-2002	13-Aug-2002	Contract Calibrate Sand	31-Aug-2002
13-Aug-2002	Contract Veneer Sand	31-Aug-2002	13-Aug-2002	Contract Calibrate Sand	23-Aug-2002
13-Aug-2002	Contract Calibrate Sand	21-Aug-2002	13-Aug-2002	Contract Calibrate Sand	16-Aug-2002
13-Aug-2002	Contract Calibrate Sand	14-Aug-2002	13-Aug-2002	Contract Calibrate Sand	14-Aug-2002
13-Aug-2002	Contract Calibrate Sand	14-Aug-2002	14-Aug-2002	Contract Calibrate Sand	22-Aug-2002
14-Aug-2002	Contract Veneer Sand	22-Aug-2002	14-Aug-2002	Contract Calibrate Sand	21-Aug-2002
14-Aug-2002	Contract Calibrate Sand	21-Aug-2002	14-Aug-2002	Contract Calibrate Sand	19-Aug-2002
14-Aug-2002	Contract Calibrate Sand	19-Aug-2002	14-Aug-2002	Contract Calibrate Sand	14-Aug-2002
14-Aug-2002	Contract Calibrate Sand	14-Aug-2002	14-Aug-2002	Contract Calibrate Sand	14-Aug-2002
14-Aug-2002	Contract Calibrate Sand	20-Aug-2002	15-Aug-2002	Contract Calibrate Sand	28-Aug-2002
15-Aug-2002	Contract Calibrate Sand	26-Aug-2002	15-Aug-2002	Contract Calibrate Sand	23-Aug-2002
15-Aug-2002	Veneer Over Edge	6-Sep-2002	16-Aug-2002	Contract Edging	28-Aug-2002
16-Aug-2002	Contract Calibrate Sand	23-Aug-2002	16-Aug-2002	Contract Calibrate Sand	19-Aug-2002
16-Aug-2002	Shaker Doors	16-Aug-2002	16-Aug-2002	Contract Cut	19-Aug-2002
19-Aug-2002	Contract Calibrate Sand	29-Aug-2002	19-Aug-2002	Contract Calibrate Sand	26-Aug-2002
19-Aug-2002	Contract Calibrate Sand	23-Aug-2002	19-Aug-2002	Contract Calibrate Sand	21-Aug-2002
19-Aug-2002	Contract Calibrate Sand	21-Aug-2002	19-Aug-2002	Veneer Over Edge	26-Sep-2002
20-Aug-2002	Contract Calibrate Sand	21-Aug-2002	20-Aug-2002	Contract Veneer Sand	21-Aug-2002
20-Aug-2002	Contract Veneer Sand	30-Aug-2002	20-Aug-2002	Contract Calibrate Sand	30-Aug-2002
20-Aug-2002	Contract Veneer Sand	29-Aug-2002	20-Aug-2002	Contract Calibrate Sand	29-Aug-2002
20-Aug-2002	Contract Calibrate Sand	26-Aug-2002	20-Aug-2002	Contract Calibrate Sand	23-Aug-2002
20-Aug-2002	Contract Calibrate Sand	23-Aug-2002	20-Aug-2002	Contract Veneer Sand	26-Aug-2002
20-Aug-2002	Contract Calibrate Sand	26-Aug-2002	20-Aug-2002	Contract Veneer Sand	26-Aug-2002
20-Aug-2002	Contract Calibrate Sand	26-Aug-2002	21-Aug-2002	Board Components	31-Aug-2002
21-Aug-2002	Board Components	23-Aug-2002	21-Aug-2002	Contract Veneer Sand	29-Aug-2002
21-Aug-2002	Contract Calibrate Sand	29-Aug-2002	21-Aug-2002	Contract Calibrate Sand	23-Aug-2002
21-Aug-2002	Contract Calibrate Sand	22-Aug-2002	21-Aug-2002	Contract Veneer Sand	22-Aug-2002
21-Aug-2002	Contract Spray: Stain Top Coat	18-Sep-2002	21-Aug-2002	Contract Spray Lacquer Top and Base Coat	6-Sep-2002
21-Aug-2002	Poster Box	3-Sep-2002	21-Aug-2002	Poster Box	3-Sep-2002
21-Aug-2002	Poster Box	3-Sep-2002	21-Aug-2002	Contract Cut	10-Oct-2002
22-Aug-2002	Contract Calibrate Sand	23-Aug-2002	22-Aug-2002	Contract Calibrate Sand	29-Aug-2002
22-Aug-2002	Contract Veneer Sand	28-Aug-2002	22-Aug-2002	Contract Calibrate Sand	22-Aug-2002
22-Aug-2002	Contract Veneer Sand	29-Aug-2002	22-Aug-2002	Contract Veneer Sand	28-Aug-2002
22-Aug-2002	Shaker Doors	6-Sep-2002	23-Aug-2002	Contract Spray Lacquer Top and Base Coat	29-Aug-2002
23-Aug-2002	Poster Box	28-Aug-2002	23-Aug-2002	Poster Box	28-Aug-2002
23-Aug-2002	Contract Calibrate Sand	31-Aug-2002	23-Aug-2002	Contract Veneer Sand	31-Aug-2002
23-Aug-2002	Contract Calibrate Sand	29-Aug-2002	23-Aug-2002	Contract Veneer Sand	29-Aug-2002
23-Aug-2002	Contract Calibrate Sand	28-Aug-2002	23-Aug-2002	Contract Veneer Sand	28-Aug-2002
23-Aug-2002	Contract Veneer Sand	28-Aug-2002	23-Aug-2002	Contract Calibrate Sand	29-Aug-2002
23-Aug-2002	Veneer Over Edge	11-Sep-2002	24-Aug-2002	Unique	29-Aug-2002
24-Aug-2002	Contract Calibrate Sand	28-Aug-2002	24-Aug-2002	Contract Calibrate Sand	30-Aug-2002
26-Aug-2002	Contract Calibrate Sand	26-Aug-2002	26-Aug-2002	Contract Calibrate Sand	30-Aug-2002
27-Aug-2002	Contract Calibrate Sand	2-Sep-2002	27-Aug-2002	Contract Veneer Sand	2-Sep-2002
27-Aug-2002	Contract Calibrate Sand	2-Sep-2002	27-Aug-2002	Shaker Doors	12-Sep-2002
27-Aug-2002	Shaker Doors	12-Sep-2002	28-Aug-2002	Contract Edging	31-Aug-2002
28-Aug-2002	Contract Calibrate Sand	29-Aug-2002	28-Aug-2002	Contract Calibrate Sand	3-Sep-2002
28-Aug-2002	Contract Calibrate Sand	3-Sep-2002	28-Aug-2002	Contract Calibrate Sand	3-Sep-2002
28-Aug-2002	Contract Calibrate Sand	30-Aug-2002	28-Aug-2002	Contract Veneer Sand	3-Sep-2002
28-Aug-2002	Contract Cut	17-Sep-2002	28-Aug-2002	Board Components	17-Sep-2002
28-Aug-2002	Shaker Doors	10-Sep-2002	28-Aug-2002	Contract Cut and Edge	10-Sep-2002
28-Aug-2002	Contract Calibrate Sand	3-Sep-2002	28-Aug-2002	Contract Calibrate Sand	3-Sep-2002
28-Aug-2002	Contract Spray Lacquer Top and Base Coat	4-Oct-2002	29-Aug-2002	Contract Spray: Stain Top Coat	31-Aug-2002
29-Aug-2002	Contract Spray Lacquer Top and Base Coat	4-Sep-2002	29-Aug-2002	Contract Spray Lacquer Top and Base Coat	20-Sep-2002
29-Aug-2002	Contract Veneer Sand	5-Sep-2002	29-Aug-2002	Contract Veneer Sand	4-Sep-2002
29-Aug-2002	Contract Veneer Sand	4-Sep-2002	29-Aug-2002	Contract Calibrate Sand	4-Sep-2002
29-Aug-2002	Shaker Doors	16-Sep-2002	31-Aug-2002	Contract Calibrate Sand	31-Aug-2002

Table E.3 (continued): *The job types, arrival dates and dispatch dates for jobs accepted by LWC during August 2002.*

Start Date	Job Type	Dispatch Date	Start Date	Job Type	Dispatch Date
2-Sep-2002	Contract Calibrate Sand	30-Sep-2002	2-Sep-2002	Contract Calibrate Sand	30-Sep-2002
2-Sep-2002	Contract Calibrate Sand	30-Sep-2002	2-Sep-2002	Contract Calibrate Sand	2-Sep-2002
2-Sep-2002	Contract Calibrate Sand	2-Sep-2002	3-Sep-2002	Contract Calibrate Sand	30-Sep-2002

Table E.4: *The job types, arrival dates and dispatch dates for jobs accepted by LWC during September 2002.*

Start Date	Job Type	Dispatch Date		Start Date	Job Type	Dispatch Date
3-Sep-2002	Poster Box	23-Sep-2002		3-Sep-2002	Veneer Over Edge	20-Sep-2002
3-Sep-2002	Contract Cut and Edge	16-Sep-2002		4-Sep-2002	Veneer Over Edge	30-Sep-2002
4-Sep-2002	Contract Calibrate Sand	23-Sep-2002		4-Sep-2002	Poster Box	23-Sep-2002
4-Sep-2002	Contract Calibrate Sand	10-Sep-2002		4-Sep-2002	Contract Calibrate Sand	10-Sep-2002
4-Sep-2002	Contract Calibrate Sand	6-Sep-2002		4-Sep-2002	Contract Calibrate Sand	10-Sep-2002
4-Sep-2002	Contract Calibrate Sand	10-Sep-2002		4-Sep-2002	Unique	16-Sep-2002
4-Sep-2002	Veneer Over Edge	18-Oct-2002		5-Sep-2002	Veneer Over Edge	30-Sep-2002
5-Sep-2002	Veneer Over Edge	27-Sep-2002		5-Sep-2002	Contract Calibrate Sand	12-Sep-2002
5-Sep-2002	Contract Veneer Sand	11-Sep-2002		5-Sep-2002	Contract Calibrate Sand	5-Sep-2002
6-Sep-2002	Contract Plane all Round (PAR)	23-Sep-2002		6-Sep-2002	Contract Calibrate Sand	12-Sep-2002
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002		6-Sep-2002	Contract Calibrate Sand	12-Sep-2002
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002		6-Sep-2002	Contract Veneer Sand	12-Sep-2002
6-Sep-2002	Contract Veneer Sand	12-Sep-2002		6-Sep-2002	Contract Calibrate Sand	12-Sep-2002
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002		6-Sep-2002	Contract Veneer Sand	12-Sep-2002
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002		6-Sep-2002	Contract Calibrate Sand	12-Sep-2002
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002		6-Sep-2002	Contract Calibrate Sand	6-Sep-2002
9-Sep-2002	Contract Calibrate Sand	30-Sep-2002		9-Sep-2002	Shaker Doors	23-Sep-2002
9-Sep-2002	Contract Calibrate Sand	23-Sep-2002		9-Sep-2002	Contract Calibrate Sand	13-Sep-2002
9-Sep-2002	Contract Veneer Sand	13-Sep-2002		9-Sep-2002	Contract Calibrate Sand	13-Sep-2002
9-Sep-2002	Contract Veneer Sand	12-Sep-2002		9-Sep-2002	Contract Calibrate Sand	13-Sep-2002
9-Sep-2002	Contract Veneer Sand	9-Sep-2002		9-Sep-2002	Contract Calibrate Sand	9-Sep-2002
9-Sep-2002	Contract Calibrate Sand	13-Sep-2002		10-Sep-2002	Unique	30-Sep-2002
10-Sep-2002	Unique	30-Sep-2002		10-Sep-2002	Contract Plane all Round (PAR)	30-Sep-2002
10-Sep-2002	Contract Spray: Stain Top Coat	30-Sep-2002		10-Sep-2002	Contract Calibrate Sand	16-Sep-2002
10-Sep-2002	Contract Calibrate Sand	16-Sep-2002		10-Sep-2002	Contract Calibrate Sand	16-Sep-2002
10-Sep-2002	Contract Calibrate Sand	30-Sep-2002		10-Sep-2002	Contract Edging	13-Sep-2002
10-Sep-2002	Veneer Over Edge	12-Sep-2002		10-Sep-2002	Contract Calibrate Sand	11-Sep-2002
11-Sep-2002	Contract Spray Lacquer Top and Base Coat	30-Sep-2002		11-Sep-2002	Contract Spray Lacquer Top and Base Coat	30-Sep-2002
11-Sep-2002	Shaker Doors	26-Sep-2002		11-Sep-2002	Unique	26-Sep-2002
11-Sep-2002	Contract Calibrate Sand	30-Sep-2002		11-Sep-2002	Contract Calibrate Sand	11-Sep-2002
11-Sep-2002	Contract Spray Lacquer Top and Base Coat	17-Sep-2002		11-Sep-2002	Contract Spray Lacquer Top and Base Coat	17-Sep-2002
11-Sep-2002	Contract Cut	12-Sep-2002		11-Sep-2002	Contract Cut	12-Sep-2002
11-Sep-2002	Contract Spray Lacquer Top and Base Coat	7-Oct-2002		12-Sep-2002	Shaker Doors	30-Sep-2002
12-Sep-2002	Shaker Doors	20-Sep-2002		12-Sep-2002	Contract Calibrate Sand	18-Sep-2002
12-Sep-2002	Contract Calibrate Sand	18-Sep-2002		12-Sep-2002	Contract Veneer Sand	17-Sep-2002
12-Sep-2002	Contract Calibrate Sand	18-Sep-2002		12-Sep-2002	Contract Calibrate Sand	18-Sep-2002
12-Sep-2002	Contract Calibrate Sand	18-Sep-2002		12-Sep-2002	Contract Calibrate Sand	16-Sep-2002
12-Sep-2002	Contract Calibrate Sand	12-Sep-2002		12-Sep-2002	Contract Calibrate Sand	18-Sep-2002
12-Sep-2002	Contract Calibrate Sand	16-Sep-2002		12-Sep-2002	Contract Calibrate Sand	12-Sep-2002
13-Sep-2002	Contract Spray: Base Coat	18-Sep-2002		13-Sep-2002	Contract Calibrate Sand	19-Sep-2002
13-Sep-2002	Contract Calibrate Sand	13-Sep-2002		16-Sep-2002	Unique	27-Sep-2002
16-Sep-2002	Contract Edging	23-Sep-2002		16-Sep-2002	Contract Veneer Sand	20-Sep-2002
16-Sep-2002	Contract Calibrate Sand	20-Sep-2002		16-Sep-2002	Contract Veneer Sand	30-Sep-2002
16-Sep-2002	Contract Veneer Sand	30-Sep-2002		16-Sep-2002	Contract Calibrate Sand	20-Sep-2002
16-Sep-2002	Contract Calibrate Sand	20-Sep-2002		16-Sep-2002	Contract Calibrate Sand	20-Sep-2002
16-Sep-2002	Contract Veneer Sand	20-Sep-2002		16-Sep-2002	Contract Veneer Sand	20-Sep-2002
16-Sep-2002	Contract Calibrate Sand	20-Sep-2002		16-Sep-2002	Contract Calibrate Sand	20-Sep-2002
16-Sep-2002	Contract Calibrate Sand	16-Sep-2002		17-Sep-2002	Shaker Doors	26-Sep-2002
17-Sep-2002	Contract Calibrate Sand	23-Sep-2002		17-Sep-2002	Contract Spray Lacquer Top and Base Coat	23-Sep-2002
17-Sep-2002	Contract Spray Lacquer Top and Base Coat	20-Sep-2002		17-Sep-2002	Contract Calibrate Sand	23-Sep-2002
17-Sep-2002	Contract Calibrate Sand	23-Sep-2002		17-Sep-2002	Contract Calibrate Sand	23-Sep-2002
17-Sep-2002	Contract Spray Lacquer Top and Base Coat	10-Oct-2002		18-Sep-2002	Contract Cut	27-Sep-2002
18-Sep-2002	Contract Spray Lacquer Top and Base Coat	26-Sep-2002		18-Sep-2002	Contract Calibrate Sand	30-Sep-2002
18-Sep-2002	Contract Calibrate Sand	20-Sep-2002		18-Sep-2002	Contract Calibrate Sand	18-Sep-2002
19-Sep-2002	Contract Spray Lacquer Top and Base Coat	30-Sep-2002		19-Sep-2002	Contract Calibrate Sand	23-Sep-2002
19-Sep-2002	Contract Veneer Sand	26-Sep-2002		19-Sep-2002	Contract Calibrate Sand	30-Sep-2002
19-Sep-2002	Contract Calibrate Sand	26-Sep-2002		19-Sep-2002	Contract Calibrate Sand	26-Sep-2002
19-Sep-2002	Contract Calibrate Sand	19-Sep-2002		19-Sep-2002	Contract Spray Lacquer Top and Base Coat	14-Oct-2002
19-Sep-2002	Shaker Doors	4-Oct-2002		19-Sep-2002	Contract Spray Lacquer Top and Base Coat	4-Oct-2002
20-Sep-2002	Unique	30-Sep-2002		20-Sep-2002	Contract Cut and Edge	23-Sep-2002
20-Sep-2002	Contract Calibrate Sand	20-Sep-2002		20-Sep-2002	Contract Veneer Sand	20-Sep-2002
20-Sep-2002	Contract Cut	4-Oct-2002		21-Sep-2002	Contract Cut	23-Sep-2002
23-Sep-2002	Contract Plane all Round (PAR)	23-Sep-2002		23-Sep-2002	Contract Cut	23-Sep-2002
23-Sep-2002	Contract Veneer Sand	30-Sep-2002		23-Sep-2002	Contract Calibrate Sand	27-Sep-2002
23-Sep-2002	Contract Calibrate Sand	27-Sep-2002		23-Sep-2002	Contract Calibrate Sand	27-Sep-2002
23-Sep-2002	Contract Calibrate Sand	26-Sep-2002		23-Sep-2002	Poster Box	17-Oct-2002

Table E.4 (continued): *The job types, arrival dates and dispatch dates for jobs accepted by LWC during September 2002.*

Start Date	**Job Type**	**Dispatch Date**		**Start Date**	**Job Type**	**Dispatch Date**
23-Sep-2002	Poster Box	17-Oct-2002		23-Sep-2002	Shaker Doors	8-Oct-2002
25-Sep-2002	Contract Spray: Top and Base Coat	26-Sep-2002		26-Sep-2002	Contract Edging	30-Sep-2002
26-Sep-2002	Contract Spray: Stain Top Coat	30-Sep-2002		26-Sep-2002	Contract Calibrate Sand	27-Sep-2002
26-Sep-2002	Contract Calibrate Sand	26-Sep-2002		26-Sep-2002	Contract Calibrate Sand	2-Oct-2002
26-Sep-2002	Contract Calibrate Sand	30-Sep-2002		26-Sep-2002	Contract Calibrate Sand	3-Oct-2002
26-Sep-2002	Contract Calibrate Sand	3-Oct-2002		26-Sep-2002	Veneer Over Edge	24-Oct-2002
26-Sep-2002	Shaker Doors	10-Oct-2002		26-Sep-2002	Contract Cut	2-Oct-2002
27-Sep-2002	Shaker Doors	30-Oct-2002		27-Sep-2002	Contract Cut	30-Oct-2002
27-Sep-2002	Unique	30-Oct-2002		27-Sep-2002	Board Components	30-Oct-2002
27-Sep-2002	Veneer Over Edge	23-Oct-2002		27-Sep-2002	Unique	23-Oct-2002
27-Sep-2002	Contract Spray Lacquer Top and Base Coat	14-Oct-2002		27-Sep-2002	Contract Veneer Sand	3-Oct-2002
27-Sep-2002	Shaker Doors	4-Oct-2002		30-Sep-2002	Contract Veneer Sand	30-Sep-2002
30-Sep-2002	Contract Calibrate Sand	30-Sep-2002		30-Sep-2002	Contract Edging	30-Sep-2002
30-Sep-2002	Contract Calibrate Sand	30-Sep-2002		30-Sep-2002	Veneer Over Edge	30-Sep-2002
30-Sep-2002	Board Components	30-Oct-2002		30-Sep-2002	Board Components	14-Oct-2002
30-Sep-2002	Components on Edge	14-Oct-2002		30-Sep-2002	Board Components	14-Oct-2002
30-Sep-2002	Components on Edge	14-Oct-2002		30-Sep-2002	Contract Calibrate Sand	4-Oct-2002
30-Sep-2002	Contract Calibrate Sand	4-Oct-2002		30-Sep-2002	Contract Calibrate Sand	1-Oct-2002
30-Sep-2002	Contract Cut	4-Oct-2002		30-Sep-2002	Contract Spray Lacquer Top and Base Coat	7-Oct-2002

Table E.4 (continued): *The job types, arrival dates and dispatch dates for jobs accepted by LWC during September 2002.*

Start Date	**Job Type**	**Dispatch Date**		**Start Date**	**Job Type**	**Dispatch Date**
1-Oct-2002	Contract Calibrate Sand	1-Oct-2002		1-Oct-2002	Contract Veneer Sand	7-Oct-2002
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002		1-Oct-2002	Contract Calibrate Sand	7-Oct-2002
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002		1-Oct-2002	Contract Calibrate Sand	7-Oct-2002
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002		1-Oct-2002	Contract Calibrate Sand	7-Oct-2002
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002		1-Oct-2002	Contract Calibrate Sand	7-Oct-2002
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002		1-Oct-2002	Contract Cut	3-Oct-2002
1-Oct-2002	Components on Edge	3-Oct-2002		1-Oct-2002	Poster Box	1-Nov-2002
2-Oct-2002	Contract Calibrate Sand	2-Oct-2002		2-Oct-2002	Contract Calibrate Sand	7-Oct-2002
2-Oct-2002	Contract Calibrate Sand	7-Oct-2002		2-Oct-2002	Contract Calibrate Sand	7-Oct-2002
2-Oct-2002	Contract Calibrate Sand	7-Oct-2002		2-Oct-2002	Contract Calibrate Sand	9-Oct-2002
2-Oct-2002	Contract Edging	2-Oct-2002		2-Oct-2002	Board Components	3-Oct-2002
2-Oct-2002	Contract Cut	3-Oct-2002		2-Oct-2002	Contract Calibrate Sand	2-Oct-2002
3-Oct-2002	Board Components	24-Oct-2002		3-Oct-2002	Veneer Over Edge	24-Oct-2002
3-Oct-2002	Board Components	18-Oct-2002		3-Oct-2002	Veneer Over Edge	18-Oct-2002
3-Oct-2002	Board Components	18-Oct-2002		3-Oct-2002	Contract Spray Lacquer Top and Base Coat	18-Oct-2002
3-Oct-2002	Contract Spray Lacquer Top and Base Coat	14-Oct-2002		3-Oct-2002	Contract Spray Lacquer Top and Base Coat	14-Oct-2002
3-Oct-2002	Contract Calibrate Sand	9-Oct-2002		3-Oct-2002	Contract Veneer Sand	10-Oct-2002
3-Oct-2002	Contract Calibrate Sand	9-Oct-2002		3-Oct-2002	Contract Calibrate Sand	10-Oct-2002
3-Oct-2002	Contract Calibrate Sand	7-Oct-2002		3-Oct-2002	Contract Calibrate Sand	9-Oct-2002
3-Oct-2002	Contract Calibrate Sand	7-Oct-2002		3-Oct-2002	Veneer Over Edge	11-Oct-2002
3-Oct-2002	Contract Calibrate Sand	8-Oct-2002		3-Oct-2002	Contract Cut	3-Oct-2002
3-Oct-2002	Contract Cut, Veneer Sand and Edging	16-Dec-2002		4-Oct-2002	Unique	18-Oct-2002
4-Oct-2002	Contract Calibrate Sand	4-Oct-2002		4-Oct-2002	Contract Veneer Sand	10-Oct-2002
4-Oct-2002	Contract Calibrate Sand	9-Oct-2002		4-Oct-2002	Contract Veneer Sand	9-Oct-2002
4-Oct-2002	Contract Calibrate Sand	10-Oct-2002		4-Oct-2002	Contract Calibrate Sand	10-Oct-2002
4-Oct-2002	Contract Calibrate Sand	10-Oct-2002		4-Oct-2002	Contract Calibrate Sand	11-Oct-2002
4-Oct-2002	Contract Calibrate Sand	11-Oct-2002		4-Oct-2002	Contract Calibrate Sand	10-Oct-2002
4-Oct-2002	Contract Calibrate Sand	4-Oct-2002		4-Oct-2002	Contract Spray Lacquer Top and Base Coat	10-Oct-2002
4-Oct-2002	Contract Spray Lacquer Top and Base Coat	10-Oct-2002		4-Oct-2002	Contract Spray Lacquer Top and Base Coat	10-Oct-2002
7-Oct-2002	Poster Box	17-Oct-2002		7-Oct-2002	Poster Box	17-Oct-2002
7-Oct-2002	Contract Calibrate Sand	10-Oct-2002		7-Oct-2002	Contract Calibrate Sand	8-Oct-2002
7-Oct-2002	Poster Box	7-Oct-2002		8-Oct-2002	Poster Box	31-Oct-2002
8-Oct-2002	Veneer Over Edge	14-Oct-2002		8-Oct-2002	Contract Veneer Sand	14-Oct-2002
8-Oct-2002	Contract Calibrate Sand	8-Oct-2002		8-Oct-2002	Contract Calibrate Sand	11-Oct-2002
8-Oct-2002	Contract Calibrate Sand	14-Oct-2002		8-Oct-2002	Contract Calibrate Sand	14-Oct-2002
8-Oct-2002	Contract Calibrate Sand	14-Oct-2002		9-Oct-2002	Contract Cut	31-Oct-2002
9-Oct-2002	Contract Calibrate Sand	15-Oct-2002		9-Oct-2002	Contract Calibrate Sand	9-Oct-2002
9-Oct-2002	Contract Calibrate Sand	9-Oct-2002		10-Oct-2002	Contract Spray Lacquer Top and Base Coat	29-Oct-2002
10-Oct-2002	Shaker Doors	29-Oct-2002		10-Oct-2002	Contract Cut	31-Oct-2002
10-Oct-2002	Contract Veneer Sand	23-Oct-2002		10-Oct-2002	Contract Veneer Sand	17-Oct-2002
10-Oct-2002	Contract Calibrate Sand	14-Oct-2002		10-Oct-2002	Contract Calibrate Sand	16-Oct-2002
10-Oct-2002	Contract Calibrate Sand	16-Oct-2002		10-Oct-2002	Contract Calibrate Sand	16-Oct-2002
10-Oct-2002	Contract Plane all Round (PAR)	11-Oct-2002		11-Oct-2002	Board Components	30-Oct-2002

Table E.5: *The job types, arrival dates and dispatch dates for jobs accepted by LWC during October 2002.*

Start Date	**Job Type**	**Dispatch Date**	**Start Date**	**Job Type**	**Dispatch Date**
11-Oct-2002	Veneer Over Edge	30-Oct-2002	11-Oct-2002	Shaker Doors	30-Oct-2002
11-Oct-2002	Unique	30-Oct-2002	11-Oct-2002	Contract Cut	30-Oct-2002
11-Oct-2002	Contract Spray Lacquer Top and Base Coat	23-Oct-2002	11-Oct-2002	Contract Spray: Stain Top Coat	23-Oct-2002
11-Oct-2002	Contract Calibrate Sand	16-Oct-2002	11-Oct-2002	Contract Veneer Sand	14-Oct-2002
11-Oct-2002	Contract Calibrate Sand	11-Oct-2002	11-Oct-2002	Contract Calibrate Sand	11-Oct-2002
12-Oct-2002	Contract Cut	31-Oct-2002	14-Oct-2002	Contract Plane all Round (PAR)	17-Oct-2002
14-Oct-2002	Contract Veneer Sand	17-Oct-2002	14-Oct-2002	Contract Cut	15-Oct-2002
14-Oct-2002	Contract Calibrate Sand	18-Oct-2002	14-Oct-2002	Contract Calibrate Sand	18-Oct-2002
14-Oct-2002	Contract Calibrate Sand	18-Oct-2002	14-Oct-2002	Contract Calibrate Sand	18-Oct-2002
14-Oct-2002	Contract Spray: Top and Base Coat	14-Nov-2002	14-Oct-2002	Contract Spray Lacquer Top and Base Coat	12-Nov-2002
14-Oct-2002	Shaker Doors	6-Nov-2002	15-Oct-2002	Contract Cut	31-Oct-2002
15-Oct-2002	Contract Spray Lacquer Top and Base Coat	23-Oct-2002	15-Oct-2002	Contract Plane all Round (PAR)	17-Oct-2002
15-Oct-2002	Contract Plane all Round (PAR)	17-Oct-2002	15-Oct-2002	Contract Calibrate Sand	17-Oct-2002
15-Oct-2002	Contract Calibrate Sand	21-Oct-2002	15-Oct-2002	Contract Calibrate Sand	21-Oct-2002
15-Oct-2002	Contract Calibrate Sand	16-Oct-2002	15-Oct-2002	Contract Calibrate Sand	21-Oct-2002
15-Oct-2002	Veneer Over Edge	6-Nov-2002	16-Oct-2002	Contract Calibrate Sand	16-Oct-2002
16-Oct-2002	Shaker Doors	6-Nov-2002	17-Oct-2002	Contract Cut	31-Oct-2002
17-Oct-2002	Contract Edging	18-Oct-2002	17-Oct-2002	Contract Plane all Round (PAR)	31-Oct-2002
17-Oct-2002	Contract Calibrate Sand	23-Oct-2002	17-Oct-2002	Contract Veneer Sand	23-Oct-2002
17-Oct-2002	Contract Calibrate Sand	23-Oct-2002	17-Oct-2002	Contract Calibrate Sand	23-Oct-2002
17-Oct-2002	Contract Calibrate Sand	23-Oct-2002	17-Oct-2002	Contract Cut	12-Nov-2002
18-Oct-2002	Contract Cut	31-Oct-2002	18-Oct-2002	Unique	18-Oct-2002
18-Oct-2002	Contract Veneer Sand	24-Oct-2002	18-Oct-2002	Contract Calibrate Sand	24-Oct-2002
18-Oct-2002	Contract Calibrate Sand	24-Oct-2002	18-Oct-2002	Contract Calibrate Sand	24-Oct-2002
21-Oct-2002	Contract Calibrate Sand	25-Oct-2002	21-Oct-2002	Shaker Doors	8-Nov-2002
21-Oct-2002	Veneer Over Edge	8-Nov-2002	21-Oct-2002	Board Components	8-Nov-2002
21-Oct-2002	Shaker Doors	8-Nov-2002	21-Oct-2002	Veneer Over Edge	8-Nov-2002
22-Oct-2002	Contract Spray: Stain Top Coat	31-Oct-2002	22-Oct-2002	Contract Calibrate Sand	29-Oct-2002
22-Oct-2002	Contract Spray Lacquer Top and Base Coat	29-Oct-2002	22-Oct-2002	Contract Calibrate Sand	28-Oct-2002
22-Oct-2002	Contract Calibrate Sand	28-Oct-2002	22-Oct-2002	Contract Calibrate Sand	22-Oct-2002
22-Oct-2002	Veneer Over Edge	5-Nov-2002	23-Oct-2002	Board Components	31-Oct-2002
23-Oct-2002	Contract Calibrate Sand	25-Oct-2002	23-Oct-2002	Veneer Over Edge	14-Nov-2002
23-Oct-2002	Veneer Over Edge	12-Nov-2002	24-Oct-2002	Contract Calibrate Sand	31-Oct-2002
24-Oct-2002	Board Components	31-Oct-2002	24-Oct-2002	Shaker Doors	31-Oct-2002
24-Oct-2002	Contract Edging	28-Oct-2002	24-Oct-2002	Contract Cut	28-Oct-2002
24-Oct-2002	Contract Spray Lacquer Top and Base Coat	28-Oct-2002	24-Oct-2002	Contract Calibrate Sand	24-Oct-2002
24-Oct-2002	Contract Calibrate Sand	28-Oct-2002	24-Oct-2002	Contract Calibrate Sand	30-Oct-2002
24-Oct-2002	Contract Calibrate Sand	30-Oct-2002	24-Oct-2002	Contract Calibrate Sand	24-Oct-2002
24-Oct-2002	Contract Calibrate Sand	24-Oct-2002	24-Oct-2002	Contract Spray Lacquer Top and Base Coat	27-Nov-2002
24-Oct-2002	Shaker Doors	20-Nov-2002	24-Oct-2002	Contract Cut	20-Nov-2002
24-Oct-2002	Shaker Doors	5-Dec-2002	24-Oct-2002	Veneer Over Edge	5-Dec-2002
25-Oct-2002	Contract Plane all Round (PAR)	29-Oct-2002	25-Oct-2002	Contract Edging	29-Oct-2002
25-Oct-2002	Contract Cut	31-Oct-2002	25-Oct-2002	Unique	31-Oct-2002
25-Oct-2002	Contract Calibrate Sand	31-Oct-2002	25-Oct-2002	Contract Calibrate Sand	31-Oct-2002
25-Oct-2002	Contract Veneer Sand	31-Oct-2002	25-Oct-2002	Veneer Over Edge	7-Nov-2002
25-Oct-2002	Contract Veneer Sand	5-Dec-2002	26-Oct-2002	Board Components	31-Oct-2002
26-Oct-2002	Contract Cut	31-Oct-2002	26-Oct-2002	Board Components	31-Oct-2002
26-Oct-2002	Contract Cut	31-Oct-2002	28-Oct-2002	Contract Spray: Stain Top Coat	31-Oct-2002
28-Oct-2002	Board Components	31-Oct-2002	28-Oct-2002	Board Components	31-Oct-2002
28-Oct-2002	Contract Calibrate Sand	31-Oct-2002	28-Oct-2002	Contract Calibrate Sand	31-Oct-2002
28-Oct-2002	Contract Calibrate Sand	31-Oct-2002	28-Oct-2002	Contract Calibrate Sand	31-Oct-2002
28-Oct-2002	Contract Calibrate Sand	31-Oct-2002	28-Oct-2002	Contract Veneer Sand	31-Oct-2002
28-Oct-2002	Contract Calibrate Sand	31-Oct-2002	28-Oct-2002	Contract Spray Lacquer Top and Base Coat	27-Nov-2002
28-Oct-2002	Contract Cut	18-Nov-2002	28-Oct-2002	Contract Calibrate Sand	1-Nov-2002
29-Oct-2002	Veneer Over Edge	29-Oct-2002	29-Oct-2002	Contract Calibrate Sand	29-Oct-2002
29-Oct-2002	Contract Calibrate Sand	29-Oct-2002	29-Oct-2002	Veneer Over Edge	26-Nov-2002
29-Oct-2002	Contract Cut	21-Nov-2002	29-Oct-2002	Contract Cut	21-Nov-2002
29-Oct-2002	Contract Spray: Lacquer Top and Base Coat and Calibrate and Veneer Sand	12-Nov-2002	30-Oct-2002	Contract Cut	31-Oct-2002
30-Oct-2002	Contract Cut	31-Oct-2002	30-Oct-2002	Contract Cut	30-Oct-2002
30-Oct-2002	Contract Calibrate Sand	31-Oct-2002	30-Oct-2002	Contract Spray Lacquer Top and Base Coat	8-Nov-2002
30-Oct-2002	Contract Spray Lacquer Top and Base Coat	8-Nov-2002	30-Oct-2002	Contract Plane all Round (PAR)	5-Nov-2002
30-Oct-2002	Contract Spray: Stain Top Coat	6-Nov-2002	31-Oct-2002	Contract Cut	31-Oct-2002
31-Oct-2002	Contract Cut	31-Oct-2002	31-Oct-2002	Contract Edging	31-Oct-2002
31-Oct-2002	Contract Calibrate Sand	31-Oct-2002	31-Oct-2002	Veneer Over Edge	21-Nov-2002
31-Oct-2002	Shaker Doors	29-Nov-2002	31-Oct-2002	Veneer Over Edge	15-Nov-2002
31-Oct-2002	Contract Cut	21-Nov-2002	31-Oct-2002	Contract Calibrate and Veneer Sand	14-Nov-2002

Table E.5 (continued): *The job types, arrival dates and dispatch dates for jobs accepted by LWC during October 2002.*

Start Date	Job Type	Dispatch Date	Start Date	Job Type	Dispatch Date
31-Oct-2002	Veneer Over Edge	11-Nov-2002	31-Oct-2002	Contract Calibrate Sand	6-Nov-2002
31-Oct-2002	Contract Veneer Sand	6-Nov-2002	31-Oct-2002	Contract Calibrate Sand	6-Nov-2002
31-Oct-2002	Contract Calibrate Sand	1-Nov-2002			

Table E.5 (continued): *The job types, arrival dates and dispatch dates for jobs accepted by LWC during October 2002.*

Start Date	Job Type	Dispatch Date	Start Date	Job Type	Dispatch Date
1-Nov-2002	Veneer Over Edge	20-Nov-2002	1-Nov-2002	Contract Calibrate Sand	7-Nov-2002
1-Nov-2002	Contract Cut	6-Nov-2002	1-Nov-2002	Contract Cut, Edge and Calibrate Sand	7-Nov-2002
1-Nov-2002	Contract Calibrate Sand	5-Nov-2002	1-Nov-2002	Contract Calibrate Sand	4-Nov-2002
4-Nov-2002	Contract Calibrate Sand	6-Nov-2002	4-Nov-2002	Contract Cut	6-Nov-2002
4-Nov-2002	Contract Veneer Sand	8-Nov-2002	4-Nov-2002	Contract Calibrate Sand	8-Nov-2002
4-Nov-2002	Contract Calibrate Sand	5-Nov-2002	5-Nov-2002	Board Components	13-Nov-2002
5-Nov-2002	Contract Calibrate Sand	11-Nov-2002	5-Nov-2002	Contract Veneer Sand	11-Nov-2002
5-Nov-2002	Contract Calibrate Sand	11-Nov-2002	5-Nov-2002	Contract Calibrate Sand	11-Nov-2002
5-Nov-2002	Contract Calibrate Sand	7-Nov-2002	5-Nov-2002	Contract Calibrate Sand	6-Nov-2002
5-Nov-2002	Contract Calibrate Sand	5-Nov-2002	6-Nov-2002	Contract Calibrate Sand	6-Nov-2002
6-Nov-2002	Veneer Over Edge	2-Dec-2002	6-Nov-2002	Unique	27-Nov-2002
6-Nov-2002	Contract Calibrate Sand	12-Nov-2002	6-Nov-2002	Contract Calibrate Sand	12-Nov-2002
6-Nov-2002	Contract Calibrate Sand	12-Nov-2002	6-Nov-2002	Contract Calibrate Sand	12-Nov-2002
7-Nov-2002	Contract Veneer Sand	7-Nov-2002	7-Nov-2002	Contract Calibrate Sand	7-Nov-2002
7-Nov-2002	Components on Edge	28-Nov-2002	7-Nov-2002	Contract Edging	28-Nov-2002
7-Nov-2002	Board Components	27-Nov-2002	7-Nov-2002	Shaker Doors	27-Nov-2002
7-Nov-2002	Contract Cut	8-Nov-2002	7-Nov-2002	Contract Cut	15-Nov-2002
7-Nov-2002	Contract Spray Lacquer Top and Base Coat	13-Nov-2002	7-Nov-2002	Shaker Doors	4-Dec-2002
8-Nov-2002	Veneer Over Edge	28-Nov-2002	8-Nov-2002	Veneer Over Edge	28-Nov-2002
8-Nov-2002	Veneer Over Edge	28-Nov-2002	8-Nov-2002	Contract Spray Lacquer Top and Base Coat	21-Nov-2002
8-Nov-2002	Contract Cut	12-Nov-2002	8-Nov-2002	Contract Cut and Spray	15-Nov-2002
8-Nov-2002	Contract Calibrate Sand	14-Nov-2002	8-Nov-2002	Contract Calibrate Sand	14-Nov-2002
8-Nov-2002	Contract Calibrate Sand	14-Nov-2002	8-Nov-2002	Contract Veneer Sand	12-Nov-2002
8-Nov-2002	Contract Veneer Sand	12-Nov-2002	8-Nov-2002	Contract Calibrate Sand	14-Nov-2002
9-Nov-2002	Contract Calibrate and Veneer Sand	12-Nov-2002	11-Nov-2002	Poster Box	27-Nov-2002
11-Nov-2002	Veneer Over Edge	14-Nov-2002	11-Nov-2002	Contract Edging	15-Nov-2002
11-Nov-2002	Contract Spray: Top and Base Coat	13-Nov-2002	11-Nov-2002	Contract Cut	11-Nov-2002
11-Nov-2002	Contract Spray Lacquer Top and Base Coat	11-Nov-2002	11-Nov-2002	Contract Spray: Stain Top Coat	14-Nov-2002
11-Nov-2002	Contract Calibrate Sand	15-Nov-2002	11-Nov-2002	Contract Calibrate Sand	15-Nov-2002
11-Nov-2002	Contract Calibrate Sand	15-Nov-2002	11-Nov-2002	Contract Calibrate Sand	15-Nov-2002
11-Nov-2002	Contract Veneer Sand	15-Nov-2002	11-Nov-2002	Contract Veneer Sand	15-Nov-2002
11-Nov-2002	Contract Veneer Sand	15-Nov-2002	11-Nov-2002	Contract Calibrate Sand	15-Nov-2002
11-Nov-2002	Contract Calibrate Sand	15-Nov-2002	11-Nov-2002	Contract Calibrate Sand	15-Nov-2002
11-Nov-2002	Contract Calibrate Sand	15-Nov-2002	11-Nov-2002	Contract Veneer Sand	3-Dec-2002
11-Nov-2002	Contract Veneer Sand	3-Dec-2002	11-Nov-2002	Contract Veneer Sand	3-Dec-2002
11-Nov-2002	Board Components	10-Dec-2002	11-Nov-2002	Shaker Doors	10-Dec-2002
11-Nov-2002	Shaker Doors	13-Dec-2002	11-Nov-2002	Board Components	13-Dec-2002
11-Nov-2002	Shaker Doors	13-Dec-2002	11-Nov-2002	Veneer Over Edge	4-Dec-2002
11-Nov-2002	Contract Calibrate and Veneer Sand	14-Nov-2002	11-Nov-2002	Poster Box	3-Dec-2002
12-Nov-2002	Contract Calibrate Sand	12-Nov-2002	12-Nov-2002	Contract Cut	15-Nov-2002
12-Nov-2002	Contract Veneer Sand	18-Nov-2002	12-Nov-2002	Contract Veneer Sand	18-Nov-2002
12-Nov-2002	Contract Veneer Sand	18-Nov-2002	12-Nov-2002	Contract Veneer Sand	18-Nov-2002
12-Nov-2002	Contract Veneer Sand	18-Nov-2002	12-Nov-2002	Contract Veneer Sand	18-Nov-2002
12-Nov-2002	Contract Veneer Sand	18-Nov-2002	12-Nov-2002	Contract Veneer Sand	18-Nov-2002
12-Nov-2002	Contract Calibrate Sand	18-Nov-2002	12-Nov-2002	Contract Calibrate Sand	18-Nov-2002
12-Nov-2002	Contract Calibrate Sand	18-Nov-2002	13-Nov-2002	Contract Plane all Round (PAR)	21-Nov-2002
13-Nov-2002	Contract Cut and Edge	26-Nov-2002	13-Nov-2002	Contract Cut	15-Nov-2002
13-Nov-2002	Contract Spray Lacquer Top and Base Coat	29-Nov-2002	13-Nov-2002	Contract Veneer Sand	19-Nov-2002
13-Nov-2002	Contract Veneer Sand	20-Nov-2002	13-Nov-2002	Contract Veneer Sand	19-Nov-2002
13-Nov-2002	Contract Calibrate Sand	20-Nov-2002	13-Nov-2002	Shaker Doors	17-Dec-2002
14-Nov-2002	Shaker Doors	28-Nov-2002	14-Nov-2002	Contract Spray Lacquer Top and Base Coat	18-Nov-2002
14-Nov-2002	Contract Spray Lacquer Top and Base Coat	18-Nov-2002	14-Nov-2002	Contract Calibrate Sand	15-Nov-2002
14-Nov-2002	Shaker Doors	16-Dec-2002	14-Nov-2002	Shaker Doors	10-Dec-2002
14-Nov-2002	Board Components	10-Dec-2002	14-Nov-2002	Shaker Doors	10-Dec-2002
14-Nov-2002	Board Components	10-Dec-2002	14-Nov-2002	Contract Spray: Base Coat	10-Dec-2002
15-Nov-2002	Unique	27-Nov-2002	15-Nov-2002	Contract Calibrate Sand	21-Nov-2002
15-Nov-2002	Contract Veneer Sand	21-Nov-2002	15-Nov-2002	Contract Calibrate Sand	21-Nov-2002
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002	15-Nov-2002	Contract Calibrate Sand	21-Nov-2002

Table E.6: *The job types, arrival dates and dispatch dates for jobs accepted by LWC during November 2002.*

Start Date	Job Type	Dispatch Date		Start Date	Job Type	Dispatch Date
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002		15-Nov-2002	Contract Calibrate Sand	21-Nov-2002
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002		15-Nov-2002	Contract Calibrate Sand	21-Nov-2002
15-Nov-2002	Contract Calibrate Sand	20-Nov-2002		15-Nov-2002	Contract Calibrate Sand	21-Nov-2002
18-Nov-2002	Contract Calibrate Sand	18-Nov-2002		18-Nov-2002	Contract Calibrate Sand	18-Nov-2002
18-Nov-2002	Contract Spray Lacquer Top and Base Coat	22-Nov-2002		18-Nov-2002	Contract Spray Lacquer Top and Base Coat	21-Nov-2002
18-Nov-2002	Contract Cut	20-Nov-2002		18-Nov-2002	Contract Calibrate Sand	26-Nov-2002
18-Nov-2002	Contract Calibrate Sand	26-Nov-2002		18-Nov-2002	Contract Calibrate Sand	21-Nov-2002
18-Nov-2002	Contract Calibrate Sand	21-Nov-2002		18-Nov-2002	Contract Calibrate Sand	22-Nov-2002
18-Nov-2002	Contract Calibrate Sand	22-Nov-2002		18-Nov-2002	Contract Calibrate Sand	22-Nov-2002
18-Nov-2002	Contract Calibrate Sand	22-Nov-2002		18-Nov-2002	Contract Calibrate Sand	22-Nov-2002
18-Nov-2002	Contract Calibrate Sand	22-Nov-2002		18-Nov-2002	Contract Calibrate Sand	21-Nov-2002
18-Nov-2002	Contract Cut and Assembly	29-Jan-2003		18-Nov-2002	Contract Spray Lacquer Top and Base Coat	12-Dec-2002
19-Nov-2002	Contract Spray: Stain Top Coat	27-Nov-2002		19-Nov-2002	Contract Calibrate Sand	20-Nov-2002
19-Nov-2002	Contract Calibrate Sand	19-Nov-2002		19-Nov-2002	Contract Edging	20-Nov-2002
19-Nov-2002	Board Components	20-Nov-2002		19-Nov-2002	Contract Calibrate Sand	27-Nov-2002
19-Nov-2002	Contract Calibrate Sand	25-Nov-2002		19-Nov-2002	Contract Calibrate Sand	25-Nov-2002
19-Nov-2002	Contract Calibrate Sand	25-Nov-2002		19-Nov-2002	Contract Calibrate Sand	19-Nov-2002
19-Nov-2002	Veneer Over Edge	13-Dec-2002		19-Nov-2002	Components on Edge	13-Dec-2002
19-Nov-2002	Board Components	13-Dec-2002		19-Nov-2002	Shaker Doors	5-Dec-2002
20-Nov-2002	Board Components	22-Nov-2002		20-Nov-2002	Contract Veneer Sand	21-Nov-2002
20-Nov-2002	Contract Cut	20-Nov-2002		20-Nov-2002	Contract Calibrate Sand	27-Nov-2002
20-Nov-2002	Contract Calibrate Sand	28-Nov-2002		20-Nov-2002	Contract Cut and Spray	5-Dec-2002
20-Nov-2002	Shaker Doors	4-Dec-2002		21-Nov-2002	Contract Calibrate Sand	21-Nov-2002
21-Nov-2002	Contract Calibrate Sand	21-Nov-2002		21-Nov-2002	Contract Calibrate Sand	21-Nov-2002
21-Nov-2002	Contract Calibrate Sand	21-Nov-2002		21-Nov-2002	Contract Spray Lacquer Top and Base Coat	27-Nov-2002
21-Nov-2002	Contract Spray: Stain Top Coat	26-Nov-2002		21-Nov-2002	Contract Plane all Round (PAR)	22-Nov-2002
21-Nov-2002	Contract Plane all Round (PAR)	22-Nov-2002		21-Nov-2002	Contract Calibrate Sand	22-Nov-2002
21-Nov-2002	Contract Calibrate Sand	22-Nov-2002		21-Nov-2002	Contract Edging and Calibrate Sand	21-Nov-2002
21-Nov-2002	Veneer Over Edge	17-Dec-2002		21-Nov-2002	Veneer Over Edge	17-Dec-2002
21-Nov-2002	Shaker Doors	5-Dec-2002		21-Nov-2002	Board Components	5-Dec-2002
22-Nov-2002	Contract Edging	22-Nov-2002		22-Nov-2002	Contract Spray: Stain Top Coat	27-Nov-2002
22-Nov-2002	Contract Calibrate Sand	28-Nov-2002		22-Nov-2002	Contract Calibrate Sand	3-Dec-2002
25-Nov-2002	Contract Calibrate Sand	26-Nov-2002		25-Nov-2002	Contract Calibrate Sand	26-Nov-2002
25-Nov-2002	Contract Calibrate Sand	4-Dec-2002		25-Nov-2002	Contract Calibrate Sand	4-Dec-2002
25-Nov-2002	Contract Calibrate Sand	4-Dec-2002		25-Nov-2002	Contract Calibrate Sand	4-Dec-2002
25-Nov-2002	Contract Calibrate Sand	29-Nov-2002		25-Nov-2002	Contract Calibrate Sand	4-Dec-2002
25-Nov-2002	Contract Calibrate Sand	4-Dec-2002		25-Nov-2002	Contract Calibrate Sand	4-Dec-2002
25-Nov-2002	Contract Calibrate Sand	29-Nov-2002		25-Nov-2002	Veneer Over Edge	17-Dec-2002
26-Nov-2002	Contract Cut	26-Nov-2002		26-Nov-2002	Contract Calibrate Sand	27-Nov-2002
26-Nov-2002	Contract Plane all Round (PAR)	28-Nov-2002		26-Nov-2002	Contract Plane all Round (PAR)	28-Nov-2002
26-Nov-2002	Contract Calibrate Sand	28-Nov-2002		26-Nov-2002	Board Components	27-Nov-2002
26-Nov-2002	Veneer Over Edge	27-Nov-2002		26-Nov-2002	Veneer Over Edge	27-Nov-2002
26-Nov-2002	Contract Cut	26-Nov-2002		26-Nov-2002	Contract Calibrate Sand	4-Dec-2002
26-Nov-2002	Contract Calibrate Sand	5-Dec-2002		26-Nov-2002	Contract Calibrate Sand	5-Dec-2002
26-Nov-2002	Contract Calibrate Sand	3-Dec-2002		26-Nov-2002	Contract Calibrate Sand	13-Dec-2002
26-Nov-2002	Contract Veneer Sand	4-Dec-2002		26-Nov-2002	Shaker Doors	16-Dec-2002
26-Nov-2002	Veneer Over Edge	16-Dec-2002		26-Nov-2002	Contract Spray Lacquer Top and Base Coat	28-Nov-2002
26-Nov-2002	Contract PAR, Rip and Groove	11-Dec-2002		26-Nov-2002	Contract Plane all Round (PAR)	11-Dec-2002
26-Nov-2002	Veneer Over Edge	10-Dec-2002		26-Nov-2002	Contract Spray: Base Coat and Route	10-Dec-2002
27-Nov-2002	Contract Cut	29-Nov-2002		27-Nov-2002	Contract Calibrate Sand	29-Nov-2002
27-Nov-2002	Contract Calibrate Sand	29-Nov-2002		27-Nov-2002	Contract Calibrate Sand	27-Nov-2002
27-Nov-2002	Contract Calibrate Sand	27-Nov-2002		27-Nov-2002	Shaker Doors	17-Dec-2002
27-Nov-2002	Contract Veneer Sand	4-Dec-2002		27-Nov-2002	Contract Calibrate Sand	3-Dec-2002
27-Nov-2002	Contract Calibrate Sand	3-Dec-2002		27-Nov-2002	Veneer Over Edge	13-Dec-2002
27-Nov-2002	Contract Edging	6-Dec-2002		27-Nov-2002	Contract Cut	6-Dec-2002
28-Nov-2002	Contract Calibrate Sand	6-Dec-2002		28-Nov-2002	Contract Calibrate Sand	6-Dec-2002
28-Nov-2002	Contract Calibrate Sand	6-Dec-2002		28-Nov-2002	Contract Calibrate Sand	4-Dec-2002
29-Nov-2002	Contract Calibrate Sand	29-Nov-2002		29-Nov-2002	Contract Calibrate Sand	6-Dec-2002
29-Nov-2002	Contract Veneer Sand	5-Dec-2002		29-Nov-2002	Contract Veneer Sand	4-Dec-2002
29-Nov-2002	Contract Calibrate Sand	3-Dec-2002		29-Nov-2002	Veneer Over Edge	11-Dec-2002
29-Nov-2002	Board Components	11-Dec-2002		29-Nov-2002	Contract Cut and Edge	3-Dec-2002
29-Nov-2002	Contract Cut	3-Dec-2002				

Table E.6 (continued): *The job types, arrival dates and dispatch dates for jobs accepted by LWC during November 2002.*

Start Date	Job Type	Dispatch Date		Start Date	Job Type	Dispatch Date
2-Dec-2002	Veneer Over Edge	11-Dec-2002		2-Dec-2002	Contract Veneer Sand	13-Dec-2002
2-Dec-2002	Contract Calibrate Sand	5-Dec-2002		2-Dec-2002	Contract Calibrate Sand	3-Dec-2002
2-Dec-2002	Veneer Over Edge	12-Dec-2002		2-Dec-2002	Contract Edging	10-Dec-2002

Table E.7: *The job types, arrival dates and dispatch dates for jobs accepted by LWC during December 2002.*

Start Date	Job Type	Dispatch Date		Start Date	Job Type	Dispatch Date
2-Dec-2002	Contract Calibrate and Veneer Sand	3-Dec-2002		2-Dec-2002	Contract Calibrate Sand	3-Dec-2002
3-Dec-2002	Contract Veneer Sand	13-Dec-2002		3-Dec-2002	Contract Calibrate Sand	13-Dec-2002
3-Dec-2002	Contract Calibrate Sand	11-Dec-2002		3-Dec-2002	Contract Calibrate Sand	11-Dec-2002
3-Dec-2002	Contract Cut and Calibrate Sand	10-Dec-2002		3-Dec-2002	Contract Calibrate Sand	10-Dec-2002
3-Dec-2002	Contract Calibrate Sand	10-Dec-2002		3-Dec-2002	Contract Calibrate Sand	5-Dec-2002
3-Dec-2002	Contract PAR and Edging	5-Dec-2002		3-Dec-2002	Contract Cut	3-Dec-2002
3-Dec-2002	Contract Cut and Edge	3-Dec-2002		4-Dec-2002	Contract Calibrate Sand	12-Dec-2002
4-Dec-2002	Contract Calibrate Sand	10-Dec-2002		4-Dec-2002	Contract Calibrate Sand	9-Dec-2002
4-Dec-2002	Contract Plane all Round (PAR)	4-Dec-2002		5-Dec-2002	Shaker Doors	17-Dec-2002
5-Dec-2002	Contract Calibrate Sand	12-Dec-2002		5-Dec-2002	Contract Calibrate Sand	11-Dec-2002
5-Dec-2002	Contract Calibrate Sand	10-Dec-2002		5-Dec-2002	Contract Calibrate Sand	10-Dec-2002
5-Dec-2002	Contract Calibrate Sand	10-Dec-2002		5-Dec-2002	Contract Calibrate Sand	10-Dec-2002
6-Dec-2002	Contract Calibrate Sand	11-Dec-2002		6-Dec-2002	Contract Calibrate Sand	11-Dec-2002
6-Dec-2002	Contract Calibrate Sand	10-Dec-2002		6-Dec-2002	Shaker Doors	13-Dec-2002
6-Dec-2002	Veneer Over Edge	13-Dec-2002		6-Dec-2002	Board Components	13-Dec-2002
6-Dec-2002	Veneer Over Edge	13-Dec-2002		6-Dec-2002	Contract Calibrate Sand	11-Dec-2002
6-Dec-2002	Contract Calibrate and Veneer Sand	6-Dec-2002		8-Dec-2002	Shaker Doors	12-Dec-2002
9-Dec-2002	Veneer Over Edge	17-Dec-2002		9-Dec-2002	Components on Edge	17-Dec-2002
9-Dec-2002	Veneer Over Edge	17-Dec-2002		9-Dec-2002	Components on Edge	17-Dec-2002
9-Dec-2002	Contract Calibrate and Veneer Sand	17-Dec-2002		9-Dec-2002	Contract Veneer Sand	13-Dec-2002
9-Dec-2002	Contract Veneer Sand	13-Dec-2002		9-Dec-2002	Contract Calibrate Sand	13-Dec-2002
9-Dec-2002	Contract Calibrate Sand	13-Dec-2002		9-Dec-2002	Contract Calibrate Sand	11-Dec-2002
9-Dec-2002	Contract PAR, Calibrate and Veneer Sand	10-Dec-2002		9-Dec-2002	Contract Calibrate and Veneer Sand	9-Dec-2002
10-Dec-2002	Contract Spray: Top and Base Coat and Edging	17-Dec-2002		10-Dec-2002	Shaker Doors	17-Dec-2002
10-Dec-2002	Contract Calibrate Sand	12-Dec-2002		10-Dec-2002	Contract Calibrate Sand	12-Dec-2002
10-Dec-2002	Contract Calibrate Sand	12-Dec-2002		10-Dec-2002	Contract Calibrate Sand	12-Dec-2002
10-Dec-2002	Contract Calibrate Sand	19-Dec-2002		10-Dec-2002	Board Components	13-Dec-2002
10-Dec-2002	Veneer Over Edge	11-Dec-2002		10-Dec-2002	Contract Groove	10-Dec-2002
10-Dec-2002	Contract Calibrate and Veneer Sand	10-Dec-2002		10-Dec-2002	Contract Calibrate and Veneer Sand	10-Dec-2002
11-Dec-2002	Contract Calibrate Sand	13-Dec-2002		11-Dec-2002	Contract Cut	18-Dec-2002
11-Dec-2002	Shaker Doors	17-Dec-2002		11-Dec-2002	Contract Calibrate Sand	11-Dec-2002
11-Dec-2002	Shaker Doors	19-Dec-2002		11-Dec-2002	Board Components	19-Dec-2002
11-Dec-2002	Shaker Doors	19-Dec-2002		12-Dec-2002	Contract Edging	12-Dec-2002
12-Dec-2002	Contract Cut	19-Dec-2002		12-Dec-2002	Contract Veneer Sand	13-Dec-2002
13-Dec-2002	Contract Calibrate Sand	18-Dec-2002		13-Dec-2002	Contract Calibrate Sand	19-Dec-2002
13-Dec-2002	Contract Calibrate and Veneer Sand	16-Dec-2002		13-Dec-2002	Contract Calibrate Sand	18-Dec-2002
16-Dec-2002	Contract Calibrate Sand	18-Dec-2002		16-Dec-2002	Contract Calibrate Sand	17-Dec-2002
17-Dec-2002	Contract Veneer Sand	17-Dec-2002		17-Dec-2002	Contract Cut	18-Dec-2002

Table E.7 (continued)*: The job types, arrival dates and dispatch dates for jobs accepted by LWC during December 2002.*

Appendix F

Improvement on the LWC Schedules

In this appendix the improvement by the tabu search method performed in §6.3 on the net flow time for each job processed at LWC during the six months, from June 2002 to December 2002, are presented. In §F.1 the improvement for the best tabu search solution obtained, assuming a ramp cost of 5 minutes, is presented, whereas the improvement for the best solution obtained, assuming a ramp cost of 20 minutes, is presented in §F.2.

F.1 Ramp cost of 5 minutes

The best objective function value obtained with the assumption of a ramp cost of 5 minutes was obtained during a run with a tabu list length of 5 and a backtrack list length of 25. This run exhibited a 67.03% improvement on the actual (manual) scheduling done at LWC.

		LWC		**Tabu**			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improvement**	**%Improvement**
7-Jun-2002	Contract Cut and Route	7-Jun-2002	1	7-Jun-2002	1	0	0.00 %
10-Jun-2002	Contract Cut	28-Aug-2002	62	10-Jun-2002	1	61	98.39 %
10-Jun-2002	Contract Calibrate Sand	28-Aug-2002	62	10-Jun-2002	1	61	98.39 %
12-Jun-2002	Shaker Doors	2-Jul-2002	16	14-Jun-2002	3	13	81.25 %
12-Jun-2002	Shaker Doors	2-Jul-2002	16	14-Jun-2002	3	13	81.25 %
21-Jun-2002	Veneer Over Edge	10-Jul-2002	15	28-Jun-2002	6	9	60.00 %
25-Jun-2002	Contract Calibrate Sand	17-Jul-2002	18	25-Jun-2002	1	17	94.44 %
25-Jun-2002	Contract Veneer Sand	3-Jul-2002	8	25-Jun-2002	1	7	87.50 %
25-Jun-2002	Contract Veneer Sand	3-Jul-2002	8	25-Jun-2002	1	7	87.50 %
25-Jun-2002	Contract Calibrate Sand	2-Jul-2002	7	25-Jun-2002	1	6	85.71 %
26-Jun-2002	Shaker Doors	2-Jul-2002	6	28-Jun-2002	3	3	50.00 %
26-Jun-2002	Contract Veneer Sand	4-Jul-2002	8	26-Jun-2002	1	7	87.50 %
26-Jun-2002	Contract Calibrate Sand	3-Jul-2002	7	26-Jun-2002	1	6	85.71 %
26-Jun-2002	Contract Veneer Sand	3-Jul-2002	7	26-Jun-2002	1	6	85.71 %
26-Jun-2002	Contract Veneer Sand	3-Jul-2002	7	26-Jun-2002	1	6	85.71 %
27-Jun-2002	Contract Plane all Round (PAR)	1-Jul-2002	4	27-Jun-2002	1	3	75.00 %
27-Jun-2002	Contract Spray: Top and Base Coat, Calibrate and Veneer Sand	1-Jul-2002	4	27-Jun-2002	1	3	75.00 %
27-Jun-2002	Contract Cut	17-Jul-2002	16	27-Jun-2002	1	15	93.75 %
27-Jun-2002	Veneer Over Edge	23-Jul-2002	21	2-Jul-2002	5	16	76.19 %
27-Jun-2002	Contract Veneer Sand	3-Jul-2002	6	27-Jun-2002	1	5	83.33 %
27-Jun-2002	Contract Calibrate Sand	3-Jul-2002	6	27-Jun-2002	1	5	83.33 %
27-Jun-2002	Contract Veneer Sand	3-Jul-2002	6	27-Jun-2002	1	5	83.33 %
28-Jun-2002	Contract Calibrate Sand	3-Jul-2002	5	28-Jun-2002	1	4	80.00 %
29-Jun-2002	Veneer Over Edge	3-Jul-2002	4	4-Jul-2002	5	–1	–25.00 %

Table F.1: *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of 5 minutes.*

		LWC		**Tabu**			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improvement**	**%Improvement**
1-Jul-2002	Shaker Doors	5-Jul-2002	5	2-Jul-2002	2	3	60.00 %
1-Jul-2002	Veneer Over Edge	23-Jul-2002	18	12-Jul-2002	10	8	44.44 %
1-Jul-2002	Contract Calibrate Sand	3-Jul-2002	3	1-Jul-2002	1	2	66.67 %
2-Jul-2002	Contract Spray: Top and Base Coat	5-Jul-2002	4	2-Jul-2002	1	3	75.00 %
2-Jul-2002	Veneer Over Edge	22-Jul-2002	16	12-Jul-2002	9	7	43.75 %
2-Jul-2002	Veneer Over Edge	23-Jul-2002	17	12-Jul-2002	9	8	47.06 %
2-Jul-2002	Veneer Over Edge	23-Jul-2002	17	12-Jul-2002	9	8	47.06 %
2-Jul-2002	Veneer Over Edge	17-Jul-2002	12	12-Jul-2002	9	3	25.00 %
2-Jul-2002	Veneer Over Edge	19-Jul-2002	14	12-Jul-2002	9	5	35.71 %
2-Jul-2002	Veneer Over Edge	17-Jul-2002	12	12-Jul-2002	9	3	25.00 %
2-Jul-2002	Contract Veneer Sand	10-Jul-2002	7	2-Jul-2002	1	6	85.71 %
2-Jul-2002	Contract Calibrate Sand	3-Jul-2002	2	2-Jul-2002	1	1	50.00 %
2-Jul-2002	Contract Calibrate Sand	3-Jul-2002	2	2-Jul-2002	1	1	50.00 %
3-Jul-2002	Contract Calibrate Sand	12-Jul-2002	8	3-Jul-2002	1	7	87.50 %
3-Jul-2002	Contract Calibrate Sand	10-Jul-2002	6	3-Jul-2002	1	5	83.33 %
3-Jul-2002	Contract Calibrate Sand	3-Jul-2002	1	3-Jul-2002	1	0	0.00 %
3-Jul-2002	Contract Veneer Sand	3-Jul-2002	1	3-Jul-2002	1	0	0.00 %
4-Jul-2002	Contract Calibrate Sand	8-Jul-2002	3	4-Jul-2002	1	2	66.67 %
4-Jul-2002	Contract Calibrate Sand	10-Jul-2002	5	4-Jul-2002	1	4	80.00 %
4-Jul-2002	Veneer Over Edge	18-Jul-2002	11	15-Jul-2002	8	3	27.27 %
4-Jul-2002	Contract Cut and Edge	18-Jul-2002	11	4-Jul-2002	1	10	90.91 %
5-Jul-2002	Veneer Over Edge	8-Jul-2002	2	12-Jul-2002	6	–4	–200.00 %
5-Jul-2002	Veneer Over Edge	23-Jul-2002	14	12-Jul-2002	6	8	57.14 %
5-Jul-2002	Contract Cut	23-Jul-2002	14	16-Jul-2002	8	6	42.86 %
5-Jul-2002	Contract Calibrate and Veneer Sand	5-Jul-2002	1	12-Jul-2002	6	–5	–500.00 %
5-Jul-2002	Contract Calibrate and Veneer Sand	5-Jul-2002	1	12-Jul-2002	6	–5	–500.00 %
5-Jul-2002	Contract Calibrate Sand	5-Jul-2002	1	15-Jul-2002	7	–6	–600.00 %
5-Jul-2002	Contract Edging	11-Jul-2002	5	8-Jul-2002	2	3	60.00 %
5-Jul-2002	Veneer Over Edge	26-Jul-2002	17	12-Jul-2002	6	11	64.71 %
5-Jul-2002	Contract Cut	5-Jul-2002	1	12-Jul-2002	6	–5	–500.00 %
5-Jul-2002	Shaker Doors	26-Jul-2002	17	12-Jul-2002	6	11	64.71 %
5-Jul-2002	Contract Veneer Sand	8-Jul-2002	2	12-Jul-2002	6	–4	–200.00 %
5-Jul-2002	Contract Calibrate Sand	18-Jul-2002	10	12-Jul-2002	6	4	40.00 %
5-Jul-2002	Contract Veneer Sand	18-Jul-2002	10	15-Jul-2002	7	3	30.00 %
5-Jul-2002	Contract Veneer Sand	18-Jul-2002	10	12-Jul-2002	6	4	40.00 %
5-Jul-2002	Contract Veneer Sand	10-Jul-2002	4	12-Jul-2002	6	–2	–50.00 %
5-Jul-2002	Contract Calibrate Sand	10-Jul-2002	4	12-Jul-2002	6	–2	–50.00 %
5-Jul-2002	Contract Calibrate Sand	10-Jul-2002	4	12-Jul-2002	6	–2	–50.00 %
5-Jul-2002	Contract Calibrate Sand	8-Jul-2002	2	12-Jul-2002	6	–4	–200.00 %
5-Jul-2002	Contract Calibrate Sand	8-Jul-2002	2	11-Jul-2002	5	–3	–150.00 %
8-Jul-2002	Contract Cut	30-Jul-2002	19	10-Jul-2002	3	16	84.21 %
8-Jul-2002	Contract Veneer Sand	8-Jul-2002	1	12-Jul-2002	5	–4	–400.00 %
8-Jul-2002	Contract Cut and Edge	9-Jul-2002	2	10-Jul-2002	3	–1	–50.00 %
8-Jul-2002	Contract Cut	10-Jul-2002	3	10-Jul-2002	3	0	0.00 %
8-Jul-2002	Contract Calibrate and Veneer Sand	8-Jul-2002	1	12-Jul-2002	5	–4	–400.00 %
8-Jul-2002	Contract Calibrate and Veneer Sand	8-Jul-2002	1	11-Jul-2002	4	–3	–300.00 %
8-Jul-2002	Contract Calibrate Sand	8-Jul-2002	1	12-Jul-2002	5	–4	–400.00 %
8-Jul-2002	Contract Veneer Sand	26-Jul-2002	16	11-Jul-2002	4	12	75.00 %
8-Jul-2002	Contract Veneer Sand	16-Jul-2002	7	15-Jul-2002	6	1	14.29 %
8-Jul-2002	Contract Veneer Sand	12-Jul-2002	5	12-Jul-2002	5	0	0.00 %
8-Jul-2002	Contract Calibrate Sand	10-Jul-2002	3	12-Jul-2002	5	–2	–66.67 %
8-Jul-2002	Contract Calibrate Sand	10-Jul-2002	3	15-Jul-2002	6	–3	–100.00 %
8-Jul-2002	Contract Calibrate Sand	10-Jul-2002	3	15-Jul-2002	6	–3	–100.00 %
8-Jul-2002	Contract Calibrate Sand	10-Jul-2002	3	11-Jul-2002	4	–1	–33.33 %
9-Jul-2002	Contract Spray Lacquer Top and Base Coat	10-Jul-2002	2	12-Jul-2002	4	–2	–100.00 %
9-Jul-2002	Contract Calibrate Sand	10-Jul-2002	2	12-Jul-2002	4	–2	–100.00 %
9-Jul-2002	Contract Calibrate Sand	10-Jul-2002	2	11-Jul-2002	3	–1	–50.00 %
10-Jul-2002	Contract Cut	11-Jul-2002	2	12-Jul-2002	3	–1	–50.00 %
10-Jul-2002	Contract Calibrate Sand	18-Jul-2002	7	12-Jul-2002	3	4	57.14 %
10-Jul-2002	Contract Calibrate Sand	12-Jul-2002	3	11-Jul-2002	2	1	33.33 %
10-Jul-2002	Unique	5-Aug-2002	21	12-Jul-2002	3	18	85.71 %
11-Jul-2002	Contract Calibrate Sand	12-Jul-2002	2	12-Jul-2002	2	0	0.00 %
11-Jul-2002	Contract Veneer Sand	12-Jul-2002	2	15-Jul-2002	3	–1	–50.00 %
11-Jul-2002	Contract Cut	12-Jul-2002	2	12-Jul-2002	2	0	0.00 %
11-Jul-2002	Contract Veneer Sand	12-Jul-2002	2	12-Jul-2002	2	0	0.00 %
11-Jul-2002	Contract Cut	12-Jul-2002	2	15-Jul-2002	3	–1	–50.00 %

Table F.1 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 5 *minutes.*

		LWC		**Tabu**			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
11-Jul-2002	Contract Spray Lacquer Top and Base Coat	17-Jul-2002	5	12-Jul-2002	2	3	60.00 %
11-Jul-2002	Contract Spray: Stain Top Coat	17-Jul-2002	5	12-Jul-2002	2	3	60.00 %
11-Jul-2002	Veneer Over Edge	18-Jul-2002	6	17-Jul-2002	5	1	16.67 %
11-Jul-2002	Veneer Over Edge	23-Jul-2002	10	17-Jul-2002	5	5	50.00 %
11-Jul-2002	Contract Cut	11-Jul-2002	1	11-Jul-2002	1	0	0.00 %
11-Jul-2002	Contract Veneer Sand	11-Jul-2002	1	11-Jul-2002	1	0	0.00 %
11-Jul-2002	Contract Calibrate and Veneer Sand	11-Jul-2002	1	15-Jul-2002	3	–2	–200.00 %
11-Jul-2002	Contract Calibrate and Veneer Sand	11-Jul-2002	1	12-Jul-2002	2	–1	–100.00 %
11-Jul-2002	Contract Calibrate Sand	16-Jul-2002	4	15-Jul-2002	3	1	25.00 %
11-Jul-2002	Contract Calibrate Sand	16-Jul-2002	4	12-Jul-2002	2	2	50.00 %
11-Jul-2002	Contract Calibrate Sand	16-Jul-2002	4	12-Jul-2002	2	2	50.00 %
12-Jul-2002	Contract Cut and Edge	12-Jul-2002	1	12-Jul-2002	1	0	0.00 %
12-Jul-2002	Contract Calibrate Sand	22-Jul-2002	8	15-Jul-2002	2	6	75.00 %
12-Jul-2002	Contract Calibrate Sand	22-Jul-2002	8	12-Jul-2002	1	7	87.50 %
12-Jul-2002	Contract Calibrate Sand	18-Jul-2002	5	15-Jul-2002	2	3	60.00 %
12-Jul-2002	Contract Calibrate Sand	18-Jul-2002	5	12-Jul-2002	1	4	80.00 %
12-Jul-2002	Contract Calibrate Sand	12-Jul-2002	1	15-Jul-2002	2	–1	–100.00 %
15-Jul-2002	Contract Cut	15-Jul-2002	1	16-Jul-2002	2	–1	–100.00 %
15-Jul-2002	Veneer Over Edge	23-Jul-2002	8	19-Jul-2002	5	3	37.50 %
15-Jul-2002	Contract Cut, Edge and Groove	24-Jul-2002	9	15-Jul-2002	1	8	88.89 %
15-Jul-2002	Contract Veneer Sand	24-Jul-2002	9	15-Jul-2002	1	8	88.89 %
15-Jul-2002	Contract Cut	16-Jul-2002	2	16-Jul-2002	2	0	0.00 %
15-Jul-2002	Contract Calibrate Sand	22-Jul-2002	7	15-Jul-2002	1	6	85.71 %
15-Jul-2002	Contract Calibrate Sand	22-Jul-2002	7	15-Jul-2002	1	6	85.71 %
15-Jul-2002	Contract Veneer Sand	23-Jul-2002	8	15-Jul-2002	1	7	87.50 %
15-Jul-2002	Contract Veneer Sand	23-Jul-2002	8	15-Jul-2002	1	7	87.50 %
15-Jul-2002	Contract Calibrate Sand	19-Jul-2002	5	15-Jul-2002	1	4	80.00 %
15-Jul-2002	Contract Veneer Sand	19-Jul-2002	5	15-Jul-2002	1	4	80.00 %
15-Jul-2002	Contract Veneer Sand	18-Jul-2002	4	15-Jul-2002	1	3	75.00 %
15-Jul-2002	Contract Calibrate Sand	15-Jul-2002	1	15-Jul-2002	1	0	0.00 %
15-Jul-2002	Contract Calibrate Sand	16-Jul-2002	2	15-Jul-2002	1	1	50.00 %
15-Jul-2002	Contract Calibrate Sand	16-Jul-2002	2	15-Jul-2002	1	1	50.00 %
15-Jul-2002	Contract Calibrate Sand	16-Jul-2002	2	15-Jul-2002	1	1	50.00 %
16-Jul-2002	Contract Calibrate and Veneer Sand	16-Jul-2002	1	16-Jul-2002	1	0	0.00 %
16-Jul-2002	Contract Calibrate Sand	16-Jul-2002	1	16-Jul-2002	1	0	0.00 %
17-Jul-2002	Contract Calibrate and Veneer Sand	18-Jul-2002	2	17-Jul-2002	1	1	50.00 %
17-Jul-2002	Contract Veneer Sand	23-Jul-2002	6	17-Jul-2002	1	5	83.33 %
17-Jul-2002	Contract Calibrate Sand	19-Jul-2002	3	17-Jul-2002	1	2	66.67 %
17-Jul-2002	Contract Calibrate Sand	19-Jul-2002	3	17-Jul-2002	1	2	66.67 %
17-Jul-2002	Contract Calibrate Sand	6-Aug-2002	17	17-Jul-2002	1	16	94.12 %
17-Jul-2002	Veneer Over Edge	12-Aug-2002	21	24-Jul-2002	7	14	66.67 %
17-Jul-2002	Veneer Over Edge	8-Aug-2002	19	25-Jul-2002	8	11	57.89 %
17-Jul-2002	Veneer Over Edge	8-Aug-2002	19	24-Jul-2002	7	12	63.16 %
17-Jul-2002	Veneer Over Edge	16-Sep-2002	48	22-Jul-2002	5	43	89.58 %
18-Jul-2002	Contract Calibrate and Veneer Sand	24-Jul-2002	6	18-Jul-2002	1	5	83.33 %
18-Jul-2002	Contract Veneer Sand	19-Jul-2002	2	18-Jul-2002	1	1	50.00 %
18-Jul-2002	Veneer Over Edge	23-Jul-2002	5	25-Jul-2002	7	–2	–40.00 %
18-Jul-2002	Contract Veneer Sand	30-Jul-2002	11	18-Jul-2002	1	10	90.91 %
18-Jul-2002	Contract Veneer Sand	30-Jul-2002	11	18-Jul-2002	1	10	90.91 %
18-Jul-2002	Contract Veneer Sand	29-Jul-2002	10	18-Jul-2002	1	9	90.00 %
18-Jul-2002	Contract Veneer Sand	23-Jul-2002	5	18-Jul-2002	1	4	80.00 %
18-Jul-2002	Contract Calibrate Sand	19-Jul-2002	2	18-Jul-2002	1	1	50.00 %
18-Jul-2002	Shaker Doors	18-Jul-2002	1	19-Jul-2002	2	–1	–100.00 %
19-Jul-2002	Contract Veneer Sand	30-Jul-2002	10	19-Jul-2002	1	9	90.00 %
19-Jul-2002	Contract Veneer Sand	30-Jul-2002	10	19-Jul-2002	1	9	90.00 %
19-Jul-2002	Contract Calibrate Sand	29-Jul-2002	9	19-Jul-2002	1	8	88.89 %
19-Jul-2002	Contract Veneer Sand	29-Jul-2002	9	19-Jul-2002	1	8	88.89 %
19-Jul-2002	Contract Veneer Sand	26-Jul-2002	7	19-Jul-2002	1	6	85.71 %
19-Jul-2002	Contract Veneer Sand	26-Jul-2002	7	19-Jul-2002	1	6	85.71 %
19-Jul-2002	Contract Calibrate Sand	23-Jul-2002	4	19-Jul-2002	1	3	75.00 %
19-Jul-2002	Contract Calibrate Sand	22-Jul-2002	3	19-Jul-2002	1	2	66.67 %
19-Jul-2002	Contract Calibrate Sand	22-Jul-2002	3	19-Jul-2002	1	2	66.67 %
19-Jul-2002	Contract Calibrate Sand	22-Jul-2002	3	19-Jul-2002	1	2	66.67 %
19-Jul-2002	Contract Calibrate Sand	22-Jul-2002	3	19-Jul-2002	1	2	66.67 %
19-Jul-2002	Contract Calibrate Sand	22-Jul-2002	3	19-Jul-2002	1	2	66.67 %
19-Jul-2002	Contract Calibrate Sand	19-Jul-2002	1	19-Jul-2002	1	0	0.00 %
19-Jul-2002	Contract Calibrate Sand	2-Aug-2002	13	19-Jul-2002	1	12	92.31 %

Table F.1 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 5 *minutes.*

		LWC		**Tabu**		**Improve–ment**	**%Improve–ment**
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**		
20-Jul-2002	Contract Veneer Sand	2-Aug-2002	12	20-Jul-2002	1	11	91.67 %
22-Jul-2002	Contract Cut	24-Jul-2002	3	22-Jul-2002	1	2	66.67 %
22-Jul-2002	Contract Calibrate and Veneer Sand	22-Jul-2002	1	25-Jul-2002	4	–3	–300.00 %
22-Jul-2002	Contract Calibrate and Veneer Sand	22-Jul-2002	1	25-Jul-2002	4	–3	–300.00 %
22-Jul-2002	Contract Calibrate and Veneer Sand	22-Jul-2002	1	25-Jul-2002	4	–3	–300.00 %
22-Jul-2002	Contract Veneer Sand	30-Jul-2002	8	24-Jul-2002	3	5	62.50 %
22-Jul-2002	Contract Veneer Sand	30-Jul-2002	8	25-Jul-2002	4	4	50.00 %
22-Jul-2002	Contract Calibrate Sand	25-Jul-2002	4	24-Jul-2002	3	1	25.00 %
22-Jul-2002	Contract Calibrate Sand	23-Jul-2002	2	25-Jul-2002	4	–2	–100.00 %
22-Jul-2002	Contract Calibrate Sand	23-Jul-2002	2	24-Jul-2002	3	–1	–50.00 %
22-Jul-2002	Contract Calibrate Sand	22-Jul-2002	1	24-Jul-2002	3	–2	–200.00 %
22-Jul-2002	Veneer Over Edge	8-Aug-2002	15	29-Jul-2002	7	8	53.33 %
23-Jul-2002	Contract Cut	25-Jul-2002	3	23-Jul-2002	1	2	66.67 %
23-Jul-2002	Contract Edging	26-Jul-2002	4	23-Jul-2002	1	3	75.00 %
23-Jul-2002	Contract Edging	23-Jul-2002	1	23-Jul-2002	1	0	0.00 %
23-Jul-2002	Contract Spray: Stain Top Coat	24-Jul-2002	2	25-Jul-2002	3	–1	–50.00 %
23-Jul-2002	Contract Calibrate Sand	26-Jul-2002	4	24-Jul-2002	2	2	50.00 %
23-Jul-2002	Contract Calibrate Sand	25-Jul-2002	3	24-Jul-2002	2	1	33.33 %
23-Jul-2002	Contract Spray Lacquer Top and Base Coat	31-Aug-2002	32	23-Jul-2002	1	31	96.88 %
23-Jul-2002	Board Components	19-Aug-2002	21	25-Jul-2002	3	18	85.71 %
23-Jul-2002	Shaker Doors	19-Aug-2002	21	25-Jul-2002	3	18	85.71 %
23-Jul-2002	Veneer Over Edge	19-Aug-2002	21	29-Jul-2002	6	15	71.43 %
23-Jul-2002	Board Components	19-Aug-2002	21	25-Jul-2002	3	18	85.71 %
23-Jul-2002	Veneer Over Edge	19-Aug-2002	21	29-Jul-2002	6	15	71.43 %
23-Jul-2002	Veneer Over Edge	8-Aug-2002	14	29-Jul-2002	6	8	57.14 %
23-Jul-2002	Board Components	5-Aug-2002	11	23-Jul-2002	1	10	90.91 %
23-Jul-2002	Contract Cut	5-Aug-2002	11	25-Jul-2002	3	8	72.73 %
23-Jul-2002	Veneer Over Edge	5-Aug-2002	11	29-Jul-2002	6	5	45.45 %
24-Jul-2002	Contract Spray Lacquer Top and Base Coat	24-Jul-2002	1	25-Jul-2002	2	–1	–100.00 %
24-Jul-2002	Contract Spray: Stain Top Coat	24-Jul-2002	1	25-Jul-2002	2	–1	–100.00 %
24-Jul-2002	Components on Edge	24-Jul-2002	1	29-Jul-2002	5	–4	–400.00 %
24-Jul-2002	Contract Calibrate Sand	24-Jul-2002	1	24-Jul-2002	1	0	0.00 %
24-Jul-2002	Veneer Over Edge	24-Jul-2002	1	29-Jul-2002	5	–4	–400.00 %
24-Jul-2002	Contract Veneer Sand	24-Jul-2002	1	24-Jul-2002	1	0	0.00 %
24-Jul-2002	Contract Veneer Sand	30-Jul-2002	6	24-Jul-2002	1	5	83.33 %
24-Jul-2002	Contract Calibrate Sand	29-Jul-2002	5	24-Jul-2002	1	4	80.00 %
24-Jul-2002	Contract Veneer Sand	29-Jul-2002	5	25-Jul-2002	2	3	60.00 %
24-Jul-2002	Contract Calibrate Sand	25-Jul-2002	2	24-Jul-2002	1	1	50.00 %
24-Jul-2002	Contract Calibrate Sand	25-Jul-2002	2	25-Jul-2002	2	0	0.00 %
24-Jul-2002	Contract Calibrate Sand	24-Jul-2002	1	24-Jul-2002	1	0	0.00 %
24-Jul-2002	Contract Calibrate Sand	2-Aug-2002	9	25-Jul-2002	2	7	77.78 %
25-Jul-2002	Contract Calibrate Sand	25-Jul-2002	1	25-Jul-2002	1	0	0.00 %
25-Jul-2002	Contract Cut	25-Jul-2002	1	29-Jul-2002	4	–3	–300.00 %
25-Jul-2002	Contract Calibrate and Veneer Sand	26-Jul-2002	2	25-Jul-2002	1	1	50.00 %
25-Jul-2002	Contract Calibrate Sand	25-Jul-2002	1	25-Jul-2002	1	0	0.00 %
25-Jul-2002	Contract Calibrate Sand	29-Jul-2002	4	25-Jul-2002	1	3	75.00 %
25-Jul-2002	Contract Calibrate Sand	29-Jul-2002	4	25-Jul-2002	1	3	75.00 %
25-Jul-2002	Contract Calibrate Sand	29-Jul-2002	4	25-Jul-2002	1	3	75.00 %
25-Jul-2002	Contract Veneer Sand	29-Jul-2002	4	25-Jul-2002	1	3	75.00 %
25-Jul-2002	Contract Veneer Sand	29-Jul-2002	4	25-Jul-2002	1	3	75.00 %
25-Jul-2002	Contract Veneer Sand	29-Jul-2002	4	25-Jul-2002	1	3	75.00 %
25-Jul-2002	Contract Veneer Sand	26-Aug-2002	25	25-Jul-2002	1	24	96.00 %
25-Jul-2002	Contract Calibrate Sand	7-Aug-2002	11	25-Jul-2002	1	10	90.91 %
25-Jul-2002	Contract Calibrate Sand	7-Aug-2002	11	25-Jul-2002	1	10	90.91 %
25-Jul-2002	Shaker Doors	8-Aug-2002	12	29-Jul-2002	4	8	66.67 %
25-Jul-2002	Contract Cut	2-Aug-2002	8	25-Jul-2002	1	7	87.50 %
25-Jul-2002	Contract Calibrate Sand	2-Aug-2002	8	25-Jul-2002	1	7	87.50 %
26-Jul-2002	Contract Calibrate Sand	29-Jul-2002	3	29-Jul-2002	3	0	0.00 %
26-Jul-2002	Contract Calibrate Sand	29-Jul-2002	3	29-Jul-2002	3	0	0.00 %
26-Jul-2002	Contract Veneer Sand	26-Jul-2002	1	29-Jul-2002	3	–2	–200.00 %
26-Jul-2002	Veneer Over Edge	6-Aug-2002	9	1-Aug-2002	6	3	33.33 %
26-Jul-2002	Contract Spray Lacquer Top and Base Coat	31-Jul-2002	5	29-Jul-2002	3	2	40.00 %
28-Jul-2002	Poster Box	6-Aug-2002	8	29-Jul-2002	2	6	75.00 %
29-Jul-2002	Contract Spray: Top and Base Coat and Edge Cut	2-Aug-2002	5	30-Jul-2002	2	3	60.00 %

Table F.1 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 5 *minutes.*

		LWC		**Tabu**			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
29-Jul-2002	Contract Cut	2-Aug-2002	5	1-Aug-2002	4	1	20.00 %
29-Jul-2002	Contract Calibrate Sand	31-Jul-2002	3	29-Jul-2002	1	2	66.67 %
30-Jul-2002	Contract Calibrate Sand	30-Jul-2002	1	30-Jul-2002	1	0	0.00 %
30-Jul-2002	Contract Veneer Sand	30-Jul-2002	1	30-Jul-2002	1	0	0.00 %
30-Jul-2002	Veneer Over Edge	26-Aug-2002	21	7-Aug-2002	7	14	66.67 %
30-Jul-2002	Shaker Doors	26-Aug-2002	21	1-Aug-2002	3	18	85.71 %
30-Jul-2002	Contract Calibrate Sand	19-Aug-2002	15	30-Jul-2002	1	14	93.33 %
30-Jul-2002	Contract Calibrate Sand	16-Aug-2002	14	30-Jul-2002	1	13	92.86 %
30-Jul-2002	Contract Veneer Sand	7-Aug-2002	7	30-Jul-2002	1	6	85.71 %
30-Jul-2002	Contract Calibrate Sand	7-Aug-2002	7	30-Jul-2002	1	6	85.71 %
30-Jul-2002	Contract Calibrate Sand	8-Aug-2002	8	30-Jul-2002	1	7	87.50 %
30-Jul-2002	Veneer Over Edge	13-Aug-2002	11	7-Aug-2002	7	4	36.36 %
31-Jul-2002	Contract Spray Lacquer Top and Base Coat	31-Jul-2002	1	1-Aug-2002	2	–1	–100.00 %
31-Jul-2002	Contract Spray: Stain Top Coat	31-Jul-2002	1	1-Aug-2002	2	–1	–100.00 %
31-Jul-2002	Contract Cut	31-Jul-2002	1	2-Aug-2002	3	–2	–200.00 %
31-Jul-2002	Contract Edging	31-Jul-2002	1	31-Jul-2002	1	0	0.00 %
31-Jul-2002	Contract Calibrate Sand	31-Jul-2002	1	1-Aug-2002	2	–1	–100.00 %
31-Jul-2002	Veneer Over Edge	26-Aug-2002	20	7-Aug-2002	6	14	70.00 %
31-Jul-2002	Contract Calibrate Sand	6-Aug-2002	5	1-Aug-2002	2	3	60.00 %
31-Jul-2002	Contract Calibrate Sand	2-Aug-2002	3	1-Aug-2002	2	1	33.33 %
31-Jul-2002	Contract Cut	15-Aug-2002	12	2-Aug-2002	3	9	75.00 %
31-Jul-2002	Unique	8-Aug-2002	7	2-Aug-2002	3	4	57.14 %
1-Aug-2002	Contract Calibrate and Veneer Sand	1-Aug-2002	1	1-Aug-2002	1	0	0.00 %
1-Aug-2002	Shaker Doors	23-Aug-2002	17	7-Aug-2002	5	12	70.59 %
1-Aug-2002	Contract Calibrate Sand	7-Aug-2002	5	1-Aug-2002	1	4	80.00 %
1-Aug-2002	Contract Calibrate Sand	2-Aug-2002	2	1-Aug-2002	1	1	50.00 %
1-Aug-2002	Contract Calibrate Sand	2-Aug-2002	2	1-Aug-2002	1	1	50.00 %
1-Aug-2002	Contract Veneer Sand	2-Aug-2002	2	1-Aug-2002	1	1	50.00 %
1-Aug-2002	Contract Cut, Edge and Groove	2-Aug-2002	2	1-Aug-2002	1	1	50.00 %
1-Aug-2002	Contract Cut	2-Aug-2002	2	7-Aug-2002	5	–3	–150.00 %
1-Aug-2002	Contract Veneer Sand	2-Aug-2002	2	1-Aug-2002	1	1	50.00 %
1-Aug-2002	Contract Edging	2-Aug-2002	2	1-Aug-2002	1	1	50.00 %
1-Aug-2002	Contract Veneer Sand	2-Aug-2002	2	1-Aug-2002	1	1	50.00 %
1-Aug-2002	Contract Cut, Edge and Groove	2-Aug-2002	2	2-Aug-2002	2	0	0.00 %
2-Aug-2002	Contract Edging	28-Aug-2002	20	2-Aug-2002	1	19	95.00 %
2-Aug-2002	Veneer Over Edge	26-Aug-2002	18	8-Aug-2002	5	13	72.22 %
2-Aug-2002	Veneer Over Edge	26-Aug-2002	18	8-Aug-2002	5	13	72.22 %
2-Aug-2002	Shaker Doors	26-Aug-2002	18	7-Aug-2002	4	14	77.78 %
2-Aug-2002	Contract Calibrate Sand	21-Aug-2002	14	2-Aug-2002	1	13	92.86 %
2-Aug-2002	Contract Veneer Sand	20-Aug-2002	13	2-Aug-2002	1	12	92.31 %
2-Aug-2002	Contract Calibrate Sand	19-Aug-2002	12	2-Aug-2002	1	11	91.67 %
2-Aug-2002	Contract Calibrate Sand	19-Aug-2002	12	2-Aug-2002	1	11	91.67 %
2-Aug-2002	Contract Calibrate Sand	14-Aug-2002	9	2-Aug-2002	1	8	88.89 %
2-Aug-2002	Contract Veneer Sand	8-Aug-2002	5	2-Aug-2002	1	4	80.00 %
2-Aug-2002	Contract Veneer Sand	8-Aug-2002	5	2-Aug-2002	1	4	80.00 %
2-Aug-2002	Contract Veneer Sand	8-Aug-2002	5	2-Aug-2002	1	4	80.00 %
2-Aug-2002	Contract Calibrate Sand	7-Aug-2002	4	2-Aug-2002	1	3	75.00 %
2-Aug-2002	Contract Spray Lacquer Top and Base Coat	15-Aug-2002	10	2-Aug-2002	1	9	90.00 %
2-Aug-2002	Contract Spray Lacquer Top and Base Coat	15-Aug-2002	10	7-Aug-2002	4	6	60.00 %
2-Aug-2002	Contract Spray Lacquer Top and Base Coat	15-Aug-2002	10	5-Aug-2002	2	8	80.00 %
2-Aug-2002	Contract Spray Lacquer Top and Base Coat	15-Aug-2002	10	7-Aug-2002	4	6	60.00 %
2-Aug-2002	Contract Spray Lacquer Top and Base Coat	8-Aug-2002	5	2-Aug-2002	1	4	80.00 %
2-Aug-2002	Contract Spray Lacquer Top and Base Coat	11-Sep-2002	31	7-Aug-2002	4	27	87.10 %
5-Aug-2002	Contract Calibrate Sand	16-Aug-2002	10	7-Aug-2002	3	7	70.00 %
5-Aug-2002	Contract Calibrate Sand	7-Aug-2002	3	7-Aug-2002	3	0	0.00 %
5-Aug-2002	Contract Calibrate Sand	7-Aug-2002	3	7-Aug-2002	3	0	0.00 %
5-Aug-2002	Contract Calibrate Sand	7-Aug-2002	3	7-Aug-2002	3	0	0.00 %
5-Aug-2002	Contract Calibrate Sand	14-Aug-2002	8	7-Aug-2002	3	5	62.50 %
5-Aug-2002	Contract Calibrate Sand	14-Aug-2002	8	7-Aug-2002	3	5	62.50 %
5-Aug-2002	Contract Calibrate Sand	14-Aug-2002	8	7-Aug-2002	3	5	62.50 %
5-Aug-2002	Contract Calibrate Sand	8-Aug-2002	4	7-Aug-2002	3	1	25.00 %

Table F.1 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 5 *minutes.*

		LWC		Tabu			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improvement**	**%Improvement**
5-Aug-2002	Contract Calibrate Sand	7-Aug-2002	3	7-Aug-2002	3	0	0.00 %
5-Aug-2002	Contract Cut	8-Aug-2002	4	7-Aug-2002	3	1	25.00 %
5-Aug-2002	Contract Cut	8-Aug-2002	4	7-Aug-2002	3	1	25.00 %
5-Aug-2002	Contract Calibrate Sand	5-Aug-2002	1	7-Aug-2002	3	–2	–200.00 %
5-Aug-2002	Contract Veneer Sand	5-Aug-2002	1	7-Aug-2002	3	–2	–200.00 %
6-Aug-2002	Contract Calibrate Sand	14-Aug-2002	7	7-Aug-2002	2	5	71.43 %
6-Aug-2002	Contract Calibrate Sand	14-Aug-2002	7	7-Aug-2002	2	5	71.43 %
6-Aug-2002	Contract Calibrate Sand	6-Aug-2002	1	7-Aug-2002	2	–1	–100.00 %
6-Aug-2002	Contract Calibrate Sand	6-Aug-2002	1	7-Aug-2002	2	–1	–100.00 %
6-Aug-2002	Shaker Doors	16-Aug-2002	9	7-Aug-2002	2	7	77.78 %
6-Aug-2002	Unique	13-Aug-2002	6	7-Aug-2002	2	4	66.67 %
6-Aug-2002	Contract Calibrate Sand	6-Aug-2002	1	7-Aug-2002	2	–1	–100.00 %
6-Aug-2002	Contract Calibrate Sand	6-Aug-2002	1	7-Aug-2002	2	–1	–100.00 %
6-Aug-2002	Contract Veneer Sand	6-Aug-2002	1	7-Aug-2002	2	–1	–100.00 %
7-Aug-2002	Contract Calibrate Sand	16-Aug-2002	8	7-Aug-2002	1	7	87.50 %
7-Aug-2002	Contract Calibrate Sand	14-Aug-2002	6	7-Aug-2002	1	5	83.33 %
7-Aug-2002	Contract Veneer Sand	14-Aug-2002	6	7-Aug-2002	1	5	83.33 %
7-Aug-2002	Contract Calibrate Sand	14-Aug-2002	6	7-Aug-2002	1	5	83.33 %
7-Aug-2002	Contract Calibrate Sand	14-Aug-2002	6	7-Aug-2002	1	5	83.33 %
7-Aug-2002	Contract Calibrate Sand	13-Aug-2002	5	7-Aug-2002	1	4	80.00 %
7-Aug-2002	Contract Calibrate Sand	8-Aug-2002	2	7-Aug-2002	1	1	50.00 %
7-Aug-2002	Contract Veneer Sand	8-Aug-2002	2	7-Aug-2002	1	1	50.00 %
7-Aug-2002	Contract Veneer Sand	8-Aug-2002	2	7-Aug-2002	1	1	50.00 %
7-Aug-2002	Contract Veneer Sand	8-Aug-2002	2	7-Aug-2002	1	1	50.00 %
7-Aug-2002	Contract Veneer Sand	8-Aug-2002	2	7-Aug-2002	1	1	50.00 %
7-Aug-2002	Contract Veneer Sand	8-Aug-2002	2	7-Aug-2002	1	1	50.00 %
7-Aug-2002	Contract Calibrate Sand	13-Aug-2002	5	7-Aug-2002	1	4	80.00 %
7-Aug-2002	Unique	16-Aug-2002	8	7-Aug-2002	1	7	87.50 %
8-Aug-2002	Veneer Over Edge	31-Aug-2002	19	20-Aug-2002	9	10	52.63 %
8-Aug-2002	Contract Calibrate Sand	31-Aug-2002	19	8-Aug-2002	1	18	94.74 %
8-Aug-2002	Contract Veneer Sand	31-Aug-2002	19	8-Aug-2002	1	18	94.74 %
8-Aug-2002	Contract Calibrate Sand	29-Aug-2002	17	8-Aug-2002	1	16	94.12 %
8-Aug-2002	Contract Calibrate Sand	20-Aug-2002	9	8-Aug-2002	1	8	88.89 %
8-Aug-2002	Contract Veneer Sand	20-Aug-2002	9	8-Aug-2002	1	8	88.89 %
8-Aug-2002	Contract Calibrate Sand	16-Aug-2002	7	8-Aug-2002	1	6	85.71 %
8-Aug-2002	Contract Calibrate Sand	14-Aug-2002	5	8-Aug-2002	1	4	80.00 %
10-Aug-2002	Contract Calibrate Sand	14-Aug-2002	4	10-Aug-2002	1	3	75.00 %
12-Aug-2002	Unique	26-Aug-2002	12	12-Aug-2002	1	11	91.67 %
12-Aug-2002	Veneer Over Edge	26-Aug-2002	12	21-Aug-2002	8	4	33.33 %
12-Aug-2002	Contract Veneer Sand	20-Aug-2002	7	12-Aug-2002	1	6	85.71 %
12-Aug-2002	Contract Veneer Sand	16-Aug-2002	5	12-Aug-2002	1	4	80.00 %
12-Aug-2002	Unique	15-Aug-2002	4	14-Aug-2002	3	1	25.00 %
12-Aug-2002	Contract Calibrate Sand	13-Aug-2002	2	12-Aug-2002	1	1	50.00 %
12-Aug-2002	Contract Edging	12-Aug-2002	1	12-Aug-2002	1	0	0.00 %
12-Aug-2002	Veneer Over Edge	2-Sep-2002	18	20-Aug-2002	7	11	61.11 %
12-Aug-2002	Veneer Over Edge	2-Sep-2002	18	19-Aug-2002	6	12	66.67 %
13-Aug-2002	Board Components	30-Aug-2002	15	14-Aug-2002	2	13	86.67 %
13-Aug-2002	Board Components	29-Aug-2002	14	15-Aug-2002	3	11	78.57 %
13-Aug-2002	Contract Calibrate Sand	31-Aug-2002	16	14-Aug-2002	2	14	87.50 %
13-Aug-2002	Contract Veneer Sand	31-Aug-2002	16	14-Aug-2002	2	14	87.50 %
13-Aug-2002	Contract Calibrate Sand	23-Aug-2002	9	14-Aug-2002	2	7	77.78 %
13-Aug-2002	Contract Calibrate Sand	21-Aug-2002	7	15-Aug-2002	3	4	57.14 %
13-Aug-2002	Contract Calibrate Sand	16-Aug-2002	4	14-Aug-2002	2	2	50.00 %
13-Aug-2002	Contract Calibrate Sand	14-Aug-2002	2	14-Aug-2002	2	0	0.00 %
13-Aug-2002	Contract Calibrate Sand	14-Aug-2002	2	14-Aug-2002	2	0	0.00 %
13-Aug-2002	Contract Calibrate Sand	14-Aug-2002	2	14-Aug-2002	2	0	0.00 %
14-Aug-2002	Contract Calibrate Sand	22-Aug-2002	7	14-Aug-2002	1	6	85.71 %
14-Aug-2002	Contract Veneer Sand	22-Aug-2002	7	15-Aug-2002	2	5	71.43 %
14-Aug-2002	Contract Calibrate Sand	21-Aug-2002	6	14-Aug-2002	1	5	83.33 %
14-Aug-2002	Contract Calibrate Sand	21-Aug-2002	6	14-Aug-2002	1	5	83.33 %
14-Aug-2002	Contract Calibrate Sand	19-Aug-2002	4	14-Aug-2002	1	3	75.00 %
14-Aug-2002	Contract Calibrate Sand	19-Aug-2002	4	15-Aug-2002	2	2	50.00 %
14-Aug-2002	Contract Calibrate Sand	14-Aug-2002	1	14-Aug-2002	1	0	0.00 %
14-Aug-2002	Contract Calibrate Sand	14-Aug-2002	1	15-Aug-2002	2	–1	–100.00 %
14-Aug-2002	Contract Calibrate Sand	14-Aug-2002	1	14-Aug-2002	1	0	0.00 %
14-Aug-2002	Contract Calibrate Sand	20-Aug-2002	5	14-Aug-2002	1	4	80.00 %
15-Aug-2002	Contract Calibrate Sand	28-Aug-2002	11	15-Aug-2002	1	10	90.91 %
15-Aug-2002	Contract Calibrate Sand	26-Aug-2002	9	15-Aug-2002	1	8	88.89 %
15-Aug-2002	Contract Calibrate Sand	23-Aug-2002	7	15-Aug-2002	1	6	85.71 %

Table F.1 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 5 *minutes.*

		LWC		**Tabu**			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
15-Aug-2002	Veneer Over Edge	6-Sep-2002	19	22-Aug-2002	6	13	68.42 %
16-Aug-2002	Contract Edging	28-Aug-2002	10	16-Aug-2002	1	9	90.00 %
16-Aug-2002	Contract Calibrate Sand	23-Aug-2002	6	16-Aug-2002	1	5	83.33 %
16-Aug-2002	Contract Calibrate Sand	19-Aug-2002	2	16-Aug-2002	1	1	50.00 %
16-Aug-2002	Shaker Doors	16-Aug-2002	1	22-Aug-2002	5	–4	–400.00 %
16-Aug-2002	Contract Cut	19-Aug-2002	2	16-Aug-2002	1	1	50.00 %
19-Aug-2002	Contract Calibrate Sand	29-Aug-2002	10	22-Aug-2002	4	6	60.00 %
19-Aug-2002	Contract Calibrate Sand	26-Aug-2002	7	20-Aug-2002	2	5	71.43 %
19-Aug-2002	Contract Calibrate Sand	23-Aug-2002	5	22-Aug-2002	4	1	20.00 %
19-Aug-2002	Contract Calibrate Sand	21-Aug-2002	3	20-Aug-2002	2	1	33.33 %
19-Aug-2002	Contract Calibrate Sand	21-Aug-2002	3	22-Aug-2002	4	–1	–33.33 %
19-Aug-2002	Veneer Over Edge	26-Sep-2002	32	24-Aug-2002	6	26	81.25 %
20-Aug-2002	Contract Calibrate Sand	21-Aug-2002	2	23-Aug-2002	4	–2	–100.00 %
20-Aug-2002	Contract Veneer Sand	21-Aug-2002	2	20-Aug-2002	1	1	50.00 %
20-Aug-2002	Contract Veneer Sand	30-Aug-2002	10	20-Aug-2002	1	9	90.00 %
20-Aug-2002	Contract Calibrate Sand	30-Aug-2002	10	20-Aug-2002	1	9	90.00 %
20-Aug-2002	Contract Veneer Sand	29-Aug-2002	9	20-Aug-2002	1	8	88.89 %
20-Aug-2002	Contract Calibrate Sand	29-Aug-2002	9	20-Aug-2002	1	8	88.89 %
20-Aug-2002	Contract Calibrate Sand	26-Aug-2002	6	22-Aug-2002	3	3	50.00 %
20-Aug-2002	Contract Calibrate Sand	23-Aug-2002	4	20-Aug-2002	1	3	75.00 %
20-Aug-2002	Contract Calibrate Sand	23-Aug-2002	4	20-Aug-2002	1	3	75.00 %
20-Aug-2002	Contract Veneer Sand	26-Aug-2002	6	20-Aug-2002	1	5	83.33 %
20-Aug-2002	Contract Calibrate Sand	26-Aug-2002	6	20-Aug-2002	1	5	83.33 %
20-Aug-2002	Contract Veneer Sand	26-Aug-2002	6	20-Aug-2002	1	5	83.33 %
20-Aug-2002	Contract Calibrate Sand	26-Aug-2002	6	22-Aug-2002	3	3	50.00 %
21-Aug-2002	Board Components	31-Aug-2002	10	22-Aug-2002	2	8	80.00 %
21-Aug-2002	Board Components	23-Aug-2002	3	22-Aug-2002	2	1	33.33 %
21-Aug-2002	Contract Veneer Sand	29-Aug-2002	8	22-Aug-2002	2	6	75.00 %
21-Aug-2002	Contract Calibrate Sand	29-Aug-2002	8	22-Aug-2002	2	6	75.00 %
21-Aug-2002	Contract Calibrate Sand	23-Aug-2002	3	22-Aug-2002	2	1	33.33 %
21-Aug-2002	Contract Calibrate Sand	22-Aug-2002	2	22-Aug-2002	2	0	0.00 %
21-Aug-2002	Contract Veneer Sand	22-Aug-2002	2	22-Aug-2002	2	0	0.00 %
21-Aug-2002	Contract Spray: Stain Top Coat	18-Sep-2002	23	21-Aug-2002	1	22	95.65 %
21-Aug-2002	Contract Spray Lacquer Top and Base Coat	6-Sep-2002	15	22-Aug-2002	2	13	86.67 %
21-Aug-2002	Poster Box	3-Sep-2002	12	22-Aug-2002	2	10	83.33 %
21-Aug-2002	Poster Box	3-Sep-2002	12	22-Aug-2002	2	10	83.33 %
21-Aug-2002	Poster Box	3-Sep-2002	12	22-Aug-2002	2	10	83.33 %
21-Aug-2002	Contract Cut	10-Oct-2002	40	24-Aug-2002	4	36	90.00 %
22-Aug-2002	Contract Calibrate Sand	23-Aug-2002	2	22-Aug-2002	1	1	50.00 %
22-Aug-2002	Contract Calibrate Sand	29-Aug-2002	7	22-Aug-2002	1	6	85.71 %
22-Aug-2002	Contract Veneer Sand	28-Aug-2002	6	22-Aug-2002	1	5	83.33 %
22-Aug-2002	Contract Calibrate Sand	22-Aug-2002	1	22-Aug-2002	1	0	0.00 %
22-Aug-2002	Contract Veneer Sand	29-Aug-2002	7	22-Aug-2002	1	6	85.71 %
22-Aug-2002	Contract Veneer Sand	28-Aug-2002	6	22-Aug-2002	1	5	83.33 %
22-Aug-2002	Shaker Doors	6-Sep-2002	14	26-Aug-2002	4	10	71.43 %
23-Aug-2002	Contract Spray Lacquer Top and Base Coat	29-Aug-2002	6	23-Aug-2002	1	5	83.33 %
23-Aug-2002	Poster Box	28-Aug-2002	5	26-Aug-2002	3	2	40.00 %
23-Aug-2002	Poster Box	28-Aug-2002	5	26-Aug-2002	3	2	40.00 %
23-Aug-2002	Contract Calibrate Sand	31-Aug-2002	8	24-Aug-2002	2	6	75.00 %
23-Aug-2002	Contract Veneer Sand	31-Aug-2002	8	24-Aug-2002	2	6	75.00 %
23-Aug-2002	Contract Calibrate Sand	29-Aug-2002	6	24-Aug-2002	2	4	66.67 %
23-Aug-2002	Contract Veneer Sand	29-Aug-2002	6	24-Aug-2002	2	4	66.67 %
23-Aug-2002	Contract Calibrate Sand	28-Aug-2002	5	24-Aug-2002	2	3	60.00 %
23-Aug-2002	Contract Veneer Sand	28-Aug-2002	5	24-Aug-2002	2	3	60.00 %
23-Aug-2002	Contract Veneer Sand	28-Aug-2002	5	24-Aug-2002	2	3	60.00 %
23-Aug-2002	Contract Calibrate Sand	29-Aug-2002	6	24-Aug-2002	2	4	66.67 %
23-Aug-2002	Veneer Over Edge	11-Sep-2002	16	30-Aug-2002	7	9	56.25 %
24-Aug-2002	Unique	29-Aug-2002	5	24-Aug-2002	1	4	80.00 %
24-Aug-2002	Contract Calibrate Sand	28-Aug-2002	4	24-Aug-2002	1	3	75.00 %
24-Aug-2002	Contract Calibrate Sand	30-Aug-2002	6	24-Aug-2002	1	5	83.33 %
26-Aug-2002	Contract Calibrate Sand	26-Aug-2002	1	26-Aug-2002	1	0	0.00 %
26-Aug-2002	Contract Calibrate Sand	30-Aug-2002	5	26-Aug-2002	1	4	80.00 %
27-Aug-2002	Contract Calibrate Sand	2-Sep-2002	6	27-Aug-2002	1	5	83.33 %
27-Aug-2002	Contract Veneer Sand	2-Sep-2002	6	27-Aug-2002	1	5	83.33 %
27-Aug-2002	Contract Calibrate Sand	2-Sep-2002	6	27-Aug-2002	1	5	83.33 %
27-Aug-2002	Shaker Doors	12-Sep-2002	14	30-Aug-2002	4	10	71.43 %
27-Aug-2002	Shaker Doors	12-Sep-2002	14	30-Aug-2002	4	10	71.43 %

Table F.1 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 5 *minutes.*

		LWC		Tabu			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
28-Aug-2002	Contract Edging	31-Aug-2002	4	28-Aug-2002	1	3	75.00 %
28-Aug-2002	Contract Calibrate Sand	29-Aug-2002	2	29-Aug-2002	2	0	0.00 %
28-Aug-2002	Contract Calibrate Sand	3-Sep-2002	6	29-Aug-2002	2	4	66.67 %
28-Aug-2002	Contract Calibrate Sand	3-Sep-2002	6	29-Aug-2002	2	4	66.67 %
28-Aug-2002	Contract Calibrate Sand	3-Sep-2002	6	29-Aug-2002	2	4	66.67 %
28-Aug-2002	Contract Calibrate Sand	30-Aug-2002	3	29-Aug-2002	2	1	33.33 %
28-Aug-2002	Contract Veneer Sand	3-Sep-2002	6	29-Aug-2002	2	4	66.67 %
28-Aug-2002	Contract Cut	17-Sep-2002	16	29-Aug-2002	2	14	87.50 %
28-Aug-2002	Board Components	17-Sep-2002	16	30-Aug-2002	3	13	81.25 %
28-Aug-2002	Shaker Doors	10-Sep-2002	11	30-Aug-2002	3	8	72.73 %
28-Aug-2002	Contract Cut and Edge	10-Sep-2002	11	28-Aug-2002	1	10	90.91 %
28-Aug-2002	Contract Calibrate Sand	3-Sep-2002	6	29-Aug-2002	2	4	66.67 %
28-Aug-2002	Contract Calibrate Sand	3-Sep-2002	6	29-Aug-2002	2	4	66.67 %
28-Aug-2002	Contract Spray Lacquer Top and Base Coat	4-Oct-2002	30	29-Aug-2002	2	28	93.33 %
29-Aug-2002	Contract Spray: Stain Top Coat	31-Aug-2002	3	29-Aug-2002	1	2	66.67 %
29-Aug-2002	Contract Spray Lacquer Top and Base Coat	4-Sep-2002	6	29-Aug-2002	1	5	83.33 %
29-Aug-2002	Contract Spray Lacquer Top and Base Coat	20-Sep-2002	18	29-Aug-2002	1	17	94.44 %
29-Aug-2002	Contract Veneer Sand	5-Sep-2002	7	29-Aug-2002	1	6	85.71 %
29-Aug-2002	Contract Veneer Sand	4-Sep-2002	6	29-Aug-2002	1	5	83.33 %
29-Aug-2002	Contract Veneer Sand	4-Sep-2002	6	29-Aug-2002	1	5	83.33 %
29-Aug-2002	Contract Calibrate Sand	4-Sep-2002	6	29-Aug-2002	1	5	83.33 %
29-Aug-2002	Shaker Doors	16-Sep-2002	14	30-Aug-2002	2	12	85.71 %
31-Aug-2002	Contract Calibrate Sand	31-Aug-2002	1	31-Aug-2002	1	0	0.00 %
2-Sep-2002	Contract Calibrate Sand	30-Sep-2002	22	2-Sep-2002	1	21	95.45 %
2-Sep-2002	Contract Calibrate Sand	30-Sep-2002	22	2-Sep-2002	1	21	95.45 %
2-Sep-2002	Contract Calibrate Sand	30-Sep-2002	22	2-Sep-2002	1	21	95.45 %
2-Sep-2002	Contract Calibrate Sand	2-Sep-2002	1	2-Sep-2002	1	0	0.00 %
2-Sep-2002	Contract Calibrate Sand	2-Sep-2002	1	2-Sep-2002	1	0	0.00 %
3-Sep-2002	Contract Calibrate Sand	30-Sep-2002	21	3-Sep-2002	1	20	95.24 %
3-Sep-2002	Poster Box	23-Sep-2002	16	4-Sep-2002	2	14	87.50 %
3-Sep-2002	Veneer Over Edge	20-Sep-2002	14	9-Sep-2002	5	9	64.29 %
3-Sep-2002	Contract Cut and Edge	16-Sep-2002	10	4-Sep-2002	2	8	80.00 %
4-Sep-2002	Veneer Over Edge	30-Sep-2002	20	10-Sep-2002	5	15	75.00 %
4-Sep-2002	Contract Calibrate Sand	23-Sep-2002	15	4-Sep-2002	1	14	93.33 %
4-Sep-2002	Poster Box	23-Sep-2002	15	4-Sep-2002	1	14	93.33 %
4-Sep-2002	Contract Calibrate Sand	10-Sep-2002	5	4-Sep-2002	1	4	80.00 %
4-Sep-2002	Contract Calibrate Sand	10-Sep-2002	5	4-Sep-2002	1	4	80.00 %
4-Sep-2002	Contract Calibrate Sand	6-Sep-2002	3	4-Sep-2002	1	2	66.67 %
4-Sep-2002	Contract Calibrate Sand	10-Sep-2002	5	4-Sep-2002	1	4	80.00 %
4-Sep-2002	Contract Calibrate Sand	10-Sep-2002	5	4-Sep-2002	1	4	80.00 %
4-Sep-2002	Unique	16-Sep-2002	9	6-Sep-2002	3	6	66.67 %
4-Sep-2002	Veneer Over Edge	18-Oct-2002	35	10-Sep-2002	5	30	85.71 %
5-Sep-2002	Veneer Over Edge	30-Sep-2002	19	11-Sep-2002	5	14	73.68 %
5-Sep-2002	Veneer Over Edge	27-Sep-2002	18	11-Sep-2002	5	13	72.22 %
5-Sep-2002	Contract Calibrate Sand	12-Sep-2002	6	5-Sep-2002	1	5	83.33 %
5-Sep-2002	Contract Veneer Sand	11-Sep-2002	5	5-Sep-2002	1	4	80.00 %
5-Sep-2002	Contract Calibrate Sand	5-Sep-2002	1	5-Sep-2002	1	0	0.00 %
6-Sep-2002	Contract Plane all Round (PAR)	23-Sep-2002	13	6-Sep-2002	1	12	92.31 %
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Veneer Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Veneer Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Veneer Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Calibrate Sand	6-Sep-2002	1	6-Sep-2002	1	0	0.00 %
9-Sep-2002	Contract Calibrate Sand	30-Sep-2002	17	9-Sep-2002	1	16	94.12 %
9-Sep-2002	Shaker Doors	23-Sep-2002	12	10-Sep-2002	2	10	83.33 %
9-Sep-2002	Contract Calibrate Sand	23-Sep-2002	12	9-Sep-2002	1	11	91.67 %
9-Sep-2002	Contract Calibrate Sand	13-Sep-2002	5	9-Sep-2002	1	4	80.00 %
9-Sep-2002	Contract Veneer Sand	13-Sep-2002	5	9-Sep-2002	1	4	80.00 %

Table F.1 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 5 *minutes.*

		LWC		Tabu			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improvement**	**%Improvement**
9-Sep-2002	Contract Calibrate Sand	13-Sep-2002	5	9-Sep-2002	1	4	80.00 %
9-Sep-2002	Contract Veneer Sand	12-Sep-2002	4	9-Sep-2002	1	3	75.00 %
9-Sep-2002	Contract Calibrate Sand	13-Sep-2002	5	9-Sep-2002	1	4	80.00 %
9-Sep-2002	Contract Veneer Sand	9-Sep-2002	1	9-Sep-2002	1	0	0.00 %
9-Sep-2002	Contract Calibrate Sand	9-Sep-2002	1	9-Sep-2002	1	0	0.00 %
9-Sep-2002	Contract Calibrate Sand	13-Sep-2002	5	9-Sep-2002	1	4	80.00 %
10-Sep-2002	Unique	30-Sep-2002	16	11-Sep-2002	2	14	87.50 %
10-Sep-2002	Unique	30-Sep-2002	16	12-Sep-2002	3	13	81.25 %
10-Sep-2002	Contract Plane all Round (PAR)	30-Sep-2002	16	10-Sep-2002	1	15	93.75 %
10-Sep-2002	Contract Spray: Stain Top Coat	30-Sep-2002	16	10-Sep-2002	1	15	93.75 %
10-Sep-2002	Contract Calibrate Sand	16-Sep-2002	5	10-Sep-2002	1	4	80.00 %
10-Sep-2002	Contract Calibrate Sand	16-Sep-2002	5	10-Sep-2002	1	4	80.00 %
10-Sep-2002	Contract Calibrate Sand	16-Sep-2002	5	10-Sep-2002	1	4	80.00 %
10-Sep-2002	Contract Calibrate Sand	30-Sep-2002	16	10-Sep-2002	1	15	93.75 %
10-Sep-2002	Contract Edging	13-Sep-2002	4	10-Sep-2002	1	3	75.00 %
10-Sep-2002	Veneer Over Edge	12-Sep-2002	3	16-Sep-2002	5	–2	–66.67 %
10-Sep-2002	Contract Calibrate Sand	11-Sep-2002	2	10-Sep-2002	1	1	50.00 %
11-Sep-2002	Contract Spray Lacquer Top and Base Coat	30-Sep-2002	15	11-Sep-2002	1	14	93.33 %
11-Sep-2002	Contract Spray Lacquer Top and Base Coat	30-Sep-2002	15	11-Sep-2002	1	14	93.33 %
11-Sep-2002	Shaker Doors	26-Sep-2002	13	12-Sep-2002	2	11	84.62 %
11-Sep-2002	Unique	26-Sep-2002	13	13-Sep-2002	3	10	76.92 %
11-Sep-2002	Contract Calibrate Sand	30-Sep-2002	15	11-Sep-2002	1	14	93.33 %
11-Sep-2002	Contract Calibrate Sand	11-Sep-2002	1	11-Sep-2002	1	0	0.00 %
11-Sep-2002	Contract Spray Lacquer Top and Base Coat	17-Sep-2002	5	11-Sep-2002	1	4	80.00 %
11-Sep-2002	Contract Spray Lacquer Top and Base Coat	17-Sep-2002	5	11-Sep-2002	1	4	80.00 %
11-Sep-2002	Contract Cut	12-Sep-2002	2	11-Sep-2002	1	1	50.00 %
11-Sep-2002	Contract Cut	12-Sep-2002	2	13-Sep-2002	3	–1	–50.00 %
11-Sep-2002	Contract Spray Lacquer Top and Base Coat	7-Oct-2002	20	11-Sep-2002	1	19	95.00 %
12-Sep-2002	Shaker Doors	30-Sep-2002	14	16-Sep-2002	3	11	78.57 %
12-Sep-2002	Shaker Doors	20-Sep-2002	7	16-Sep-2002	3	4	57.14 %
12-Sep-2002	Contract Calibrate Sand	18-Sep-2002	5	12-Sep-2002	1	4	80.00 %
12-Sep-2002	Contract Calibrate Sand	18-Sep-2002	5	12-Sep-2002	1	4	80.00 %
12-Sep-2002	Contract Veneer Sand	17-Sep-2002	4	12-Sep-2002	1	3	75.00 %
12-Sep-2002	Contract Calibrate Sand	18-Sep-2002	5	12-Sep-2002	1	4	80.00 %
12-Sep-2002	Contract Calibrate Sand	18-Sep-2002	5	12-Sep-2002	1	4	80.00 %
12-Sep-2002	Contract Calibrate Sand	18-Sep-2002	5	12-Sep-2002	1	4	80.00 %
12-Sep-2002	Contract Calibrate Sand	16-Sep-2002	3	12-Sep-2002	1	2	66.67 %
12-Sep-2002	Contract Calibrate Sand	12-Sep-2002	1	12-Sep-2002	1	0	0.00 %
12-Sep-2002	Contract Calibrate Sand	18-Sep-2002	5	12-Sep-2002	1	4	80.00 %
12-Sep-2002	Contract Calibrate Sand	16-Sep-2002	3	12-Sep-2002	1	2	66.67 %
12-Sep-2002	Contract Calibrate Sand	12-Sep-2002	1	12-Sep-2002	1	0	0.00 %
13-Sep-2002	Contract Spray: Base Coat	18-Sep-2002	4	16-Sep-2002	2	2	50.00 %
13-Sep-2002	Contract Calibrate Sand	19-Sep-2002	5	16-Sep-2002	2	3	60.00 %
13-Sep-2002	Contract Calibrate Sand	13-Sep-2002	1	16-Sep-2002	2	–1	–100.00 %
16-Sep-2002	Unique	27-Sep-2002	11	16-Sep-2002	1	10	90.91 %
16-Sep-2002	Contract Edging	23-Sep-2002	7	16-Sep-2002	1	6	85.71 %
16-Sep-2002	Contract Veneer Sand	20-Sep-2002	5	16-Sep-2002	1	4	80.00 %
16-Sep-2002	Contract Calibrate Sand	20-Sep-2002	5	16-Sep-2002	1	4	80.00 %
16-Sep-2002	Contract Veneer Sand	30-Sep-2002	12	16-Sep-2002	1	11	91.67 %
16-Sep-2002	Contract Veneer Sand	30-Sep-2002	12	16-Sep-2002	1	11	91.67 %
16-Sep-2002	Contract Calibrate Sand	20-Sep-2002	5	16-Sep-2002	1	4	80.00 %
16-Sep-2002	Contract Calibrate Sand	20-Sep-2002	5	16-Sep-2002	1	4	80.00 %
16-Sep-2002	Contract Calibrate Sand	20-Sep-2002	5	16-Sep-2002	1	4	80.00 %
16-Sep-2002	Contract Veneer Sand	20-Sep-2002	5	16-Sep-2002	1	4	80.00 %
16-Sep-2002	Contract Veneer Sand	20-Sep-2002	5	16-Sep-2002	1	4	80.00 %
16-Sep-2002	Contract Calibrate Sand	20-Sep-2002	5	16-Sep-2002	1	4	80.00 %
16-Sep-2002	Contract Calibrate Sand	20-Sep-2002	5	16-Sep-2002	1	4	80.00 %
16-Sep-2002	Contract Calibrate Sand	16-Sep-2002	1	16-Sep-2002	1	0	0.00 %
17-Sep-2002	Shaker Doors	26-Sep-2002	9	18-Sep-2002	2	7	77.78 %
17-Sep-2002	Contract Calibrate Sand	23-Sep-2002	6	17-Sep-2002	1	5	83.33 %
17-Sep-2002	Contract Spray Lacquer Top and Base Coat	23-Sep-2002	6	17-Sep-2002	1	5	83.33 %

Table F.1 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 5 *minutes.*

		LWC		**Tabu**			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
17-Sep-2002	Contract Spray Lacquer Top and Base Coat	20-Sep-2002	4	17-Sep-2002	1	3	75.00 %
17-Sep-2002	Contract Calibrate Sand	23-Sep-2002	6	17-Sep-2002	1	5	83.33 %
17-Sep-2002	Contract Calibrate Sand	23-Sep-2002	6	17-Sep-2002	1	5	83.33 %
17-Sep-2002	Contract Calibrate Sand	23-Sep-2002	6	17-Sep-2002	1	5	83.33 %
17-Sep-2002	Contract Spray Lacquer Top and Base Coat	10-Oct-2002	19	17-Sep-2002	1	18	94.74 %
18-Sep-2002	Contract Cut	27-Sep-2002	9	18-Sep-2002	1	8	88.89 %
18-Sep-2002	Contract Spray Lacquer Top and Base Coat	26-Sep-2002	8	18-Sep-2002	1	7	87.50 %
18-Sep-2002	Contract Calibrate Sand	30-Sep-2002	10	18-Sep-2002	1	9	90.00 %
18-Sep-2002	Contract Calibrate Sand	20-Sep-2002	3	18-Sep-2002	1	2	66.67 %
18-Sep-2002	Contract Calibrate Sand	18-Sep-2002	1	18-Sep-2002	1	0	0.00 %
19-Sep-2002	Contract Spray Lacquer Top and Base Coat	30-Sep-2002	9	19-Sep-2002	1	8	88.89 %
19-Sep-2002	Contract Calibrate Sand	23-Sep-2002	4	19-Sep-2002	1	3	75.00 %
19-Sep-2002	Contract Veneer Sand	26-Sep-2002	7	19-Sep-2002	1	6	85.71 %
19-Sep-2002	Contract Calibrate Sand	30-Sep-2002	9	19-Sep-2002	1	8	88.89 %
19-Sep-2002	Contract Calibrate Sand	26-Sep-2002	7	19-Sep-2002	1	6	85.71 %
19-Sep-2002	Contract Calibrate Sand	26-Sep-2002	7	19-Sep-2002	1	6	85.71 %
19-Sep-2002	Contract Calibrate Sand	19-Sep-2002	1	19-Sep-2002	1	0	0.00 %
19-Sep-2002	Contract Spray Lacquer Top and Base Coat	14-Oct-2002	20	19-Sep-2002	1	19	95.00 %
19-Sep-2002	Shaker Doors	4-Oct-2002	13	20-Sep-2002	2	11	84.62 %
19-Sep-2002	Contract Spray Lacquer Top and Base Coat	4-Oct-2002	13	19-Sep-2002	1	12	92.31 %
20-Sep-2002	Unique	30-Sep-2002	8	24-Sep-2002	4	4	50.00 %
20-Sep-2002	Contract Cut and Edge	23-Sep-2002	3	20-Sep-2002	1	2	66.67 %
20-Sep-2002	Contract Calibrate Sand	20-Sep-2002	1	20-Sep-2002	1	0	0.00 %
20-Sep-2002	Contract Veneer Sand	20-Sep-2002	1	20-Sep-2002	1	0	0.00 %
20-Sep-2002	Contract Cut	4-Oct-2002	12	21-Sep-2002	2	10	83.33 %
21-Sep-2002	Contract Cut	23-Sep-2002	2	21-Sep-2002	1	1	50.00 %
23-Sep-2002	Contract Plane all Round (PAR)	23-Sep-2002	1	23-Sep-2002	1	0	0.00 %
23-Sep-2002	Contract Cut	23-Sep-2002	1	24-Sep-2002	2	–1	–100.00 %
23-Sep-2002	Contract Veneer Sand	30-Sep-2002	6	23-Sep-2002	1	5	83.33 %
23-Sep-2002	Contract Calibrate Sand	27-Sep-2002	5	23-Sep-2002	1	4	80.00 %
23-Sep-2002	Contract Calibrate Sand	27-Sep-2002	5	23-Sep-2002	1	4	80.00 %
23-Sep-2002	Contract Calibrate Sand	27-Sep-2002	5	23-Sep-2002	1	4	80.00 %
23-Sep-2002	Contract Calibrate Sand	26-Sep-2002	4	23-Sep-2002	1	3	75.00 %
23-Sep-2002	Poster Box	17-Oct-2002	20	24-Sep-2002	2	18	90.00 %
23-Sep-2002	Poster Box	17-Oct-2002	20	24-Sep-2002	2	18	90.00 %
23-Sep-2002	Shaker Doors	8-Oct-2002	12	24-Sep-2002	2	10	83.33 %
25-Sep-2002	Contract Spray: Top and Base Coat	26-Sep-2002	2	25-Sep-2002	1	1	50.00 %
26-Sep-2002	Contract Edging	30-Sep-2002	3	26-Sep-2002	1	2	66.67 %
26-Sep-2002	Contract Spray: Stain Top Coat	30-Sep-2002	3	26-Sep-2002	1	2	66.67 %
26-Sep-2002	Contract Calibrate Sand	27-Sep-2002	2	26-Sep-2002	1	1	50.00 %
26-Sep-2002	Contract Calibrate Sand	26-Sep-2002	1	26-Sep-2002	1	0	0.00 %
26-Sep-2002	Contract Calibrate Sand	2-Oct-2002	5	26-Sep-2002	1	4	80.00 %
26-Sep-2002	Contract Calibrate Sand	30-Sep-2002	3	26-Sep-2002	1	2	66.67 %
26-Sep-2002	Contract Calibrate Sand	3-Oct-2002	6	26-Sep-2002	1	5	83.33 %
26-Sep-2002	Contract Calibrate Sand	3-Oct-2002	6	26-Sep-2002	1	5	83.33 %
26-Sep-2002	Veneer Over Edge	24-Oct-2002	22	3-Oct-2002	6	16	72.73 %
26-Sep-2002	Shaker Doors	10-Oct-2002	11	27-Sep-2002	2	9	81.82 %
26-Sep-2002	Contract Cut	2-Oct-2002	5	26-Sep-2002	1	4	80.00 %
27-Sep-2002	Shaker Doors	30-Oct-2002	26	2-Oct-2002	4	22	84.62 %
27-Sep-2002	Contract Cut	30-Oct-2002	26	2-Oct-2002	4	22	84.62 %
27-Sep-2002	Unique	30-Oct-2002	26	2-Oct-2002	4	22	84.62 %
27-Sep-2002	Board Components	30-Oct-2002	26	27-Sep-2002	1	25	96.15 %
27-Sep-2002	Veneer Over Edge	23-Oct-2002	20	12-Oct-2002	12	8	40.00 %
27-Sep-2002	Unique	23-Oct-2002	20	2-Oct-2002	4	16	80.00 %
27-Sep-2002	Contract Spray Lacquer Top and Base Coat	14-Oct-2002	13	27-Sep-2002	1	12	92.31 %
27-Sep-2002	Contract Veneer Sand	3-Oct-2002	5	27-Sep-2002	1	4	80.00 %
27-Sep-2002	Shaker Doors	4-Oct-2002	6	2-Oct-2002	4	2	33.33 %
30-Sep-2002	Contract Veneer Sand	30-Sep-2002	1	1-Oct-2002	2	–1	–100.00 %
30-Sep-2002	Contract Calibrate Sand	30-Sep-2002	1	2-Oct-2002	3	–2	–200.00 %
30-Sep-2002	Contract Edging	30-Sep-2002	1	1-Oct-2002	2	–1	–100.00 %
30-Sep-2002	Contract Calibrate Sand	30-Sep-2002	1	2-Oct-2002	3	–2	–200.00 %

Table F.1 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 5 *minutes.*

		LWC		Tabu			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improvement**	**%Improvement**
30-Sep-2002	Veneer Over Edge	30-Sep-2002	1	7-Oct-2002	6	–5	–500.00 %
30-Sep-2002	Board Components	30-Oct-2002	25	2-Oct-2002	3	22	88.00 %
30-Sep-2002	Board Components	14-Oct-2002	12	2-Oct-2002	3	9	75.00 %
30-Sep-2002	Components on Edge	14-Oct-2002	12	12-Oct-2002	11	1	8.33 %
30-Sep-2002	Board Components	14-Oct-2002	12	2-Oct-2002	3	9	75.00 %
30-Sep-2002	Components on Edge	14-Oct-2002	12	4-Oct-2002	5	7	58.33 %
30-Sep-2002	Contract Calibrate Sand	4-Oct-2002	5	2-Oct-2002	3	2	40.00 %
30-Sep-2002	Contract Calibrate Sand	4-Oct-2002	5	2-Oct-2002	3	2	40.00 %
30-Sep-2002	Contract Calibrate Sand	1-Oct-2002	2	2-Oct-2002	3	–1	–50.00 %
30-Sep-2002	Contract Cut	4-Oct-2002	5	2-Oct-2002	3	2	40.00 %
30-Sep-2002	Contract Spray Lacquer Top and Base Coat	7-Oct-2002	6	30-Sep-2002	1	5	83.33 %
1-Oct-2002	Contract Calibrate Sand	1-Oct-2002	1	2-Oct-2002	2	–1	–100.00 %
1-Oct-2002	Contract Veneer Sand	7-Oct-2002	5	2-Oct-2002	2	3	60.00 %
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002	5	2-Oct-2002	2	3	60.00 %
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002	5	2-Oct-2002	2	3	60.00 %
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002	5	2-Oct-2002	2	3	60.00 %
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002	5	1-Oct-2002	1	4	80.00 %
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002	5	2-Oct-2002	2	3	60.00 %
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002	5	1-Oct-2002	1	4	80.00 %
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002	5	2-Oct-2002	2	3	60.00 %
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002	5	1-Oct-2002	1	4	80.00 %
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002	5	2-Oct-2002	2	3	60.00 %
1-Oct-2002	Contract Cut	3-Oct-2002	3	2-Oct-2002	2	1	33.33 %
1-Oct-2002	Components on Edge	3-Oct-2002	3	12-Oct-2002	10	–7	–233.33 %
1-Oct-2002	Poster Box	1-Nov-2002	26	2-Oct-2002	2	24	92.31 %
2-Oct-2002	Contract Calibrate Sand	2-Oct-2002	1	2-Oct-2002	1	0	0.00 %
2-Oct-2002	Contract Calibrate Sand	7-Oct-2002	4	2-Oct-2002	1	3	75.00 %
2-Oct-2002	Contract Calibrate Sand	7-Oct-2002	4	2-Oct-2002	1	3	75.00 %
2-Oct-2002	Contract Calibrate Sand	7-Oct-2002	4	2-Oct-2002	1	3	75.00 %
2-Oct-2002	Contract Calibrate Sand	7-Oct-2002	4	2-Oct-2002	1	3	75.00 %
2-Oct-2002	Contract Calibrate Sand	9-Oct-2002	6	2-Oct-2002	1	5	83.33 %
2-Oct-2002	Contract Edging	2-Oct-2002	1	2-Oct-2002	1	0	0.00 %
2-Oct-2002	Board Components	3-Oct-2002	2	2-Oct-2002	1	1	50.00 %
2-Oct-2002	Contract Cut	3-Oct-2002	2	2-Oct-2002	1	1	50.00 %
2-Oct-2002	Contract Calibrate Sand	2-Oct-2002	1	2-Oct-2002	1	0	0.00 %
3-Oct-2002	Board Components	24-Oct-2002	17	7-Oct-2002	3	14	82.35 %
3-Oct-2002	Veneer Over Edge	24-Oct-2002	17	12-Oct-2002	8	9	52.94 %
3-Oct-2002	Board Components	18-Oct-2002	13	7-Oct-2002	3	10	76.92 %
3-Oct-2002	Veneer Over Edge	18-Oct-2002	13	12-Oct-2002	8	5	38.46 %
3-Oct-2002	Board Components	18-Oct-2002	13	8-Oct-2002	4	9	69.23 %
3-Oct-2002	Contract Spray Lacquer Top and Base Coat	18-Oct-2002	13	8-Oct-2002	4	9	69.23 %
3-Oct-2002	Contract Spray Lacquer Top and Base Coat	14-Oct-2002	9	10-Oct-2002	6	3	33.33 %
3-Oct-2002	Contract Spray Lacquer Top and Base Coat	14-Oct-2002	9	10-Oct-2002	6	3	33.33 %
3-Oct-2002	Contract Calibrate Sand	9-Oct-2002	5	3-Oct-2002	1	4	80.00 %
3-Oct-2002	Contract Veneer Sand	10-Oct-2002	6	3-Oct-2002	1	5	83.33 %
3-Oct-2002	Contract Calibrate Sand	9-Oct-2002	5	3-Oct-2002	1	4	80.00 %
3-Oct-2002	Contract Calibrate Sand	10-Oct-2002	6	3-Oct-2002	1	5	83.33 %
3-Oct-2002	Contract Calibrate Sand	7-Oct-2002	3	3-Oct-2002	1	2	66.67 %
3-Oct-2002	Contract Calibrate Sand	9-Oct-2002	5	3-Oct-2002	1	4	80.00 %
3-Oct-2002	Contract Calibrate Sand	7-Oct-2002	3	3-Oct-2002	1	2	66.67 %
3-Oct-2002	Veneer Over Edge	11-Oct-2002	7	11-Oct-2002	7	0	0.00 %
3-Oct-2002	Contract Calibrate Sand	8-Oct-2002	4	3-Oct-2002	1	3	75.00 %
3-Oct-2002	Contract Cut	3-Oct-2002	1	10-Oct-2002	6	–5	–500.00 %
3-Oct-2002	Contract Cut, Veneer Sand and Edging	16-Dec-2002	57	3-Oct-2002	1	56	98.25 %
4-Oct-2002	Unique	18-Oct-2002	12	11-Oct-2002	6	6	50.00 %
4-Oct-2002	Contract Calibrate Sand	4-Oct-2002	1	11-Oct-2002	6	–5	–500.00 %
4-Oct-2002	Contract Veneer Sand	10-Oct-2002	5	7-Oct-2002	2	3	60.00 %
4-Oct-2002	Contract Calibrate Sand	9-Oct-2002	4	8-Oct-2002	3	1	25.00 %
4-Oct-2002	Contract Veneer Sand	9-Oct-2002	4	7-Oct-2002	2	2	50.00 %
4-Oct-2002	Contract Calibrate Sand	10-Oct-2002	5	12-Oct-2002	7	–2	–40.00 %
4-Oct-2002	Contract Calibrate Sand	10-Oct-2002	5	7-Oct-2002	2	3	60.00 %
4-Oct-2002	Contract Calibrate Sand	10-Oct-2002	5	7-Oct-2002	2	3	60.00 %
4-Oct-2002	Contract Calibrate Sand	11-Oct-2002	6	7-Oct-2002	2	4	66.67 %
4-Oct-2002	Contract Calibrate Sand	11-Oct-2002	6	8-Oct-2002	3	3	50.00 %

Table F.1 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 5 *minutes.*

		LWC		Tabu			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
4-Oct-2002	Contract Calibrate Sand	10-Oct-2002	5	7-Oct-2002	2	3	60.00 %
4-Oct-2002	Contract Calibrate Sand	4-Oct-2002	1	7-Oct-2002	2	–1	–100.00 %
4-Oct-2002	Contract Spray Lacquer Top and Base Coat	10-Oct-2002	5	8-Oct-2002	3	2	40.00 %
4-Oct-2002	Contract Spray Lacquer Top and Base Coat	10-Oct-2002	5	10-Oct-2002	5	0	0.00 %
4-Oct-2002	Contract Spray Lacquer Top and Base Coat	10-Oct-2002	5	8-Oct-2002	3	2	40.00 %
7-Oct-2002	Poster Box	17-Oct-2002	10	12-Oct-2002	6	4	40.00 %
7-Oct-2002	Poster Box	17-Oct-2002	10	12-Oct-2002	6	4	40.00 %
7-Oct-2002	Contract Calibrate Sand	10-Oct-2002	4	7-Oct-2002	1	3	75.00 %
7-Oct-2002	Contract Calibrate Sand	8-Oct-2002	2	12-Oct-2002	6	–4	–200.00 %
7-Oct-2002	Poster Box	7-Oct-2002	1	12-Oct-2002	6	–5	–500.00 %
8-Oct-2002	Poster Box	31-Oct-2002	20	12-Oct-2002	5	15	75.00 %
8-Oct-2002	Veneer Over Edge	14-Oct-2002	6	12-Oct-2002	5	1	16.67 %
8-Oct-2002	Contract Veneer Sand	14-Oct-2002	6	8-Oct-2002	1	5	83.33 %
8-Oct-2002	Contract Calibrate Sand	8-Oct-2002	1	12-Oct-2002	5	–4	–400.00 %
8-Oct-2002	Contract Calibrate Sand	11-Oct-2002	4	8-Oct-2002	1	3	75.00 %
8-Oct-2002	Contract Calibrate Sand	14-Oct-2002	6	12-Oct-2002	5	1	16.67 %
8-Oct-2002	Contract Calibrate Sand	14-Oct-2002	6	12-Oct-2002	5	1	16.67 %
8-Oct-2002	Contract Calibrate Sand	14-Oct-2002	6	11-Oct-2002	4	2	33.33 %
9-Oct-2002	Contract Cut	31-Oct-2002	19	9-Oct-2002	1	18	94.74 %
9-Oct-2002	Contract Calibrate Sand	15-Oct-2002	6	12-Oct-2002	4	2	33.33 %
9-Oct-2002	Contract Calibrate Sand	9-Oct-2002	1	12-Oct-2002	4	–3	–300.00 %
9-Oct-2002	Contract Calibrate Sand	9-Oct-2002	1	12-Oct-2002	4	–3	–300.00 %
10-Oct-2002	Contract Spray Lacquer Top and Base Coat	29-Oct-2002	16	10-Oct-2002	1	15	93.75 %
10-Oct-2002	Shaker Doors	29-Oct-2002	16	12-Oct-2002	3	13	81.25 %
10-Oct-2002	Contract Cut	31-Oct-2002	18	10-Oct-2002	1	17	94.44 %
10-Oct-2002	Contract Veneer Sand	23-Oct-2002	11	12-Oct-2002	3	8	72.73 %
10-Oct-2002	Contract Veneer Sand	17-Oct-2002	7	10-Oct-2002	1	6	85.71 %
10-Oct-2002	Contract Calibrate Sand	14-Oct-2002	4	11-Oct-2002	2	2	50.00 %
10-Oct-2002	Contract Calibrate Sand	16-Oct-2002	6	10-Oct-2002	1	5	83.33 %
10-Oct-2002	Contract Calibrate Sand	16-Oct-2002	6	11-Oct-2002	2	4	66.67 %
10-Oct-2002	Contract Calibrate Sand	16-Oct-2002	6	10-Oct-2002	1	5	83.33 %
10-Oct-2002	Contract Plane all Round (PAR)	11-Oct-2002	2	10-Oct-2002	1	1	50.00 %
11-Oct-2002	Board Components	30-Oct-2002	16	12-Oct-2002	2	14	87.50 %
11-Oct-2002	Veneer Over Edge	30-Oct-2002	16	16-Oct-2002	5	11	68.75 %
11-Oct-2002	Shaker Doors	30-Oct-2002	16	12-Oct-2002	2	14	87.50 %
11-Oct-2002	Unique	30-Oct-2002	16	12-Oct-2002	2	14	87.50 %
11-Oct-2002	Contract Cut	30-Oct-2002	16	12-Oct-2002	2	14	87.50 %
11-Oct-2002	Contract Spray Lacquer Top and Base Coat	23-Oct-2002	10	12-Oct-2002	2	8	80.00 %
11-Oct-2002	Contract Spray: Stain Top Coat	23-Oct-2002	10	12-Oct-2002	2	8	80.00 %
11-Oct-2002	Contract Calibrate Sand	16-Oct-2002	5	12-Oct-2002	2	3	60.00 %
11-Oct-2002	Contract Veneer Sand	14-Oct-2002	3	12-Oct-2002	2	1	33.33 %
11-Oct-2002	Contract Calibrate Sand	11-Oct-2002	1	11-Oct-2002	1	0	0.00 %
11-Oct-2002	Contract Calibrate Sand	11-Oct-2002	1	11-Oct-2002	1	0	0.00 %
12-Oct-2002	Contract Cut	31-Oct-2002	16	12-Oct-2002	1	15	93.75 %
14-Oct-2002	Contract Plane all Round (PAR)	17-Oct-2002	4	14-Oct-2002	1	3	75.00 %
14-Oct-2002	Contract Veneer Sand	17-Oct-2002	4	14-Oct-2002	1	3	75.00 %
14-Oct-2002	Contract Cut	15-Oct-2002	2	14-Oct-2002	1	1	50.00 %
14-Oct-2002	Contract Calibrate Sand	18-Oct-2002	5	14-Oct-2002	1	4	80.00 %
14-Oct-2002	Contract Calibrate Sand	18-Oct-2002	5	14-Oct-2002	1	4	80.00 %
14-Oct-2002	Contract Calibrate Sand	18-Oct-2002	5	14-Oct-2002	1	4	80.00 %
14-Oct-2002	Contract Calibrate Sand	18-Oct-2002	5	14-Oct-2002	1	4	80.00 %
14-Oct-2002	Contract Spray: Top and Base Coat	14-Nov-2002	26	14-Oct-2002	1	25	96.15 %
14-Oct-2002	Contract Spray Lacquer Top and Base Coat	12-Nov-2002	24	14-Oct-2002	1	23	95.83 %
14-Oct-2002	Shaker Doors	6-Nov-2002	19	16-Oct-2002	3	16	84.21 %
15-Oct-2002	Contract Cut	31-Oct-2002	14	15-Oct-2002	1	13	92.86 %
15-Oct-2002	Contract Spray Lacquer Top and Base Coat	23-Oct-2002	7	16-Oct-2002	2	5	71.43 %
15-Oct-2002	Contract Plane all Round (PAR)	17-Oct-2002	3	15-Oct-2002	1	2	66.67 %
15-Oct-2002	Contract Plane all Round (PAR)	17-Oct-2002	3	15-Oct-2002	1	2	66.67 %
15-Oct-2002	Contract Calibrate Sand	17-Oct-2002	3	15-Oct-2002	1	2	66.67 %
15-Oct-2002	Contract Calibrate Sand	21-Oct-2002	5	15-Oct-2002	1	4	80.00 %
15-Oct-2002	Contract Calibrate Sand	21-Oct-2002	5	15-Oct-2002	1	4	80.00 %

Table F.1 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 5 *minutes.*

		LWC		Tabu			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
15-Oct-2002	Contract Calibrate Sand	16-Oct-2002	2	15-Oct-2002	1	1	50.00 %
15-Oct-2002	Contract Calibrate Sand	21-Oct-2002	5	15-Oct-2002	1	4	80.00 %
15-Oct-2002	Veneer Over Edge	6-Nov-2002	18	21-Oct-2002	5	13	72.22 %
16-Oct-2002	Contract Calibrate Sand	16-Oct-2002	1	16-Oct-2002	1	0	0.00 %
16-Oct-2002	Shaker Doors	6-Nov-2002	17	17-Oct-2002	2	15	88.24 %
17-Oct-2002	Contract Cut	31-Oct-2002	12	17-Oct-2002	1	11	91.67 %
17-Oct-2002	Contract Edging	18-Oct-2002	2	17-Oct-2002	1	1	50.00 %
17-Oct-2002	Contract Plane all Round (PAR)	31-Oct-2002	12	17-Oct-2002	1	11	91.67 %
17-Oct-2002	Contract Calibrate Sand	23-Oct-2002	5	17-Oct-2002	1	4	80.00 %
17-Oct-2002	Contract Veneer Sand	23-Oct-2002	5	17-Oct-2002	1	4	80.00 %
17-Oct-2002	Contract Calibrate Sand	23-Oct-2002	5	17-Oct-2002	1	4	80.00 %
17-Oct-2002	Contract Calibrate Sand	23-Oct-2002	5	17-Oct-2002	1	4	80.00 %
17-Oct-2002	Contract Calibrate Sand	23-Oct-2002	5	17-Oct-2002	1	4	80.00 %
17-Oct-2002	Contract Cut	12-Nov-2002	21	24-Oct-2002	6	15	71.43 %
18-Oct-2002	Contract Cut	31-Oct-2002	11	18-Oct-2002	1	10	90.91 %
18-Oct-2002	Unique	18-Oct-2002	1	21-Oct-2002	2	–1	–100.00 %
18-Oct-2002	Contract Veneer Sand	24-Oct-2002	5	18-Oct-2002	1	4	80.00 %
18-Oct-2002	Contract Calibrate Sand	24-Oct-2002	5	18-Oct-2002	1	4	80.00 %
18-Oct-2002	Contract Calibrate Sand	24-Oct-2002	5	18-Oct-2002	1	4	80.00 %
18-Oct-2002	Contract Calibrate Sand	24-Oct-2002	5	18-Oct-2002	1	4	80.00 %
21-Oct-2002	Contract Calibrate Sand	25-Oct-2002	5	21-Oct-2002	1	4	80.00 %
21-Oct-2002	Shaker Doors	8-Nov-2002	16	23-Oct-2002	3	13	81.25 %
21-Oct-2002	Veneer Over Edge	8-Nov-2002	16	30-Oct-2002	9	7	43.75 %
21-Oct-2002	Board Components	8-Nov-2002	16	21-Oct-2002	1	15	93.75 %
21-Oct-2002	Shaker Doors	8-Nov-2002	16	23-Oct-2002	3	13	81.25 %
21-Oct-2002	Veneer Over Edge	8-Nov-2002	16	30-Oct-2002	9	7	43.75 %
22-Oct-2002	Contract Spray: Stain Top Coat	31-Oct-2002	9	22-Oct-2002	1	8	88.89 %
22-Oct-2002	Contract Calibrate Sand	29-Oct-2002	7	23-Oct-2002	2	5	71.43 %
22-Oct-2002	Contract Spray Lacquer Top and Base Coat	29-Oct-2002	7	23-Oct-2002	2	5	71.43 %
22-Oct-2002	Contract Calibrate Sand	28-Oct-2002	6	23-Oct-2002	2	4	66.67 %
22-Oct-2002	Contract Calibrate Sand	28-Oct-2002	6	23-Oct-2002	2	4	66.67 %
22-Oct-2002	Contract Calibrate Sand	22-Oct-2002	1	23-Oct-2002	2	–1	–100.00 %
22-Oct-2002	Veneer Over Edge	5-Nov-2002	12	30-Oct-2002	8	4	33.33 %
23-Oct-2002	Board Components	31-Oct-2002	8	23-Oct-2002	1	7	87.50 %
23-Oct-2002	Contract Calibrate Sand	25-Oct-2002	3	23-Oct-2002	1	2	66.67 %
23-Oct-2002	Veneer Over Edge	14-Nov-2002	19	30-Oct-2002	7	12	63.16 %
23-Oct-2002	Veneer Over Edge	12-Nov-2002	17	30-Oct-2002	7	10	58.82 %
24-Oct-2002	Contract Calibrate Sand	31-Oct-2002	7	24-Oct-2002	1	6	85.71 %
24-Oct-2002	Board Components	31-Oct-2002	7	24-Oct-2002	1	6	85.71 %
24-Oct-2002	Shaker Doors	31-Oct-2002	7	30-Oct-2002	6	1	14.29 %
24-Oct-2002	Contract Edging	28-Oct-2002	4	24-Oct-2002	1	3	75.00 %
24-Oct-2002	Contract Cut	28-Oct-2002	4	24-Oct-2002	1	3	75.00 %
24-Oct-2002	Contract Spray Lacquer Top and Base Coat	28-Oct-2002	4	24-Oct-2002	1	3	75.00 %
24-Oct-2002	Contract Calibrate Sand	24-Oct-2002	1	24-Oct-2002	1	0	0.00 %
24-Oct-2002	Contract Calibrate Sand	28-Oct-2002	4	24-Oct-2002	1	3	75.00 %
24-Oct-2002	Contract Calibrate Sand	30-Oct-2002	6	24-Oct-2002	1	5	83.33 %
24-Oct-2002	Contract Calibrate Sand	30-Oct-2002	6	24-Oct-2002	1	5	83.33 %
24-Oct-2002	Contract Calibrate Sand	24-Oct-2002	1	24-Oct-2002	1	0	0.00 %
24-Oct-2002	Contract Calibrate Sand	24-Oct-2002	1	24-Oct-2002	1	0	0.00 %
24-Oct-2002	Contract Spray Lacquer Top and Base Coat	27-Nov-2002	27	24-Oct-2002	1	26	96.30 %
24-Oct-2002	Shaker Doors	20-Nov-2002	22	29-Oct-2002	5	17	77.27 %
24-Oct-2002	Contract Cut	20-Nov-2002	22	1-Nov-2002	8	14	63.64 %
24-Oct-2002	Shaker Doors	5-Dec-2002	33	28-Oct-2002	4	29	87.88 %
24-Oct-2002	Veneer Over Edge	5-Dec-2002	33	30-Oct-2002	6	27	81.82 %
25-Oct-2002	Contract Plane all Round (PAR)	29-Oct-2002	4	25-Oct-2002	1	3	75.00 %
25-Oct-2002	Contract Edging	29-Oct-2002	4	25-Oct-2002	1	3	75.00 %
25-Oct-2002	Contract Cut	31-Oct-2002	6	26-Oct-2002	2	4	66.67 %
25-Oct-2002	Unique	31-Oct-2002	6	5-Nov-2002	9	–3	–50.00 %
25-Oct-2002	Contract Calibrate Sand	31-Oct-2002	6	30-Oct-2002	5	1	16.67 %
25-Oct-2002	Contract Calibrate Sand	31-Oct-2002	6	28-Oct-2002	3	3	50.00 %
25-Oct-2002	Contract Veneer Sand	31-Oct-2002	6	29-Oct-2002	4	2	33.33 %
25-Oct-2002	Veneer Over Edge	7-Nov-2002	11	30-Oct-2002	5	6	54.55 %
25-Oct-2002	Contract Veneer Sand	5-Dec-2002	32	29-Oct-2002	4	28	87.50 %
26-Oct-2002	Board Components	31-Oct-2002	5	28-Oct-2002	2	3	60.00 %
26-Oct-2002	Contract Cut	31-Oct-2002	5	29-Oct-2002	3	2	40.00 %

Table F.1 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of 5 minutes.*

		LWC		Tabu			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
26-Oct-2002	Board Components	31-Oct-2002	5	29-Oct-2002	3	2	40.00 %
26-Oct-2002	Contract Cut	31-Oct-2002	5	29-Oct-2002	3	2	40.00 %
28-Oct-2002	Contract Spray: Stain Top Coat	31-Oct-2002	4	30-Oct-2002	3	1	25.00 %
28-Oct-2002	Board Components	31-Oct-2002	4	30-Oct-2002	3	1	25.00 %
28-Oct-2002	Board Components	31-Oct-2002	4	30-Oct-2002	3	1	25.00 %
28-Oct-2002	Contract Calibrate Sand	31-Oct-2002	4	29-Oct-2002	2	2	50.00 %
28-Oct-2002	Contract Calibrate Sand	31-Oct-2002	4	30-Oct-2002	3	1	25.00 %
28-Oct-2002	Contract Calibrate Sand	31-Oct-2002	4	29-Oct-2002	2	2	50.00 %
28-Oct-2002	Contract Calibrate Sand	31-Oct-2002	4	30-Oct-2002	3	1	25.00 %
28-Oct-2002	Contract Calibrate Sand	31-Oct-2002	4	30-Oct-2002	3	1	25.00 %
28-Oct-2002	Contract Veneer Sand	31-Oct-2002	4	30-Oct-2002	3	1	25.00 %
28-Oct-2002	Contract Calibrate Sand	31-Oct-2002	4	29-Oct-2002	2	2	50.00 %
28-Oct-2002	Contract Spray Lacquer Top and Base Coat	27-Nov-2002	24	28-Oct-2002	1	23	95.83 %
28-Oct-2002	Contract Cut	18-Nov-2002	17	28-Oct-2002	1	16	94.12 %
28-Oct-2002	Contract Calibrate Sand	1-Nov-2002	5	30-Oct-2002	3	2	40.00 %
29-Oct-2002	Veneer Over Edge	29-Oct-2002	1	5-Nov-2002	6	–5	–500.00 %
29-Oct-2002	Contract Calibrate Sand	29-Oct-2002	1	29-Oct-2002	1	0	0.00 %
29-Oct-2002	Contract Calibrate Sand	29-Oct-2002	1	30-Oct-2002	2	–1	–100.00 %
29-Oct-2002	Veneer Over Edge	26-Nov-2002	22	5-Nov-2002	6	16	72.73 %
29-Oct-2002	Contract Cut	21-Nov-2002	19	30-Oct-2002	2	17	89.47 %
29-Oct-2002	Contract Cut	21-Nov-2002	19	30-Oct-2002	2	17	89.47 %
29-Oct-2002	Contract Spray: Lacquer Top and Base Coat and Calibrate and Veneer Sand	12-Nov-2002	12	30-Oct-2002	2	10	83.33 %
30-Oct-2002	Contract Cut	31-Oct-2002	2	1-Nov-2002	3	–1	–50.00 %
30-Oct-2002	Contract Cut	31-Oct-2002	2	1-Nov-2002	3	–1	–50.00 %
30-Oct-2002	Contract Cut	30-Oct-2002	1	30-Oct-2002	1	0	0.00 %
30-Oct-2002	Contract Calibrate Sand	31-Oct-2002	2	30-Oct-2002	1	1	50.00 %
30-Oct-2002	Contract Spray Lacquer Top and Base Coat	8-Nov-2002	8	30-Oct-2002	1	7	87.50 %
30-Oct-2002	Contract Spray Lacquer Top and Base Coat	8-Nov-2002	8	30-Oct-2002	1	7	87.50 %
30-Oct-2002	Contract Plane all Round (PAR)	5-Nov-2002	5	30-Oct-2002	1	4	80.00 %
30-Oct-2002	Contract Spray: Stain Top Coat	6-Nov-2002	6	30-Oct-2002	1	5	83.33 %
31-Oct-2002	Contract Cut	31-Oct-2002	1	5-Nov-2002	4	–3	–300.00 %
31-Oct-2002	Contract Cut	31-Oct-2002	1	31-Oct-2002	1	0	0.00 %
31-Oct-2002	Contract Edging	31-Oct-2002	1	31-Oct-2002	1	0	0.00 %
31-Oct-2002	Contract Calibrate Sand	31-Oct-2002	1	31-Oct-2002	1	0	0.00 %
31-Oct-2002	Veneer Over Edge	21-Nov-2002	17	7-Nov-2002	6	11	64.71 %
31-Oct-2002	Shaker Doors	29-Nov-2002	23	1-Nov-2002	2	21	91.30 %
31-Oct-2002	Veneer Over Edge	15-Nov-2002	13	7-Nov-2002	6	7	53.85 %
31-Oct-2002	Contract Cut	21-Nov-2002	17	4-Nov-2002	3	14	82.35 %
31-Oct-2002	Contract Calibrate and Veneer Sand	14-Nov-2002	12	31-Oct-2002	1	11	91.67 %
31-Oct-2002	Veneer Over Edge	11-Nov-2002	9	9-Nov-2002	8	1	11.11 %
31-Oct-2002	Contract Calibrate Sand	6-Nov-2002	5	31-Oct-2002	1	4	80.00 %
31-Oct-2002	Contract Veneer Sand	6-Nov-2002	5	31-Oct-2002	1	4	80.00 %
31-Oct-2002	Contract Calibrate Sand	6-Nov-2002	5	31-Oct-2002	1	4	80.00 %
31-Oct-2002	Contract Calibrate Sand	1-Nov-2002	2	31-Oct-2002	1	1	50.00 %
1-Nov-2002	Veneer Over Edge	20-Nov-2002	15	8-Nov-2002	6	9	60.00 %
1-Nov-2002	Contract Calibrate Sand	7-Nov-2002	5	1-Nov-2002	1	4	80.00 %
1-Nov-2002	Contract Cut	6-Nov-2002	4	5-Nov-2002	3	1	25.00 %
1-Nov-2002	Contract Cut, Edge and Calibrate Sand	7-Nov-2002	5	1-Nov-2002	1	4	80.00 %
1-Nov-2002	Contract Calibrate Sand	5-Nov-2002	3	1-Nov-2002	1	2	66.67 %
1-Nov-2002	Contract Calibrate Sand	4-Nov-2002	2	1-Nov-2002	1	1	50.00 %
4-Nov-2002	Contract Calibrate Sand	6-Nov-2002	3	5-Nov-2002	2	1	33.33 %
4-Nov-2002	Contract Cut	6-Nov-2002	3	4-Nov-2002	1	2	66.67 %
4-Nov-2002	Contract Veneer Sand	8-Nov-2002	5	5-Nov-2002	2	3	60.00 %
4-Nov-2002	Contract Calibrate Sand	8-Nov-2002	5	5-Nov-2002	2	3	60.00 %
4-Nov-2002	Contract Calibrate Sand	5-Nov-2002	2	5-Nov-2002	2	0	0.00 %
5-Nov-2002	Board Components	13-Nov-2002	8	5-Nov-2002	1	7	87.50 %
5-Nov-2002	Contract Calibrate Sand	11-Nov-2002	6	5-Nov-2002	1	5	83.33 %
5-Nov-2002	Contract Veneer Sand	11-Nov-2002	6	5-Nov-2002	1	5	83.33 %
5-Nov-2002	Contract Calibrate Sand	11-Nov-2002	6	5-Nov-2002	1	5	83.33 %
5-Nov-2002	Contract Calibrate Sand	11-Nov-2002	6	5-Nov-2002	1	5	83.33 %
5-Nov-2002	Contract Calibrate Sand	7-Nov-2002	3	5-Nov-2002	1	2	66.67 %
5-Nov-2002	Contract Calibrate Sand	6-Nov-2002	2	5-Nov-2002	1	1	50.00 %
5-Nov-2002	Contract Calibrate Sand	5-Nov-2002	1	5-Nov-2002	1	0	0.00 %
6-Nov-2002	Contract Calibrate Sand	6-Nov-2002	1	6-Nov-2002	1	0	0.00 %
6-Nov-2002	Veneer Over Edge	2-Dec-2002	20	18-Nov-2002	10	10	50.00 %

Table F.1 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 5 *minutes.*

		LWC		Tabu			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
6-Nov-2002	Unique	27-Nov-2002	17	9-Nov-2002	4	13	76.47 %
6-Nov-2002	Contract Calibrate Sand	12-Nov-2002	6	6-Nov-2002	1	5	83.33 %
6-Nov-2002	Contract Calibrate Sand	12-Nov-2002	6	6-Nov-2002	1	5	83.33 %
6-Nov-2002	Contract Calibrate Sand	12-Nov-2002	6	6-Nov-2002	1	5	83.33 %
6-Nov-2002	Contract Calibrate Sand	12-Nov-2002	6	6-Nov-2002	1	5	83.33 %
7-Nov-2002	Contract Veneer Sand	7-Nov-2002	1	9-Nov-2002	3	–2	–200.00 %
7-Nov-2002	Contract Calibrate Sand	7-Nov-2002	1	9-Nov-2002	3	–2	–200.00 %
7-Nov-2002	Components on Edge	28-Nov-2002	17	12-Nov-2002	5	12	70.59 %
7-Nov-2002	Contract Edging	28-Nov-2002	17	7-Nov-2002	1	16	94.12 %
7-Nov-2002	Board Components	27-Nov-2002	16	7-Nov-2002	1	15	93.75 %
7-Nov-2002	Shaker Doors	27-Nov-2002	16	9-Nov-2002	3	13	81.25 %
7-Nov-2002	Contract Cut	8-Nov-2002	2	9-Nov-2002	3	–1	–50.00 %
7-Nov-2002	Contract Cut	15-Nov-2002	8	9-Nov-2002	3	5	62.50 %
7-Nov-2002	Contract Spray Lacquer Top and Base Coat	13-Nov-2002	6	7-Nov-2002	1	5	83.33 %
7-Nov-2002	Shaker Doors	4-Dec-2002	21	9-Nov-2002	3	18	85.71 %
8-Nov-2002	Veneer Over Edge	28-Nov-2002	16	19-Nov-2002	9	7	43.75 %
8-Nov-2002	Veneer Over Edge	28-Nov-2002	16	19-Nov-2002	9	7	43.75 %
8-Nov-2002	Veneer Over Edge	28-Nov-2002	16	19-Nov-2002	9	7	43.75 %
8-Nov-2002	Contract Spray Lacquer Top and Base Coat	21-Nov-2002	11	8-Nov-2002	1	10	90.91 %
8-Nov-2002	Contract Cut	12-Nov-2002	4	8-Nov-2002	1	3	75.00 %
8-Nov-2002	Contract Cut and Spray	15-Nov-2002	7	9-Nov-2002	2	5	71.43 %
8-Nov-2002	Contract Calibrate Sand	14-Nov-2002	6	9-Nov-2002	2	4	66.67 %
8-Nov-2002	Contract Calibrate Sand	14-Nov-2002	6	9-Nov-2002	2	4	66.67 %
8-Nov-2002	Contract Calibrate Sand	14-Nov-2002	6	9-Nov-2002	2	4	66.67 %
8-Nov-2002	Contract Veneer Sand	12-Nov-2002	4	9-Nov-2002	2	2	50.00 %
8-Nov-2002	Contract Veneer Sand	12-Nov-2002	4	9-Nov-2002	2	2	50.00 %
8-Nov-2002	Contract Calibrate Sand	14-Nov-2002	6	9-Nov-2002	2	4	66.67 %
9-Nov-2002	Contract Calibrate and Veneer Sand	12-Nov-2002	3	9-Nov-2002	1	2	66.67 %
11-Nov-2002	Poster Box	27-Nov-2002	13	14-Nov-2002	4	9	69.23 %
11-Nov-2002	Veneer Over Edge	14-Nov-2002	4	19-Nov-2002	7	–3	–75.00 %
11-Nov-2002	Contract Edging	15-Nov-2002	5	11-Nov-2002	1	4	80.00 %
11-Nov-2002	Contract Spray: Top and Base Coat	13-Nov-2002	3	19-Nov-2002	7	–4	–133.33 %
11-Nov-2002	Contract Cut	11-Nov-2002	1	15-Nov-2002	5	–4	–400.00 %
11-Nov-2002	Contract Spray Lacquer Top and Base Coat	11-Nov-2002	1	19-Nov-2002	7	–6	–600.00 %
11-Nov-2002	Contract Spray: Stain Top Coat	14-Nov-2002	4	19-Nov-2002	7	–3	–75.00 %
11-Nov-2002	Contract Calibrate Sand	15-Nov-2002	5	14-Nov-2002	4	1	20.00 %
11-Nov-2002	Contract Calibrate Sand	15-Nov-2002	5	19-Nov-2002	7	–2	–40.00 %
11-Nov-2002	Contract Calibrate Sand	15-Nov-2002	5	11-Nov-2002	1	4	80.00 %
11-Nov-2002	Contract Calibrate Sand	15-Nov-2002	5	14-Nov-2002	4	1	20.00 %
11-Nov-2002	Contract Veneer Sand	15-Nov-2002	5	18-Nov-2002	6	–1	–20.00 %
11-Nov-2002	Contract Veneer Sand	15-Nov-2002	5	14-Nov-2002	4	1	20.00 %
11-Nov-2002	Contract Veneer Sand	15-Nov-2002	5	19-Nov-2002	7	–2	–40.00 %
11-Nov-2002	Contract Calibrate Sand	15-Nov-2002	5	14-Nov-2002	4	1	20.00 %
11-Nov-2002	Contract Calibrate Sand	15-Nov-2002	5	19-Nov-2002	7	–2	–40.00 %
11-Nov-2002	Contract Calibrate Sand	15-Nov-2002	5	19-Nov-2002	7	–2	–40.00 %
11-Nov-2002	Contract Calibrate Sand	15-Nov-2002	5	19-Nov-2002	7	–2	–40.00 %
11-Nov-2002	Contract Veneer Sand	3-Dec-2002	17	14-Nov-2002	4	13	76.47 %
11-Nov-2002	Contract Veneer Sand	3-Dec-2002	17	11-Nov-2002	1	16	94.12 %
11-Nov-2002	Contract Veneer Sand	3-Dec-2002	17	19-Nov-2002	7	10	58.82 %
11-Nov-2002	Board Components	10-Dec-2002	23	19-Nov-2002	7	16	69.57 %
11-Nov-2002	Shaker Doors	10-Dec-2002	23	18-Nov-2002	6	17	73.91 %
11-Nov-2002	Shaker Doors	13-Dec-2002	26	19-Nov-2002	7	19	73.08 %
11-Nov-2002	Board Components	13-Dec-2002	26	19-Nov-2002	7	19	73.08 %
11-Nov-2002	Shaker Doors	13-Dec-2002	26	14-Nov-2002	4	22	84.62 %
11-Nov-2002	Veneer Over Edge	4-Dec-2002	18	19-Nov-2002	7	11	61.11 %
11-Nov-2002	Contract Calibrate and Veneer Sand	14-Nov-2002	4	19-Nov-2002	7	–3	–75.00 %
11-Nov-2002	Poster Box	3-Dec-2002	17	19-Nov-2002	7	10	58.82 %
12-Nov-2002	Contract Calibrate Sand	12-Nov-2002	1	14-Nov-2002	3	–2	–200.00 %
12-Nov-2002	Contract Cut	15-Nov-2002	4	13-Nov-2002	2	2	50.00 %
12-Nov-2002	Contract Veneer Sand	18-Nov-2002	5	19-Nov-2002	6	–1	–20.00 %
12-Nov-2002	Contract Veneer Sand	18-Nov-2002	5	14-Nov-2002	3	2	40.00 %
12-Nov-2002	Contract Veneer Sand	18-Nov-2002	5	18-Nov-2002	5	0	0.00 %
12-Nov-2002	Contract Veneer Sand	18-Nov-2002	5	14-Nov-2002	3	2	40.00 %
12-Nov-2002	Contract Veneer Sand	18-Nov-2002	5	19-Nov-2002	6	–1	–20.00 %
12-Nov-2002	Contract Veneer Sand	18-Nov-2002	5	14-Nov-2002	3	2	40.00 %
12-Nov-2002	Contract Veneer Sand	18-Nov-2002	5	19-Nov-2002	6	–1	–20.00 %

Table F.1 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 5 *minutes.*

		LWC		**Tabu**			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
12-Nov-2002	Contract Veneer Sand	18-Nov-2002	5	19-Nov-2002	6	–1	–20.00 %
12-Nov-2002	Contract Calibrate Sand	18-Nov-2002	5	18-Nov-2002	5	0	0.00 %
12-Nov-2002	Contract Calibrate Sand	18-Nov-2002	5	14-Nov-2002	3	2	40.00 %
12-Nov-2002	Contract Calibrate Sand	18-Nov-2002	5	19-Nov-2002	6	–1	–20.00 %
13-Nov-2002	Contract Plane all Round (PAR)	21-Nov-2002	7	13-Nov-2002	1	6	85.71 %
13-Nov-2002	Contract Cut and Edge	26-Nov-2002	10	15-Nov-2002	3	7	70.00 %
13-Nov-2002	Contract Cut	15-Nov-2002	3	13-Nov-2002	1	2	66.67 %
13-Nov-2002	Contract Spray Lacquer Top and Base Coat	29-Nov-2002	13	14-Nov-2002	2	11	84.62 %
13-Nov-2002	Contract Veneer Sand	19-Nov-2002	5	14-Nov-2002	2	3	60.00 %
13-Nov-2002	Contract Veneer Sand	20-Nov-2002	6	18-Nov-2002	4	2	33.33 %
13-Nov-2002	Contract Veneer Sand	19-Nov-2002	5	14-Nov-2002	2	3	60.00 %
13-Nov-2002	Contract Calibrate Sand	20-Nov-2002	6	19-Nov-2002	5	1	16.67 %
13-Nov-2002	Shaker Doors	17-Dec-2002	26	19-Nov-2002	5	21	80.77 %
14-Nov-2002	Shaker Doors	28-Nov-2002	11	19-Nov-2002	4	7	63.64 %
14-Nov-2002	Contract Spray Lacquer Top and Base Coat	18-Nov-2002	3	19-Nov-2002	4	–1	–33.33 %
14-Nov-2002	Contract Spray Lacquer Top and Base Coat	18-Nov-2002	3	19-Nov-2002	4	–1	–33.33 %
14-Nov-2002	Contract Calibrate Sand	15-Nov-2002	2	19-Nov-2002	4	–2	–100.00 %
14-Nov-2002	Shaker Doors	16-Dec-2002	24	19-Nov-2002	4	20	83.33 %
14-Nov-2002	Shaker Doors	10-Dec-2002	20	18-Nov-2002	3	17	85.00 %
14-Nov-2002	Board Components	10-Dec-2002	20	19-Nov-2002	4	16	80.00 %
14-Nov-2002	Shaker Doors	10-Dec-2002	20	19-Nov-2002	4	16	80.00 %
14-Nov-2002	Board Components	10-Dec-2002	20	19-Nov-2002	4	16	80.00 %
14-Nov-2002	Contract Spray: Base Coat	10-Dec-2002	20	19-Nov-2002	4	16	80.00 %
15-Nov-2002	Unique	27-Nov-2002	9	15-Nov-2002	1	8	88.89 %
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002	5	19-Nov-2002	3	2	40.00 %
15-Nov-2002	Contract Veneer Sand	21-Nov-2002	5	18-Nov-2002	2	3	60.00 %
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002	5	19-Nov-2002	3	2	40.00 %
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002	5	18-Nov-2002	2	3	60.00 %
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002	5	19-Nov-2002	3	2	40.00 %
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002	5	18-Nov-2002	2	3	60.00 %
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002	5	19-Nov-2002	3	2	40.00 %
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002	5	18-Nov-2002	2	3	60.00 %
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002	5	19-Nov-2002	3	2	40.00 %
15-Nov-2002	Contract Calibrate Sand	20-Nov-2002	4	18-Nov-2002	2	2	50.00 %
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002	5	19-Nov-2002	3	2	40.00 %
18-Nov-2002	Contract Calibrate Sand	18-Nov-2002	1	18-Nov-2002	1	0	0.00 %
18-Nov-2002	Contract Calibrate Sand	18-Nov-2002	1	19-Nov-2002	2	–1	–100.00 %
18-Nov-2002	Contract Spray Lacquer Top and Base Coat	22-Nov-2002	5	19-Nov-2002	2	3	60.00 %
18-Nov-2002	Contract Spray Lacquer Top and Base Coat	21-Nov-2002	4	18-Nov-2002	1	3	75.00 %
18-Nov-2002	Contract Cut	20-Nov-2002	3	19-Nov-2002	2	1	33.33 %
18-Nov-2002	Contract Calibrate Sand	26-Nov-2002	7	19-Nov-2002	2	5	71.43 %
18-Nov-2002	Contract Calibrate Sand	26-Nov-2002	7	19-Nov-2002	2	5	71.43 %
18-Nov-2002	Contract Calibrate Sand	21-Nov-2002	4	19-Nov-2002	2	2	50.00 %
18-Nov-2002	Contract Calibrate Sand	21-Nov-2002	4	18-Nov-2002	1	3	75.00 %
18-Nov-2002	Contract Calibrate Sand	22-Nov-2002	5	19-Nov-2002	2	3	60.00 %
18-Nov-2002	Contract Calibrate Sand	22-Nov-2002	5	18-Nov-2002	1	4	80.00 %
18-Nov-2002	Contract Calibrate Sand	22-Nov-2002	5	19-Nov-2002	2	3	60.00 %
18-Nov-2002	Contract Calibrate Sand	22-Nov-2002	5	18-Nov-2002	1	4	80.00 %
18-Nov-2002	Contract Calibrate Sand	22-Nov-2002	5	19-Nov-2002	2	3	60.00 %
18-Nov-2002	Contract Calibrate Sand	22-Nov-2002	5	19-Nov-2002	2	3	60.00 %
18-Nov-2002	Contract Calibrate Sand	21-Nov-2002	4	19-Nov-2002	2	2	50.00 %
18-Nov-2002	Contract Cut and Assembly	29-Jan-2003	52	18-Nov-2002	1	51	98.08 %
18-Nov-2002	Contract Spray Lacquer Top and Base Coat	12-Dec-2002	20	19-Nov-2002	2	18	90.00 %
19-Nov-2002	Contract Spray: Stain Top Coat	27-Nov-2002	7	19-Nov-2002	1	6	85.71 %
19-Nov-2002	Contract Calibrate Sand	20-Nov-2002	2	19-Nov-2002	1	1	50.00 %
19-Nov-2002	Contract Calibrate Sand	19-Nov-2002	1	19-Nov-2002	1	0	0.00 %
19-Nov-2002	Contract Edging	20-Nov-2002	2	19-Nov-2002	1	1	50.00 %
19-Nov-2002	Board Components	20-Nov-2002	2	19-Nov-2002	1	1	50.00 %
19-Nov-2002	Contract Calibrate Sand	27-Nov-2002	7	19-Nov-2002	1	6	85.71 %
19-Nov-2002	Contract Calibrate Sand	25-Nov-2002	5	19-Nov-2002	1	4	80.00 %
19-Nov-2002	Contract Calibrate Sand	25-Nov-2002	5	19-Nov-2002	1	4	80.00 %
19-Nov-2002	Contract Calibrate Sand	25-Nov-2002	5	19-Nov-2002	1	4	80.00 %
19-Nov-2002	Contract Calibrate Sand	19-Nov-2002	1	19-Nov-2002	1	0	0.00 %

Table F.1 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 5 *minutes.*

		LWC		Tabu			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
19-Nov-2002	Veneer Over Edge	13-Dec-2002	20	26-Nov-2002	6	14	70.00 %
19-Nov-2002	Components on Edge	13-Dec-2002	20	25-Nov-2002	5	15	75.00 %
19-Nov-2002	Board Components	13-Dec-2002	20	19-Nov-2002	1	19	95.00 %
19-Nov-2002	Shaker Doors	5-Dec-2002	13	21-Nov-2002	3	10	76.92 %
20-Nov-2002	Board Components	22-Nov-2002	3	21-Nov-2002	2	1	33.33 %
20-Nov-2002	Contract Veneer Sand	21-Nov-2002	2	21-Nov-2002	2	0	0.00 %
20-Nov-2002	Contract Cut	20-Nov-2002	1	22-Nov-2002	3	–2	–200.00 %
20-Nov-2002	Contract Calibrate Sand	27-Nov-2002	6	21-Nov-2002	2	4	66.67 %
20-Nov-2002	Contract Calibrate Sand	28-Nov-2002	7	21-Nov-2002	2	5	71.43 %
20-Nov-2002	Contract Cut and Spray	5-Dec-2002	12	21-Nov-2002	2	10	83.33 %
20-Nov-2002	Shaker Doors	4-Dec-2002	11	21-Nov-2002	2	9	81.82 %
21-Nov-2002	Contract Calibrate Sand	21-Nov-2002	1	21-Nov-2002	1	0	0.00 %
21-Nov-2002	Contract Calibrate Sand	21-Nov-2002	1	21-Nov-2002	1	0	0.00 %
21-Nov-2002	Contract Calibrate Sand	21-Nov-2002	1	21-Nov-2002	1	0	0.00 %
21-Nov-2002	Contract Calibrate Sand	21-Nov-2002	1	21-Nov-2002	1	0	0.00 %
21-Nov-2002	Contract Spray Lacquer Top and Base Coat	27-Nov-2002	5	21-Nov-2002	1	4	80.00 %
21-Nov-2002	Contract Spray: Stain Top Coat	26-Nov-2002	4	21-Nov-2002	1	3	75.00 %
21-Nov-2002	Contract Plane all Round (PAR)	22-Nov-2002	2	21-Nov-2002	1	1	50.00 %
21-Nov-2002	Contract Plane all Round (PAR)	22-Nov-2002	2	21-Nov-2002	1	1	50.00 %
21-Nov-2002	Contract Calibrate Sand	22-Nov-2002	2	21-Nov-2002	1	1	50.00 %
21-Nov-2002	Contract Calibrate Sand	22-Nov-2002	2	21-Nov-2002	1	1	50.00 %
21-Nov-2002	Contract Edging and Calibrate Sand	21-Nov-2002	1	21-Nov-2002	1	0	0.00 %
21-Nov-2002	Veneer Over Edge	17-Dec-2002	20	29-Nov-2002	7	13	65.00 %
21-Nov-2002	Veneer Over Edge	17-Dec-2002	20	29-Nov-2002	7	13	65.00 %
21-Nov-2002	Shaker Doors	5-Dec-2002	11	22-Nov-2002	2	9	81.82 %
21-Nov-2002	Board Components	5-Dec-2002	11	21-Nov-2002	1	10	90.91 %
22-Nov-2002	Contract Edging	22-Nov-2002	1	22-Nov-2002	1	0	0.00 %
22-Nov-2002	Contract Spray: Stain Top Coat	27-Nov-2002	4	22-Nov-2002	1	3	75.00 %
22-Nov-2002	Contract Calibrate Sand	28-Nov-2002	5	22-Nov-2002	1	4	80.00 %
22-Nov-2002	Contract Calibrate Sand	3-Dec-2002	8	22-Nov-2002	1	7	87.50 %
25-Nov-2002	Contract Calibrate Sand	26-Nov-2002	2	26-Nov-2002	2	0	0.00 %
25-Nov-2002	Contract Calibrate Sand	26-Nov-2002	2	26-Nov-2002	2	0	0.00 %
25-Nov-2002	Contract Calibrate Sand	4-Dec-2002	8	26-Nov-2002	2	6	75.00 %
25-Nov-2002	Contract Calibrate Sand	4-Dec-2002	8	25-Nov-2002	1	7	87.50 %
25-Nov-2002	Contract Calibrate Sand	4-Dec-2002	8	26-Nov-2002	2	6	75.00 %
25-Nov-2002	Contract Calibrate Sand	4-Dec-2002	8	26-Nov-2002	2	6	75.00 %
25-Nov-2002	Contract Calibrate Sand	29-Nov-2002	5	26-Nov-2002	2	3	60.00 %
25-Nov-2002	Contract Calibrate Sand	4-Dec-2002	8	25-Nov-2002	1	7	87.50 %
25-Nov-2002	Contract Calibrate Sand	4-Dec-2002	8	26-Nov-2002	2	6	75.00 %
25-Nov-2002	Contract Calibrate Sand	4-Dec-2002	8	25-Nov-2002	1	7	87.50 %
25-Nov-2002	Contract Calibrate Sand	29-Nov-2002	5	26-Nov-2002	2	3	60.00 %
25-Nov-2002	Veneer Over Edge	17-Dec-2002	18	5-Dec-2002	9	9	50.00 %
26-Nov-2002	Contract Cut	26-Nov-2002	1	28-Nov-2002	3	–2	–200.00 %
26-Nov-2002	Contract Calibrate Sand	27-Nov-2002	2	26-Nov-2002	1	1	50.00 %
26-Nov-2002	Contract Plane all Round (PAR)	28-Nov-2002	3	26-Nov-2002	1	2	66.67 %
26-Nov-2002	Contract Plane all Round (PAR)	28-Nov-2002	3	26-Nov-2002	1	2	66.67 %
26-Nov-2002	Contract Calibrate Sand	28-Nov-2002	3	26-Nov-2002	1	2	66.67 %
26-Nov-2002	Board Components	27-Nov-2002	2	26-Nov-2002	1	1	50.00 %
26-Nov-2002	Veneer Over Edge	27-Nov-2002	2	5-Dec-2002	8	–6	–300.00 %
26-Nov-2002	Veneer Over Edge	27-Nov-2002	2	5-Dec-2002	8	–6	–300.00 %
26-Nov-2002	Contract Cut	26-Nov-2002	1	29-Nov-2002	4	–3	–300.00 %
26-Nov-2002	Contract Calibrate Sand	4-Dec-2002	7	26-Nov-2002	1	6	85.71 %
26-Nov-2002	Contract Calibrate Sand	5-Dec-2002	8	26-Nov-2002	1	7	87.50 %
26-Nov-2002	Contract Calibrate Sand	5-Dec-2002	8	26-Nov-2002	1	7	87.50 %
26-Nov-2002	Contract Calibrate Sand	3-Dec-2002	6	26-Nov-2002	1	5	83.33 %
26-Nov-2002	Contract Calibrate Sand	13-Dec-2002	15	26-Nov-2002	1	14	93.33 %
26-Nov-2002	Contract Veneer Sand	4-Dec-2002	7	26-Nov-2002	1	6	85.71 %
26-Nov-2002	Shaker Doors	16-Dec-2002	16	28-Nov-2002	3	13	81.25 %
26-Nov-2002	Veneer Over Edge	16-Dec-2002	16	5-Dec-2002	8	8	50.00 %
26-Nov-2002	Contract Spray Lacquer Top and Base Coat	28-Nov-2002	3	26-Nov-2002	1	2	66.67 %
26-Nov-2002	Contract PAR, Rip and Groove	11-Dec-2002	13	26-Nov-2002	1	12	92.31 %
26-Nov-2002	Contract Plane all Round (PAR)	11-Dec-2002	13	26-Nov-2002	1	12	92.31 %
26-Nov-2002	Veneer Over Edge	10-Dec-2002	12	5-Dec-2002	8	4	33.33 %
26-Nov-2002	Contract Spray: Base Coat and Route	10-Dec-2002	12	26-Nov-2002	1	11	91.67 %
27-Nov-2002	Contract Cut	29-Nov-2002	3	29-Nov-2002	3	0	0.00 %
27-Nov-2002	Contract Calibrate Sand	29-Nov-2002	3	29-Nov-2002	3	0	0.00 %
27-Nov-2002	Contract Calibrate Sand	29-Nov-2002	3	29-Nov-2002	3	0	0.00 %

Table F.1 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of 5 minutes.*

		LWC		Tabu			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improvement**	**%Improvement**
27-Nov-2002	Contract Calibrate Sand	27-Nov-2002	1	29-Nov-2002	3	–2	–200.00 %
27-Nov-2002	Contract Calibrate Sand	27-Nov-2002	1	29-Nov-2002	3	–2	–200.00 %
27-Nov-2002	Shaker Doors	17-Dec-2002	16	29-Nov-2002	3	13	81.25 %
27-Nov-2002	Contract Veneer Sand	4-Dec-2002	6	29-Nov-2002	3	3	50.00 %
27-Nov-2002	Contract Calibrate Sand	3-Dec-2002	5	29-Nov-2002	3	2	40.00 %
27-Nov-2002	Contract Calibrate Sand	3-Dec-2002	5	29-Nov-2002	3	2	40.00 %
27-Nov-2002	Veneer Over Edge	13-Dec-2002	14	4-Dec-2002	6	8	57.14 %
27-Nov-2002	Contract Edging	6-Dec-2002	8	27-Nov-2002	1	7	87.50 %
27-Nov-2002	Contract Cut	6-Dec-2002	8	29-Nov-2002	3	5	62.50 %
28-Nov-2002	Contract Calibrate Sand	6-Dec-2002	7	29-Nov-2002	2	5	71.43 %
28-Nov-2002	Contract Calibrate Sand	6-Dec-2002	7	29-Nov-2002	2	5	71.43 %
28-Nov-2002	Contract Calibrate Sand	6-Dec-2002	7	29-Nov-2002	2	5	71.43 %
28-Nov-2002	Contract Calibrate Sand	4-Dec-2002	5	29-Nov-2002	2	3	60.00 %
29-Nov-2002	Contract Calibrate Sand	29-Nov-2002	1	29-Nov-2002	1	0	0.00 %
29-Nov-2002	Contract Calibrate Sand	6-Dec-2002	6	29-Nov-2002	1	5	83.33 %
29-Nov-2002	Contract Veneer Sand	5-Dec-2002	5	29-Nov-2002	1	4	80.00 %
29-Nov-2002	Contract Veneer Sand	4-Dec-2002	4	29-Nov-2002	1	3	75.00 %
29-Nov-2002	Contract Calibrate Sand	3-Dec-2002	3	29-Nov-2002	1	2	66.67 %
29-Nov-2002	Veneer Over Edge	11-Dec-2002	10	5-Dec-2002	5	5	50.00 %
29-Nov-2002	Board Components	11-Dec-2002	10	29-Nov-2002	1	9	90.00 %
29-Nov-2002	Contract Cut and Edge	3-Dec-2002	3	29-Nov-2002	1	2	66.67 %
29-Nov-2002	Contract Cut	3-Dec-2002	3	4-Dec-2002	4	–1	–33.33 %
2-Dec-2002	Veneer Over Edge	11-Dec-2002	9	9-Dec-2002	7	2	22.22 %
2-Dec-2002	Contract Veneer Sand	13-Dec-2002	11	5-Dec-2002	4	7	63.64 %
2-Dec-2002	Contract Calibrate Sand	5-Dec-2002	4	5-Dec-2002	4	0	0.00 %
2-Dec-2002	Contract Calibrate Sand	3-Dec-2002	2	4-Dec-2002	3	–1	–50.00 %
2-Dec-2002	Veneer Over Edge	12-Dec-2002	10	6-Dec-2002	5	5	50.00 %
2-Dec-2002	Contract Edging	10-Dec-2002	8	2-Dec-2002	1	7	87.50 %
2-Dec-2002	Contract Calibrate and Veneer Sand	3-Dec-2002	2	5-Dec-2002	4	–2	–100.00 %
2-Dec-2002	Contract Calibrate Sand	3-Dec-2002	2	5-Dec-2002	4	–2	–100.00 %
3-Dec-2002	Contract Veneer Sand	13-Dec-2002	10	5-Dec-2002	3	7	70.00 %
3-Dec-2002	Contract Calibrate Sand	13-Dec-2002	10	5-Dec-2002	3	7	70.00 %
3-Dec-2002	Contract Calibrate Sand	11-Dec-2002	8	5-Dec-2002	3	5	62.50 %
3-Dec-2002	Contract Calibrate Sand	11-Dec-2002	8	5-Dec-2002	3	5	62.50 %
3-Dec-2002	Contract Cut and Calibrate Sand	10-Dec-2002	7	5-Dec-2002	3	4	57.14 %
3-Dec-2002	Contract Calibrate Sand	10-Dec-2002	7	5-Dec-2002	3	4	57.14 %
3-Dec-2002	Contract Calibrate Sand	10-Dec-2002	7	5-Dec-2002	3	4	57.14 %
3-Dec-2002	Contract Calibrate Sand	5-Dec-2002	3	5-Dec-2002	3	0	0.00 %
3-Dec-2002	Contract PAR and Edging	5-Dec-2002	3	3-Dec-2002	1	2	66.67 %
3-Dec-2002	Contract Cut	3-Dec-2002	1	4-Dec-2002	2	–1	–100.00 %
3-Dec-2002	Contract Cut and Edge	3-Dec-2002	1	4-Dec-2002	2	–1	–100.00 %
4-Dec-2002	Contract Calibrate Sand	12-Dec-2002	8	5-Dec-2002	2	6	75.00 %
4-Dec-2002	Contract Calibrate Sand	10-Dec-2002	6	5-Dec-2002	2	4	66.67 %
4-Dec-2002	Contract Calibrate Sand	9-Dec-2002	5	5-Dec-2002	2	3	60.00 %
4-Dec-2002	Contract Plane all Round(PAR)	4-Dec-2002	1	4-Dec-2002	1	0	0.00 %
5-Dec-2002	Shaker Doors	17-Dec-2002	10	6-Dec-2002	2	8	80.00 %
5-Dec-2002	Contract Calibrate Sand	12-Dec-2002	7	5-Dec-2002	1	6	85.71 %
5-Dec-2002	Contract Calibrate Sand	11-Dec-2002	6	5-Dec-2002	1	5	83.33 %
5-Dec-2002	Contract Calibrate Sand	10-Dec-2002	5	5-Dec-2002	1	4	80.00 %
5-Dec-2002	Contract Calibrate Sand	10-Dec-2002	5	5-Dec-2002	1	4	80.00 %
5-Dec-2002	Contract Calibrate Sand	10-Dec-2002	5	5-Dec-2002	1	4	80.00 %
5-Dec-2002	Contract Calibrate Sand	10-Dec-2002	5	5-Dec-2002	1	4	80.00 %
6-Dec-2002	Contract Calibrate Sand	11-Dec-2002	5	6-Dec-2002	1	4	80.00 %
6-Dec-2002	Contract Calibrate Sand	11-Dec-2002	5	6-Dec-2002	1	4	80.00 %
6-Dec-2002	Contract Calibrate Sand	10-Dec-2002	4	9-Dec-2002	3	1	25.00 %
6-Dec-2002	Shaker Doors	13-Dec-2002	7	9-Dec-2002	3	4	57.14 %
6-Dec-2002	Veneer Over Edge	13-Dec-2002	7	11-Dec-2002	5	2	28.57 %
6-Dec-2002	Board Components	13-Dec-2002	7	9-Dec-2002	3	4	57.14 %
6-Dec-2002	Veneer Over Edge	13-Dec-2002	7	11-Dec-2002	5	2	28.57 %
6-Dec-2002	Contract Calibrate Sand	11-Dec-2002	5	6-Dec-2002	1	4	80.00 %
6-Dec-2002	Contract Calibrate and Veneer Sand	6-Dec-2002	1	6-Dec-2002	1	0	0.00 %
8-Dec-2002	Shaker Doors	12-Dec-2002	5	9-Dec-2002	2	3	60.00 %
9-Dec-2002	Veneer Over Edge	17-Dec-2002	7	13-Dec-2002	5	2	28.57 %
9-Dec-2002	Components on Edge	17-Dec-2002	7	13-Dec-2002	5	2	28.57 %
9-Dec-2002	Veneer Over Edge	17-Dec-2002	7	13-Dec-2002	5	2	28.57 %
9-Dec-2002	Components on Edge	17-Dec-2002	7	13-Dec-2002	5	2	28.57 %
9-Dec-2002	Contract Calibrate and Veneer Sand	17-Dec-2002	7	9-Dec-2002	1	6	85.71 %
9-Dec-2002	Contract Veneer Sand	13-Dec-2002	5	9-Dec-2002	1	4	80.00 %
9-Dec-2002	Contract Veneer Sand	13-Dec-2002	5	9-Dec-2002	1	4	80.00 %

Table F.1 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 5 *minutes.*

Start Date	Job Type	LWC		Tabu		Improve–ment	%Improve–ment
		Dispatch	Net Flow Time	Dispatch	Net Flow Time		
9-Dec-2002	Contract Calibrate Sand	13-Dec-2002	5	9-Dec-2002	1	4	80.00 %
9-Dec-2002	Contract Calibrate Sand	13-Dec-2002	5	9-Dec-2002	1	4	80.00 %
9-Dec-2002	Contract Calibrate Sand	11-Dec-2002	3	9-Dec-2002	1	2	66.67 %
9-Dec-2002	Contract PAR, Calibrate and Veneer Sand	10-Dec-2002	2	9-Dec-2002	1	1	50.00 %
9-Dec-2002	Contract Calibrate and Veneer Sand	9-Dec-2002	1	9-Dec-2002	1	0	0.00 %
10-Dec-2002	Contract Spray: Top and Base Coat and Edging	17-Dec-2002	6	10-Dec-2002	1	5	83.33 %
10-Dec-2002	Shaker Doors	17-Dec-2002	6	11-Dec-2002	2	4	66.67 %
10-Dec-2002	Contract Calibrate Sand	12-Dec-2002	3	10-Dec-2002	1	2	66.67 %
10-Dec-2002	Contract Calibrate Sand	12-Dec-2002	3	10-Dec-2002	1	2	66.67 %
10-Dec-2002	Contract Calibrate Sand	12-Dec-2002	3	10-Dec-2002	1	2	66.67 %
10-Dec-2002	Contract Calibrate Sand	12-Dec-2002	3	10-Dec-2002	1	2	66.67 %
10-Dec-2002	Contract Calibrate Sand	19-Dec-2002	8	10-Dec-2002	1	7	87.50 %
10-Dec-2002	Board Components	13-Dec-2002	4	10-Dec-2002	1	3	75.00 %
10-Dec-2002	Veneer Over Edge	11-Dec-2002	2	16-Dec-2002	5	–3	–150.00 %
10-Dec-2002	Contract Groove	10-Dec-2002	1	10-Dec-2002	1	0	0.00 %
10-Dec-2002	Contract Calibrate and Veneer Sand	10-Dec-2002	1	10-Dec-2002	1	0	0.00 %
10-Dec-2002	Contract Calibrate and Veneer Sand	10-Dec-2002	1	10-Dec-2002	1	0	0.00 %
11-Dec-2002	Contract Calibrate Sand	13-Dec-2002	3	11-Dec-2002	1	2	66.67 %
11-Dec-2002	Contract Cut	18-Dec-2002	6	11-Dec-2002	1	5	83.33 %
11-Dec-2002	Shaker Doors	17-Dec-2002	5	13-Dec-2002	3	2	40.00 %
11-Dec-2002	Contract Calibrate Sand	11-Dec-2002	1	11-Dec-2002	1	0	0.00 %
11-Dec-2002	Shaker Doors	19-Dec-2002	7	13-Dec-2002	3	4	57.14 %
11-Dec-2002	Board Components	19-Dec-2002	7	11-Dec-2002	1	6	85.71 %
11-Dec-2002	Shaker Doors	19-Dec-2002	7	13-Dec-2002	3	4	57.14 %
12-Dec-2002	Contract Edging	12-Dec-2002	1	12-Dec-2002	1	0	0.00 %
12-Dec-2002	Contract Cut	19-Dec-2002	6	13-Dec-2002	2	4	66.67 %
12-Dec-2002	Contract Veneer Sand	13-Dec-2002	2	13-Dec-2002	2	0	0.00 %
13-Dec-2002	Contract Calibrate Sand	18-Dec-2002	4	13-Dec-2002	1	3	75.00 %
13-Dec-2002	Contract Calibrate Sand	19-Dec-2002	5	13-Dec-2002	1	4	80.00 %
13-Dec-2002	Contract Calibrate and Veneer Sand	16-Dec-2002	2	13-Dec-2002	1	1	50.00 %
13-Dec-2002	Contract Calibrate Sand	18-Dec-2002	4	13-Dec-2002	1	3	75.00 %
16-Dec-2002	Contract Calibrate Sand	18-Dec-2002	3	16-Dec-2002	1	2	66.67 %
16-Dec-2002	Contract Calibrate Sand	17-Dec-2002	2	16-Dec-2002	1	1	50.00 %
17-Dec-2002	Contract Veneer Sand	17-Dec-2002	1	17-Dec-2002	1	0	0.00 %
17-Dec-2002	Contract Cut	18-Dec-2002	2	17-Dec-2002	1	1	50.00 %

Table F.1 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 5 *minutes.*

F.2 Ramp cost of 20 minutes

The best objective function value obtained with the assumption of a ramp cost of 20 minutes was obtained during a run with a tabu list length of 15 and a backtrack list length of 5. This run exhibited a 59.46% improvement on the actual (manual) scheduling done at LWC.

Start Date	Job Type	LWC		Tabu		Improve–ment	%Improve–ment
		Dispatch	Net Flow Time	Dispatch	Net Flow Time		
7-Jun-2002	Contract Cut and Route	7-Jun-2002	1	10-Jun-2002	1	0	0.00 %
10-Jun-2002	Contract Cut	28-Aug-2002	62	13-Jun-2002	1	61	98.39 %
10-Jun-2002	Contract Calibrate Sand	28-Aug-2002	62	14-Jun-2002	1	61	98.39 %

Table F.2: *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 20 *minutes.*

		LWC		**Tabu**			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
12-Jun-2002	Shaker Doors	2-Jul-2002	16	28-Jun-2002	2	14	87.50 %
12-Jun-2002	Shaker Doors	2-Jul-2002	16	25-Jun-2002	3	13	81.25 %
21-Jun-2002	Veneer Over Edge	10-Jul-2002	15	25-Jun-2002	6	9	60.00 %
25-Jun-2002	Contract Calibrate Sand	17-Jul-2002	18	25-Jun-2002	1	17	94.44 %
25-Jun-2002	Contract Veneer Sand	3-Jul-2002	8	25-Jun-2002	1	7	87.50 %
25-Jun-2002	Contract Veneer Sand	3-Jul-2002	8	28-Jun-2002	1	7	87.50 %
25-Jun-2002	Contract Calibrate Sand	2-Jul-2002	7	26-Jun-2002	1	6	85.71 %
26-Jun-2002	Shaker Doors	2-Jul-2002	6	26-Jun-2002	3	3	50.00 %
26-Jun-2002	Contract Veneer Sand	4-Jul-2002	8	26-Jun-2002	1	7	87.50 %
26-Jun-2002	Contract Calibrate Sand	3-Jul-2002	7	26-Jun-2002	1	6	85.71 %
26-Jun-2002	Contract Calibrate Sand	3-Jul-2002	7	27-Jun-2002	1	6	85.71 %
26-Jun-2002	Contract Veneer Sand	3-Jul-2002	7	28-Jun-2002	1	6	85.71 %
27-Jun-2002	Contract Plane all Round(PAR)	1-Jul-2002	4	27-Jun-2002	1	3	75.00 %
27-Jun-2002	Contract Spray: Top and Base Coat, Calibrate and Veneer Sand	1-Jul-2002	4	2-Jul-2002	2	2	50.00 %
27-Jun-2002	Contract Cut	17-Jul-2002	16	28-Jun-2002	1	15	93.75 %
27-Jun-2002	Veneer Over Edge	23-Jul-2002	21	28-Jun-2002	5	16	76.19 %
27-Jun-2002	Contract Veneer Sand	3-Jul-2002	6	28-Jun-2002	2	4	66.67 %
27-Jun-2002	Contract Calibrate Sand	3-Jul-2002	6	28-Jun-2002	2	4	66.67 %
27-Jun-2002	Contract Veneer Sand	3-Jul-2002	6	5-Jul-2002	2	4	66.67 %
28-Jun-2002	Contract Calibrate Sand	3-Jul-2002	5	4-Jul-2002	1	4	80.00 %
29-Jun-2002	Veneer Over Edge	3-Jul-2002	4	12-Jul-2002	6	-2	-50.00 %
1-Jul-2002	Shaker Doors	5-Jul-2002	5	1-Jul-2002	4	1	20.00 %
1-Jul-2002	Veneer Over Edge	23-Jul-2002	18	2-Jul-2002	10	8	44.44 %
1-Jul-2002	Contract Calibrate Sand	3-Jul-2002	3	12-Jul-2002	1	2	66.67 %
2-Jul-2002	Contract Spray: Top and Base Coat	5-Jul-2002	4	12-Jul-2002	1	3	75.00 %
2-Jul-2002	Veneer Over Edge	22-Jul-2002	16	12-Jul-2002	9	7	43.75 %
2-Jul-2002	Veneer Over Edge	23-Jul-2002	17	12-Jul-2002	9	8	47.06 %
2-Jul-2002	Veneer Over Edge	23-Jul-2002	17	10-Jul-2002	9	8	47.06 %
2-Jul-2002	Veneer Over Edge	17-Jul-2002	12	12-Jul-2002	9	3	25.00 %
2-Jul-2002	Veneer Over Edge	19-Jul-2002	14	12-Jul-2002	7	7	50.00 %
2-Jul-2002	Veneer Over Edge	17-Jul-2002	12	4-Jul-2002	9	3	25.00 %
2-Jul-2002	Veneer Over Edge	12-Jul-2002	9	4-Jul-2002	9	0	0.00 %
2-Jul-2002	Contract Veneer Sand	10-Jul-2002	7	4-Jul-2002	3	4	57.14 %
2-Jul-2002	Contract Veneer Sand	10-Jul-2002	7	4-Jul-2002	3	4	57.14 %
2-Jul-2002	Contract Calibrate Sand	3-Jul-2002	2	4-Jul-2002	3	-1	-50.00 %
2-Jul-2002	Contract Calibrate Sand	3-Jul-2002	2	4-Jul-2002	3	-1	-50.00 %
3-Jul-2002	Contract Calibrate Sand	12-Jul-2002	8	4-Jul-2002	2	6	75.00 %
3-Jul-2002	Contract Calibrate Sand	10-Jul-2002	6	4-Jul-2002	2	4	66.67 %
3-Jul-2002	Contract Calibrate Sand	3-Jul-2002	1	4-Jul-2002	2	-1	-100.00 %
3-Jul-2002	Contract Veneer Sand	3-Jul-2002	1	4-Jul-2002	2	-1	-100.00 %
4-Jul-2002	Contract Calibrate Sand	8-Jul-2002	3	10-Jul-2002	1	2	66.67 %
4-Jul-2002	Contract Calibrate Sand	10-Jul-2002	5	4-Jul-2002	1	4	80.00 %
4-Jul-2002	Veneer Over Edge	18-Jul-2002	11	12-Jul-2002	5	6	54.55 %
4-Jul-2002	Contract Cut and Edge	18-Jul-2002	11	12-Jul-2002	1	10	90.91 %
5-Jul-2002	Veneer Over Edge	8-Jul-2002	2	15-Jul-2002	6	-4	-200.00 %
5-Jul-2002	Veneer Over Edge	23-Jul-2002	14	5-Jul-2002	6	8	57.14 %
5-Jul-2002	Contract Cut	23-Jul-2002	14	5-Jul-2002	7	7	50.00 %
5-Jul-2002	Contract Calibrate and Veneer Sand	5-Jul-2002	1	5-Jul-2002	1	0	0.00 %
5-Jul-2002	Contract Calibrate and Veneer Sand	5-Jul-2002	1	5-Jul-2002	1	0	0.00 %
5-Jul-2002	Contract Calibrate Sand	5-Jul-2002	1	12-Jul-2002	1	0	0.00 %
5-Jul-2002	Contract Edging	11-Jul-2002	5	12-Jul-2002	1	4	80.00 %
5-Jul-2002	Veneer Over Edge	26-Jul-2002	17	12-Jul-2002	6	11	64.71 %
5-Jul-2002	Contract Cut	5-Jul-2002	1	5-Jul-2002	6	-5	-500.00 %
5-Jul-2002	Shaker Doors	26-Jul-2002	17	5-Jul-2002	6	11	64.71 %
5-Jul-2002	Contract Veneer Sand	8-Jul-2002	2	5-Jul-2002	1	1	50.00 %
5-Jul-2002	Contract Calibrate Sand	18-Jul-2002	10	5-Jul-2002	1	9	90.00 %
5-Jul-2002	Contract Veneer Sand	18-Jul-2002	10	5-Jul-2002	1	9	90.00 %
5-Jul-2002	Contract Veneer Sand	18-Jul-2002	10	5-Jul-2002	1	9	90.00 %
5-Jul-2002	Contract Veneer Sand	10-Jul-2002	4	5-Jul-2002	1	3	75.00 %
5-Jul-2002	Contract Calibrate Sand	10-Jul-2002	4	5-Jul-2002	1	3	75.00 %
5-Jul-2002	Contract Calibrate Sand	10-Jul-2002	4	5-Jul-2002	1	3	75.00 %
5-Jul-2002	Contract Calibrate Sand	8-Jul-2002	2	12-Jul-2002	1	1	50.00 %
5-Jul-2002	Contract Calibrate Sand	8-Jul-2002	2	12-Jul-2002	1	1	50.00 %
8-Jul-2002	Contract Cut	30-Jul-2002	19	10-Jul-2002	5	14	73.68 %
8-Jul-2002	Contract Veneer Sand	8-Jul-2002	1	10-Jul-2002	5	-4	-400.00 %
8-Jul-2002	Contract Cut and Edge	9-Jul-2002	2	12-Jul-2002	3	-1	-50.00 %
8-Jul-2002	Contract Cut	10-Jul-2002	3	12-Jul-2002	3	0	0.00 %

Table F.2 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 20 *minutes.*

		LWC		Tabu			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
8-Jul-2002	Contract Calibrate and Veneer Sand	8-Jul-2002	1	10-Jul-2002	5	-4	-400.00 %
8-Jul-2002	Contract Calibrate and Veneer Sand	8-Jul-2002	1	10-Jul-2002	5	-4	-400.00 %
8-Jul-2002	Contract Calibrate Sand	8-Jul-2002	1	12-Jul-2002	3	-2	-200.00 %
8-Jul-2002	Contract Veneer Sand	26-Jul-2002	16	12-Jul-2002	3	13	81.25 %
8-Jul-2002	Contract Veneer Sand	16-Jul-2002	7	12-Jul-2002	5	2	28.57 %
8-Jul-2002	Contract Veneer Sand	12-Jul-2002	5	12-Jul-2002	5	0	0.00 %
8-Jul-2002	Contract Calibrate Sand	10-Jul-2002	3	12-Jul-2002	5	-2	-66.67 %
8-Jul-2002	Contract Calibrate Sand	10-Jul-2002	3	12-Jul-2002	5	-2	-66.67 %
8-Jul-2002	Contract Calibrate Sand	10-Jul-2002	3	12-Jul-2002	5	-2	-66.67 %
8-Jul-2002	Contract Calibrate Sand	10-Jul-2002	3	12-Jul-2002	5	-2	-66.67 %
9-Jul-2002	Contract Spray Lacquer Top and Base Coat	10-Jul-2002	2	12-Jul-2002	4	-2	-100.00 %
9-Jul-2002	Contract Calibrate Sand	10-Jul-2002	2	10-Jul-2002	4	-2	-100.00 %
9-Jul-2002	Contract Calibrate Sand	10-Jul-2002	2	12-Jul-2002	4	-2	-100.00 %
10-Jul-2002	Contract Cut	11-Jul-2002	2	11-Jul-2002	1	1	50.00 %
10-Jul-2002	Contract Calibrate Sand	18-Jul-2002	7	12-Jul-2002	3	4	57.14 %
10-Jul-2002	Contract Calibrate Sand	12-Jul-2002	3	12-Jul-2002	2	1	33.33 %
10-Jul-2002	Unique	5-Aug-2002	21	12-Jul-2002	3	18	85.71 %
11-Jul-2002	Contract Calibrate Sand	12-Jul-2002	2	12-Jul-2002	2	0	0.00 %
11-Jul-2002	Contract Veneer Sand	12-Jul-2002	2	12-Jul-2002	2	0	0.00 %
11-Jul-2002	Contract Cut	12-Jul-2002	2	16-Jul-2002	2	0	0.00 %
11-Jul-2002	Contract Veneer Sand	12-Jul-2002	2	12-Jul-2002	2	0	0.00 %
11-Jul-2002	Contract Cut	12-Jul-2002	2	12-Jul-2002	4	-2	-100.00 %
11-Jul-2002	Contract Spray Lacquer Top and Base Coat	17-Jul-2002	5	17-Jul-2002	2	3	60.00 %
11-Jul-2002	Contract Spray: Stain Top Coat	17-Jul-2002	5	17-Jul-2002	2	3	60.00 %
11-Jul-2002	Veneer Over Edge	18-Jul-2002	6	11-Jul-2002	5	1	16.67 %
11-Jul-2002	Veneer Over Edge	23-Jul-2002	10	12-Jul-2002	5	5	50.00 %
11-Jul-2002	Contract Cut	11-Jul-2002	1	12-Jul-2002	1	0	0.00 %
11-Jul-2002	Contract Veneer Sand	11-Jul-2002	1	12-Jul-2002	2	-1	-100.00 %
11-Jul-2002	Contract Calibrate and Veneer Sand	11-Jul-2002	1	12-Jul-2002	2	-1	-100.00 %
11-Jul-2002	Contract Calibrate and Veneer Sand	11-Jul-2002	1	12-Jul-2002	2	-1	-100.00 %
11-Jul-2002	Contract Calibrate Sand	16-Jul-2002	4	12-Jul-2002	2	2	50.00 %
11-Jul-2002	Contract Calibrate Sand	16-Jul-2002	4	12-Jul-2002	2	2	50.00 %
11-Jul-2002	Contract Calibrate Sand	16-Jul-2002	4	12-Jul-2002	2	2	50.00 %
12-Jul-2002	Contract Cut and Edge	12-Jul-2002	1	12-Jul-2002	1	0	0.00 %
12-Jul-2002	Contract Calibrate Sand	22-Jul-2002	8	12-Jul-2002	1	7	87.50 %
12-Jul-2002	Contract Calibrate Sand	22-Jul-2002	8	12-Jul-2002	1	7	87.50 %
12-Jul-2002	Contract Calibrate Sand	18-Jul-2002	5	12-Jul-2002	1	4	80.00 %
12-Jul-2002	Contract Calibrate Sand	18-Jul-2002	5	16-Jul-2002	1	4	80.00 %
12-Jul-2002	Contract Calibrate Sand	12-Jul-2002	1	20-Jul-2002	1	0	0.00 %
15-Jul-2002	Contract Cut	15-Jul-2002	1	15-Jul-2002	2	-1	-100.00 %
15-Jul-2002	Veneer Over Edge	23-Jul-2002	8	15-Jul-2002	6	2	25.00 %
15-Jul-2002	Contract Cut, Edge and Groove	24-Jul-2002	9	16-Jul-2002	1	8	88.89 %
15-Jul-2002	Contract Veneer Sand	24-Jul-2002	9	15-Jul-2002	1	8	88.89 %
15-Jul-2002	Contract Cut	16-Jul-2002	2	15-Jul-2002	2	0	0.00 %
15-Jul-2002	Contract Calibrate Sand	22-Jul-2002	7	15-Jul-2002	1	6	85.71 %
15-Jul-2002	Contract Calibrate Sand	22-Jul-2002	7	15-Jul-2002	1	6	85.71 %
15-Jul-2002	Contract Veneer Sand	23-Jul-2002	8	15-Jul-2002	1	7	87.50 %
15-Jul-2002	Contract Veneer Sand	23-Jul-2002	8	15-Jul-2002	1	7	87.50 %
15-Jul-2002	Contract Calibrate Sand	19-Jul-2002	5	15-Jul-2002	1	4	80.00 %
15-Jul-2002	Contract Veneer Sand	19-Jul-2002	5	15-Jul-2002	1	4	80.00 %
15-Jul-2002	Contract Veneer Sand	18-Jul-2002	4	15-Jul-2002	1	3	75.00 %
15-Jul-2002	Contract Calibrate Sand	15-Jul-2002	1	15-Jul-2002	1	0	0.00 %
15-Jul-2002	Contract Calibrate Sand	16-Jul-2002	2	15-Jul-2002	1	1	50.00 %
15-Jul-2002	Contract Calibrate Sand	16-Jul-2002	2	16-Jul-2002	1	1	50.00 %
15-Jul-2002	Contract Calibrate Sand	16-Jul-2002	2	16-Jul-2002	1	1	50.00 %
16-Jul-2002	Contract Calibrate and Veneer Sand	16-Jul-2002	1	17-Jul-2002	1	0	0.00 %
16-Jul-2002	Contract Calibrate Sand	16-Jul-2002	1	17-Jul-2002	1	0	0.00 %
17-Jul-2002	Contract Calibrate and Veneer Sand	18-Jul-2002	2	17-Jul-2002	1	1	50.00 %
17-Jul-2002	Contract Veneer Sand	23-Jul-2002	6	17-Jul-2002	1	5	83.33 %
17-Jul-2002	Contract Calibrate Sand	19-Jul-2002	3	17-Jul-2002	1	2	66.67 %
17-Jul-2002	Contract Calibrate Sand	19-Jul-2002	3	24-Jul-2002	1	2	66.67 %
17-Jul-2002	Contract Calibrate Sand	6-Aug-2002	17	25-Jul-2002	1	16	94.12 %
17-Jul-2002	Veneer Over Edge	12-Aug-2002	21	24-Jul-2002	7	14	66.67 %
17-Jul-2002	Veneer Over Edge	8-Aug-2002	19	26-Jul-2002	8	11	57.89 %
17-Jul-2002	Veneer Over Edge	8-Aug-2002	19	18-Jul-2002	7	12	63.16 %
17-Jul-2002	Veneer Over Edge	16-Sep-2002	48	18-Jul-2002	9	39	81.25 %

Table F.2 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 20 *minutes.*

		LWC		Tabu			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
18-Jul-2002	Contract Calibrate and Veneer Sand	24-Jul-2002	6	26-Jul-2002	1	5	83.33 %
18-Jul-2002	Contract Veneer Sand	19-Jul-2002	2	18-Jul-2002	1	1	50.00 %
18-Jul-2002	Veneer Over Edge	23-Jul-2002	5	18-Jul-2002	8	-3	-60.00 %
18-Jul-2002	Contract Veneer Sand	30-Jul-2002	11	18-Jul-2002	1	10	90.91 %
18-Jul-2002	Contract Veneer Sand	30-Jul-2002	11	18-Jul-2002	1	10	90.91 %
18-Jul-2002	Contract Veneer Sand	29-Jul-2002	10	18-Jul-2002	1	9	90.00 %
18-Jul-2002	Contract Veneer Sand	23-Jul-2002	5	19-Jul-2002	1	4	80.00 %
18-Jul-2002	Contract Calibrate Sand	19-Jul-2002	2	19-Jul-2002	1	1	50.00 %
18-Jul-2002	Shaker Doors	18-Jul-2002	1	20-Jul-2002	2	-1	-100.00 %
19-Jul-2002	Contract Veneer Sand	30-Jul-2002	10	19-Jul-2002	1	9	90.00 %
19-Jul-2002	Contract Veneer Sand	30-Jul-2002	10	20-Jul-2002	2	8	80.00 %
19-Jul-2002	Contract Calibrate Sand	29-Jul-2002	9	19-Jul-2002	1	8	88.89 %
19-Jul-2002	Contract Veneer Sand	29-Jul-2002	9	19-Jul-2002	2	7	77.78 %
19-Jul-2002	Contract Veneer Sand	26-Jul-2002	7	19-Jul-2002	1	6	85.71 %
19-Jul-2002	Contract Veneer Sand	26-Jul-2002	7	20-Jul-2002	1	6	85.71 %
19-Jul-2002	Contract Calibrate Sand	23-Jul-2002	4	19-Jul-2002	1	3	75.00 %
19-Jul-2002	Contract Calibrate Sand	22-Jul-2002	3	20-Jul-2002	2	1	33.33 %
19-Jul-2002	Contract Calibrate Sand	22-Jul-2002	3	20-Jul-2002	1	2	66.67 %
19-Jul-2002	Contract Calibrate Sand	22-Jul-2002	3	20-Jul-2002	2	1	33.33 %
19-Jul-2002	Contract Calibrate Sand	22-Jul-2002	3	19-Jul-2002	2	1	33.33 %
19-Jul-2002	Contract Calibrate Sand	22-Jul-2002	3	20-Jul-2002	2	1	33.33 %
19-Jul-2002	Contract Calibrate Sand	19-Jul-2002	1	20-Jul-2002	1	0	0.00 %
19-Jul-2002	Contract Calibrate Sand	2-Aug-2002	13	23-Jul-2002	2	11	84.62 %
20-Jul-2002	Contract Veneer Sand	2-Aug-2002	12	26-Jul-2002	1	11	91.67 %
22-Jul-2002	Contract Cut	24-Jul-2002	3	26-Jul-2002	2	1	33.33 %
22-Jul-2002	Contract Calibrate and Veneer Sand	22-Jul-2002	1	26-Jul-2002	5	-4	-400.00 %
22-Jul-2002	Contract Calibrate and Veneer Sand	22-Jul-2002	1	26-Jul-2002	5	-4	-400.00 %
22-Jul-2002	Contract Calibrate and Veneer Sand	22-Jul-2002	1	26-Jul-2002	5	-4	-400.00 %
22-Jul-2002	Contract Veneer Sand	30-Jul-2002	8	26-Jul-2002	5	3	37.50 %
22-Jul-2002	Contract Veneer Sand	30-Jul-2002	8	26-Jul-2002	5	3	37.50 %
22-Jul-2002	Contract Calibrate Sand	25-Jul-2002	4	25-Jul-2002	5	-1	-25.00 %
22-Jul-2002	Contract Calibrate Sand	23-Jul-2002	2	24-Jul-2002	5	-3	-150.00 %
22-Jul-2002	Contract Calibrate Sand	23-Jul-2002	2	30-Jul-2002	4	-2	-100.00 %
22-Jul-2002	Contract Calibrate Sand	22-Jul-2002	1	23-Jul-2002	3	-2	-200.00 %
22-Jul-2002	Veneer Over Edge	8-Aug-2002	15	23-Jul-2002	8	7	46.67 %
23-Jul-2002	Contract Cut	25-Jul-2002	3	23-Jul-2002	1	2	66.67 %
23-Jul-2002	Contract Edging	26-Jul-2002	4	25-Jul-2002	1	3	75.00 %
23-Jul-2002	Contract Edging	23-Jul-2002	1	26-Jul-2002	1	0	0.00 %
23-Jul-2002	Contract Spray: Stain Top Coat	24-Jul-2002	2	25-Jul-2002	3	-1	-50.00 %
23-Jul-2002	Contract Calibrate Sand	26-Jul-2002	4	25-Jul-2002	4	0	0.00 %
23-Jul-2002	Contract Calibrate Sand	25-Jul-2002	3	25-Jul-2002	3	0	0.00 %
23-Jul-2002	Contract Spray Lacquer Top and Base Coat	31-Aug-2002	32	25-Jul-2002	3	29	90.63 %
23-Jul-2002	Board Components	19-Aug-2002	21	30-Jul-2002	3	18	85.71 %
23-Jul-2002	Shaker Doors	19-Aug-2002	21	25-Jul-2002	3	18	85.71 %
23-Jul-2002	Veneer Over Edge	19-Aug-2002	21	30-Jul-2002	7	14	66.67 %
23-Jul-2002	Board Components	19-Aug-2002	21	30-Jul-2002	3	18	85.71 %
23-Jul-2002	Veneer Over Edge	19-Aug-2002	21	24-Jul-2002	7	14	66.67 %
23-Jul-2002	Veneer Over Edge	8-Aug-2002	14	25-Jul-2002	7	7	50.00 %
23-Jul-2002	Board Components	5-Aug-2002	11	30-Jul-2002	2	9	81.82 %
23-Jul-2002	Contract Cut	5-Aug-2002	11	26-Jul-2002	3	8	72.73 %
23-Jul-2002	Veneer Over Edge	5-Aug-2002	11	26-Jul-2002	7	4	36.36 %
24-Jul-2002	Contract Spray Lacquer Top and Base Coat	24-Jul-2002	1	30-Jul-2002	3	-2	-200.00 %
24-Jul-2002	Contract Spray: Stain Top Coat	24-Jul-2002	1	26-Jul-2002	3	-2	-200.00 %
24-Jul-2002	Components on Edge	24-Jul-2002	1	29-Jul-2002	6	-5	-500.00 %
24-Jul-2002	Contract Calibrate Sand	24-Jul-2002	1	26-Jul-2002	3	-2	-200.00 %
24-Jul-2002	Veneer Over Edge	24-Jul-2002	1	26-Jul-2002	5	-4	-400.00 %
24-Jul-2002	Contract Veneer Sand	24-Jul-2002	1	26-Jul-2002	3	-2	-200.00 %
24-Jul-2002	Contract Veneer Sand	30-Jul-2002	6	26-Jul-2002	3	3	50.00 %
24-Jul-2002	Contract Calibrate Sand	29-Jul-2002	5	26-Jul-2002	3	2	40.00 %
24-Jul-2002	Contract Veneer Sand	29-Jul-2002	5	26-Jul-2002	3	2	40.00 %
24-Jul-2002	Contract Calibrate Sand	25-Jul-2002	2	26-Jul-2002	3	-1	-50.00 %
24-Jul-2002	Contract Calibrate Sand	25-Jul-2002	2	25-Jul-2002	3	-1	-50.00 %
24-Jul-2002	Contract Calibrate Sand	24-Jul-2002	1	25-Jul-2002	3	-2	-200.00 %
24-Jul-2002	Contract Calibrate Sand	2-Aug-2002	9	26-Jul-2002	2	7	77.78 %
25-Jul-2002	Contract Calibrate Sand	25-Jul-2002	1	26-Jul-2002	1	0	0.00 %
25-Jul-2002	Contract Cut	25-Jul-2002	1	26-Jul-2002	2	-1	-100.00 %

Table F.2 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 20 *minutes.*

		LWC		Tabu			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
25-Jul-2002	Contract Calibrate and Veneer Sand	26-Jul-2002	2	26-Jul-2002	2	0	0.00 %
25-Jul-2002	Contract Calibrate Sand	25-Jul-2002	1	26-Jul-2002	2	-1	-100.00 %
25-Jul-2002	Contract Calibrate Sand	29-Jul-2002	4	26-Jul-2002	2	2	50.00 %
25-Jul-2002	Contract Calibrate Sand	29-Jul-2002	4	26-Jul-2002	2	2	50.00 %
25-Jul-2002	Contract Calibrate Sand	29-Jul-2002	4	26-Jul-2002	2	2	50.00 %
25-Jul-2002	Contract Veneer Sand	29-Jul-2002	4	26-Jul-2002	2	2	50.00 %
25-Jul-2002	Contract Veneer Sand	29-Jul-2002	4	26-Jul-2002	2	2	50.00 %
25-Jul-2002	Contract Veneer Sand	29-Jul-2002	4	26-Jul-2002	2	2	50.00 %
25-Jul-2002	Contract Veneer Sand	26-Aug-2002	25	26-Jul-2002	2	23	92.00 %
25-Jul-2002	Contract Calibrate Sand	7-Aug-2002	11	26-Jul-2002	2	9	81.82 %
25-Jul-2002	Contract Calibrate Sand	7-Aug-2002	11	25-Jul-2002	2	9	81.82 %
25-Jul-2002	Shaker Doors	8-Aug-2002	12	26-Jul-2002	2	10	83.33 %
25-Jul-2002	Contract Cut	2-Aug-2002	8	26-Jul-2002	1	7	87.50 %
25-Jul-2002	Contract Calibrate Sand	2-Aug-2002	8	26-Jul-2002	2	6	75.00 %
26-Jul-2002	Contract Calibrate Sand	29-Jul-2002	3	26-Jul-2002	1	2	66.67 %
26-Jul-2002	Contract Calibrate Sand	29-Jul-2002	3	1-Aug-2002	1	2	66.67 %
26-Jul-2002	Contract Veneer Sand	26-Jul-2002	1	26-Jul-2002	1	0	0.00 %
26-Jul-2002	Veneer Over Edge	6-Aug-2002	9	30-Jul-2002	6	3	33.33 %
26-Jul-2002	Contract Spray Lacquer Top and Base Coat	31-Jul-2002	5	30-Jul-2002	1	4	80.00 %
28-Jul-2002	Poster Box	6-Aug-2002	8	30-Jul-2002	3	5	62.50 %
29-Jul-2002	Contract Spray: Top and Base Coat and Edge Cut	2-Aug-2002	5	30-Jul-2002	2	3	60.00 %
29-Jul-2002	Contract Cut	2-Aug-2002	5	30-Jul-2002	2	3	60.00 %
29-Jul-2002	Contract Calibrate Sand	31-Jul-2002	3	30-Jul-2002	2	1	33.33 %
30-Jul-2002	Contract Calibrate Sand	30-Jul-2002	1	8-Aug-2002	1	0	0.00 %
30-Jul-2002	Contract Veneer Sand	30-Jul-2002	1	1-Aug-2002	1	0	0.00 %
30-Jul-2002	Veneer Over Edge	26-Aug-2002	21	30-Jul-2002	8	13	61.90 %
30-Jul-2002	Shaker Doors	26-Aug-2002	21	30-Jul-2002	3	18	85.71 %
30-Jul-2002	Contract Calibrate Sand	19-Aug-2002	15	30-Jul-2002	1	14	93.33 %
30-Jul-2002	Contract Calibrate Sand	16-Aug-2002	14	30-Jul-2002	1	13	92.86 %
30-Jul-2002	Contract Veneer Sand	7-Aug-2002	7	30-Jul-2002	1	6	85.71 %
30-Jul-2002	Contract Calibrate Sand	7-Aug-2002	7	8-Aug-2002	1	6	85.71 %
30-Jul-2002	Contract Calibrate Sand	8-Aug-2002	8	1-Aug-2002	1	7	87.50 %
30-Jul-2002	Veneer Over Edge	13-Aug-2002	11	1-Aug-2002	8	3	27.27 %
31-Jul-2002	Contract Spray Lacquer Top and Base Coat	31-Jul-2002	1	2-Aug-2002	2	-1	-100.00 %
31-Jul-2002	Contract Spray: Stain Top Coat	31-Jul-2002	1	31-Jul-2002	2	-1	-100.00 %
31-Jul-2002	Contract Cut	31-Jul-2002	1	1-Aug-2002	3	-2	-200.00 %
31-Jul-2002	Contract Edging	31-Jul-2002	1	8-Aug-2002	1	0	0.00 %
31-Jul-2002	Contract Calibrate Sand	31-Jul-2002	1	1-Aug-2002	2	-1	-100.00 %
31-Jul-2002	Veneer Over Edge	26-Aug-2002	20	1-Aug-2002	7	13	65.00 %
31-Jul-2002	Contract Calibrate Sand	6-Aug-2002	5	7-Aug-2002	2	3	60.00 %
31-Jul-2002	Contract Calibrate Sand	2-Aug-2002	3	7-Aug-2002	2	1	33.33 %
31-Jul-2002	Contract Cut	15-Aug-2002	12	1-Aug-2002	6	6	50.00 %
31-Jul-2002	Unique	8-Aug-2002	7	5-Aug-2002	6	1	14.29 %
1-Aug-2002	Contract Calibrate and Veneer Sand	1-Aug-2002	1	1-Aug-2002	1	0	0.00 %
1-Aug-2002	Shaker Doors	23-Aug-2002	17	1-Aug-2002	3	14	82.35 %
1-Aug-2002	Contract Calibrate Sand	7-Aug-2002	5	1-Aug-2002	1	4	80.00 %
1-Aug-2002	Contract Calibrate Sand	2-Aug-2002	2	1-Aug-2002	1	1	50.00 %
1-Aug-2002	Contract Calibrate Sand	2-Aug-2002	2	1-Aug-2002	1	1	50.00 %
1-Aug-2002	Contract Veneer Sand	2-Aug-2002	2	7-Aug-2002	1	1	50.00 %
1-Aug-2002	Contract Cut, Edge and Groove	2-Aug-2002	2	1-Aug-2002	1	1	50.00 %
1-Aug-2002	Contract Cut	2-Aug-2002	2	2-Aug-2002	5	-3	-150.00 %
1-Aug-2002	Contract Veneer Sand	2-Aug-2002	2	1-Aug-2002	1	1	50.00 %
1-Aug-2002	Contract Edging	2-Aug-2002	2	2-Aug-2002	2	0	0.00 %
1-Aug-2002	Contract Veneer Sand	2-Aug-2002	2	2-Aug-2002	1	1	50.00 %
1-Aug-2002	Contract Cut, Edge and Groove	2-Aug-2002	2	8-Aug-2002	2	0	0.00 %
2-Aug-2002	Contract Edging	28-Aug-2002	20	8-Aug-2002	1	19	95.00 %
2-Aug-2002	Veneer Over Edge	26-Aug-2002	18	8-Aug-2002	5	13	72.22 %
2-Aug-2002	Veneer Over Edge	26-Aug-2002	18	2-Aug-2002	5	13	72.22 %
2-Aug-2002	Shaker Doors	26-Aug-2002	18	2-Aug-2002	5	13	72.22 %
2-Aug-2002	Contract Calibrate Sand	21-Aug-2002	14	2-Aug-2002	1	13	92.86 %
2-Aug-2002	Contract Veneer Sand	20-Aug-2002	13	2-Aug-2002	1	12	92.31 %
2-Aug-2002	Contract Calibrate Sand	19-Aug-2002	12	2-Aug-2002	1	11	91.67 %
2-Aug-2002	Contract Calibrate Sand	19-Aug-2002	12	2-Aug-2002	1	11	91.67 %
2-Aug-2002	Contract Calibrate Sand	14-Aug-2002	9	2-Aug-2002	1	8	88.89 %
2-Aug-2002	Contract Veneer Sand	8-Aug-2002	5	2-Aug-2002	1	4	80.00 %

Table F.2 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 20 *minutes.*

		LWC		**Tabu**			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
2-Aug-2002	Contract Veneer Sand	8-Aug-2002	5	2-Aug-2002	1	4	80.00 %
2-Aug-2002	Contract Veneer Sand	8-Aug-2002	5	2-Aug-2002	1	4	80.00 %
2-Aug-2002	Contract Calibrate Sand	7-Aug-2002	4	8-Aug-2002	1	3	75.00 %
2-Aug-2002	Contract Spray Lacquer Top and Base Coat	15-Aug-2002	10	5-Aug-2002	1	9	90.00 %
2-Aug-2002	Contract Spray Lacquer Top and Base Coat	15-Aug-2002	10	5-Aug-2002	5	5	50.00 %
2-Aug-2002	Contract Spray Lacquer Top and Base Coat	15-Aug-2002	10	2-Aug-2002	2	8	80.00 %
2-Aug-2002	Contract Spray Lacquer Top and Base Coat	15-Aug-2002	10	5-Aug-2002	2	8	80.00 %
2-Aug-2002	Contract Spray Lacquer Top and Base Coat	8-Aug-2002	5	8-Aug-2002	1	4	80.00 %
2-Aug-2002	Contract Spray Lacquer Top and Base Coat	11-Sep-2002	31	7-Aug-2002	2	29	93.55 %
5-Aug-2002	Contract Calibrate Sand	16-Aug-2002	10	7-Aug-2002	4	6	60.00 %
5-Aug-2002	Contract Calibrate Sand	7-Aug-2002	3	7-Aug-2002	3	0	0.00 %
5-Aug-2002	Contract Calibrate Sand	7-Aug-2002	3	7-Aug-2002	3	0	0.00 %
5-Aug-2002	Contract Calibrate Sand	7-Aug-2002	3	7-Aug-2002	3	0	0.00 %
5-Aug-2002	Contract Calibrate Sand	14-Aug-2002	8	7-Aug-2002	3	5	62.50 %
5-Aug-2002	Contract Calibrate Sand	14-Aug-2002	8	7-Aug-2002	3	5	62.50 %
5-Aug-2002	Contract Calibrate Sand	14-Aug-2002	8	8-Aug-2002	3	5	62.50 %
5-Aug-2002	Contract Calibrate Sand	8-Aug-2002	4	7-Aug-2002	3	1	25.00 %
5-Aug-2002	Contract Calibrate Sand	7-Aug-2002	3	7-Aug-2002	4	-1	-33.33 %
5-Aug-2002	Contract Cut	8-Aug-2002	4	7-Aug-2002	3	1	25.00 %
5-Aug-2002	Contract Cut	8-Aug-2002	4	8-Aug-2002	3	1	25.00 %
5-Aug-2002	Contract Calibrate Sand	5-Aug-2002	1	7-Aug-2002	3	-2	-200.00 %
5-Aug-2002	Contract Veneer Sand	5-Aug-2002	1	7-Aug-2002	4	-3	-300.00 %
6-Aug-2002	Contract Calibrate Sand	14-Aug-2002	7	7-Aug-2002	2	5	71.43 %
6-Aug-2002	Contract Calibrate Sand	14-Aug-2002	7	8-Aug-2002	2	5	71.43 %
6-Aug-2002	Contract Calibrate Sand	6-Aug-2002	1	8-Aug-2002	2	-1	-100.00 %
6-Aug-2002	Contract Calibrate Sand	6-Aug-2002	1	7-Aug-2002	3	-2	-200.00 %
6-Aug-2002	Shaker Doors	16-Aug-2002	9	7-Aug-2002	3	6	66.67 %
6-Aug-2002	Unique	13-Aug-2002	6	8-Aug-2002	2	4	66.67 %
6-Aug-2002	Contract Calibrate Sand	6-Aug-2002	1	7-Aug-2002	2	-1	-100.00 %
6-Aug-2002	Contract Calibrate Sand	6-Aug-2002	1	8-Aug-2002	3	-2	-200.00 %
6-Aug-2002	Contract Veneer Sand	6-Aug-2002	1	7-Aug-2002	2	-1	-100.00 %
7-Aug-2002	Contract Calibrate Sand	16-Aug-2002	8	8-Aug-2002	2	6	75.00 %
7-Aug-2002	Contract Calibrate Sand	14-Aug-2002	6	7-Aug-2002	1	5	83.33 %
7-Aug-2002	Contract Veneer Sand	14-Aug-2002	6	8-Aug-2002	2	4	66.67 %
7-Aug-2002	Contract Calibrate Sand	14-Aug-2002	6	7-Aug-2002	1	5	83.33 %
7-Aug-2002	Contract Calibrate Sand	14-Aug-2002	6	7-Aug-2002	2	4	66.67 %
7-Aug-2002	Contract Calibrate Sand	13-Aug-2002	5	7-Aug-2002	1	4	80.00 %
7-Aug-2002	Contract Calibrate Sand	8-Aug-2002	2	7-Aug-2002	1	1	50.00 %
7-Aug-2002	Contract Veneer Sand	8-Aug-2002	2	7-Aug-2002	1	1	50.00 %
7-Aug-2002	Contract Veneer Sand	8-Aug-2002	2	7-Aug-2002	1	1	50.00 %
7-Aug-2002	Contract Veneer Sand	8-Aug-2002	2	7-Aug-2002	1	1	50.00 %
7-Aug-2002	Contract Veneer Sand	8-Aug-2002	2	8-Aug-2002	1	1	50.00 %
7-Aug-2002	Contract Veneer Sand	8-Aug-2002	2	7-Aug-2002	1	1	50.00 %
7-Aug-2002	Contract Calibrate Sand	13-Aug-2002	5	15-Aug-2002	2	3	60.00 %
7-Aug-2002	Unique	16-Aug-2002	8	8-Aug-2002	1	7	87.50 %
8-Aug-2002	Veneer Over Edge	31-Aug-2002	19	8-Aug-2002	6	13	68.42 %
8-Aug-2002	Contract Calibrate Sand	31-Aug-2002	19	8-Aug-2002	1	18	94.74 %
8-Aug-2002	Contract Veneer Sand	31-Aug-2002	19	8-Aug-2002	1	18	94.74 %
8-Aug-2002	Contract Calibrate Sand	29-Aug-2002	17	8-Aug-2002	1	16	94.12 %
8-Aug-2002	Contract Calibrate Sand	20-Aug-2002	9	8-Aug-2002	1	8	88.89 %
8-Aug-2002	Contract Veneer Sand	20-Aug-2002	9	8-Aug-2002	1	8	88.89 %
8-Aug-2002	Contract Calibrate Sand	16-Aug-2002	7	10-Aug-2002	1	6	85.71 %
8-Aug-2002	Contract Calibrate Sand	14-Aug-2002	5	12-Aug-2002	1	4	80.00 %
10-Aug-2002	Contract Calibrate Sand	14-Aug-2002	4	20-Aug-2002	1	3	75.00 %
12-Aug-2002	Unique	26-Aug-2002	12	12-Aug-2002	1	11	91.67 %
12-Aug-2002	Veneer Over Edge	26-Aug-2002	12	12-Aug-2002	7	5	41.67 %
12-Aug-2002	Contract Veneer Sand	20-Aug-2002	7	13-Aug-2002	1	6	85.71 %
12-Aug-2002	Contract Veneer Sand	16-Aug-2002	5	12-Aug-2002	1	4	80.00 %
12-Aug-2002	Unique	15-Aug-2002	4	12-Aug-2002	2	2	50.00 %
12-Aug-2002	Contract Calibrate Sand	13-Aug-2002	2	20-Aug-2002	1	1	50.00 %
12-Aug-2002	Contract Edging	12-Aug-2002	1	19-Aug-2002	1	0	0.00 %
12-Aug-2002	Veneer Over Edge	2-Sep-2002	18	14-Aug-2002	7	11	61.11 %
12-Aug-2002	Veneer Over Edge	2-Sep-2002	18	14-Aug-2002	6	12	66.67 %

Table F.2 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 20 *minutes.*

		LWC		**Tabu**			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve– ment**	**%Improve– ment**
13-Aug-2002	Board Components	30-Aug-2002	15	13-Aug-2002	2	13	86.67 %
13-Aug-2002	Board Components	29-Aug-2002	14	14-Aug-2002	2	12	85.71 %
13-Aug-2002	Contract Calibrate Sand	31-Aug-2002	16	13-Aug-2002	1	15	93.75 %
13-Aug-2002	Contract Veneer Sand	31-Aug-2002	16	14-Aug-2002	2	14	87.50 %
13-Aug-2002	Contract Calibrate Sand	23-Aug-2002	9	14-Aug-2002	1	8	88.89 %
13-Aug-2002	Contract Calibrate Sand	21-Aug-2002	7	14-Aug-2002	2	5	71.43 %
13-Aug-2002	Contract Calibrate Sand	16-Aug-2002	4	14-Aug-2002	2	2	50.00 %
13-Aug-2002	Contract Calibrate Sand	14-Aug-2002	2	14-Aug-2002	2	0	0.00 %
13-Aug-2002	Contract Calibrate Sand	14-Aug-2002	2	14-Aug-2002	2	0	0.00 %
13-Aug-2002	Contract Calibrate Sand	14-Aug-2002	2	14-Aug-2002	2	0	0.00 %
14-Aug-2002	Contract Calibrate Sand	22-Aug-2002	7	14-Aug-2002	1	6	85.71 %
14-Aug-2002	Contract Veneer Sand	22-Aug-2002	7	14-Aug-2002	1	6	85.71 %
14-Aug-2002	Contract Calibrate Sand	21-Aug-2002	6	14-Aug-2002	1	5	83.33 %
14-Aug-2002	Contract Calibrate Sand	21-Aug-2002	6	14-Aug-2002	1	5	83.33 %
14-Aug-2002	Contract Calibrate Sand	19-Aug-2002	4	14-Aug-2002	1	3	75.00 %
14-Aug-2002	Contract Calibrate Sand	19-Aug-2002	4	14-Aug-2002	1	3	75.00 %
14-Aug-2002	Contract Calibrate Sand	14-Aug-2002	1	14-Aug-2002	1	0	0.00 %
14-Aug-2002	Contract Calibrate Sand	14-Aug-2002	1	14-Aug-2002	1	0	0.00 %
14-Aug-2002	Contract Calibrate Sand	14-Aug-2002	1	15-Aug-2002	1	0	0.00 %
14-Aug-2002	Contract Calibrate Sand	20-Aug-2002	5	15-Aug-2002	1	4	80.00 %
15-Aug-2002	Contract Calibrate Sand	28-Aug-2002	11	15-Aug-2002	1	10	90.91 %
15-Aug-2002	Contract Calibrate Sand	26-Aug-2002	9	21-Aug-2002	1	8	88.89 %
15-Aug-2002	Contract Calibrate Sand	23-Aug-2002	7	16-Aug-2002	1	6	85.71 %
15-Aug-2002	Veneer Over Edge	6-Sep-2002	19	20-Aug-2002	5	14	73.68 %
16-Aug-2002	Contract Edging	28-Aug-2002	10	20-Aug-2002	1	9	90.00 %
16-Aug-2002	Contract Calibrate Sand	23-Aug-2002	6	20-Aug-2002	3	3	50.00 %
16-Aug-2002	Contract Calibrate Sand	19-Aug-2002	2	20-Aug-2002	3	-1	-50.00 %
16-Aug-2002	Shaker Doors	16-Aug-2002	1	20-Aug-2002	3	-2	-200.00 %
16-Aug-2002	Contract Cut	19-Aug-2002	2	20-Aug-2002	3	-1	-50.00 %
19-Aug-2002	Contract Calibrate Sand	29-Aug-2002	10	20-Aug-2002	2	8	80.00 %
19-Aug-2002	Contract Calibrate Sand	26-Aug-2002	7	20-Aug-2002	2	5	71.43 %
19-Aug-2002	Contract Calibrate Sand	23-Aug-2002	5	20-Aug-2002	2	3	60.00 %
19-Aug-2002	Contract Calibrate Sand	21-Aug-2002	3	24-Aug-2002	2	1	33.33 %
19-Aug-2002	Contract Calibrate Sand	21-Aug-2002	3	20-Aug-2002	2	1	33.33 %
19-Aug-2002	Veneer Over Edge	26-Sep-2002	32	20-Aug-2002	6	26	81.25 %
20-Aug-2002	Contract Calibrate Sand	21-Aug-2002	2	20-Aug-2002	1	1	50.00 %
20-Aug-2002	Contract Veneer Sand	21-Aug-2002	2	20-Aug-2002	1	1	50.00 %
20-Aug-2002	Contract Veneer Sand	30-Aug-2002	10	20-Aug-2002	1	9	90.00 %
20-Aug-2002	Contract Calibrate Sand	30-Aug-2002	10	20-Aug-2002	1	9	90.00 %
20-Aug-2002	Contract Veneer Sand	29-Aug-2002	9	20-Aug-2002	1	8	88.89 %
20-Aug-2002	Contract Calibrate Sand	29-Aug-2002	9	20-Aug-2002	1	8	88.89 %
20-Aug-2002	Contract Calibrate Sand	26-Aug-2002	6	20-Aug-2002	1	5	83.33 %
20-Aug-2002	Contract Calibrate Sand	23-Aug-2002	4	20-Aug-2002	1	3	75.00 %
20-Aug-2002	Contract Calibrate Sand	23-Aug-2002	4	20-Aug-2002	1	3	75.00 %
20-Aug-2002	Contract Veneer Sand	26-Aug-2002	6	20-Aug-2002	1	5	83.33 %
20-Aug-2002	Contract Calibrate Sand	26-Aug-2002	6	20-Aug-2002	1	5	83.33 %
20-Aug-2002	Contract Veneer Sand	26-Aug-2002	6	22-Aug-2002	1	5	83.33 %
20-Aug-2002	Contract Calibrate Sand	26-Aug-2002	6	22-Aug-2002	1	5	83.33 %
21-Aug-2002	Board Components	31-Aug-2002	10	22-Aug-2002	2	8	80.00 %
21-Aug-2002	Board Components	23-Aug-2002	3	22-Aug-2002	2	1	33.33 %
21-Aug-2002	Contract Veneer Sand	29-Aug-2002	8	22-Aug-2002	2	6	75.00 %
21-Aug-2002	Contract Calibrate Sand	29-Aug-2002	8	22-Aug-2002	2	6	75.00 %
21-Aug-2002	Contract Calibrate Sand	23-Aug-2002	3	21-Aug-2002	2	1	33.33 %
21-Aug-2002	Contract Calibrate Sand	22-Aug-2002	2	21-Aug-2002	2	0	0.00 %
21-Aug-2002	Contract Veneer Sand	22-Aug-2002	2	22-Aug-2002	1	1	50.00 %
21-Aug-2002	Contract Spray: Stain Top Coat	18-Sep-2002	23	22-Aug-2002	1	22	95.65 %
21-Aug-2002	Contract Spray Lacquer Top and Base Coat	6-Sep-2002	15	22-Aug-2002	2	13	86.67 %
21-Aug-2002	Poster Box	3-Sep-2002	12	22-Aug-2002	2	10	83.33 %
21-Aug-2002	Poster Box	3-Sep-2002	12	24-Aug-2002	2	10	83.33 %
21-Aug-2002	Poster Box	3-Sep-2002	12	22-Aug-2002	2	10	83.33 %
21-Aug-2002	Contract Cut	10-Oct-2002	40	22-Aug-2002	4	36	90.00 %
22-Aug-2002	Contract Calibrate Sand	23-Aug-2002	2	22-Aug-2002	1	1	50.00 %
22-Aug-2002	Contract Calibrate Sand	29-Aug-2002	7	22-Aug-2002	1	6	85.71 %
22-Aug-2002	Contract Veneer Sand	28-Aug-2002	6	22-Aug-2002	1	5	83.33 %
22-Aug-2002	Contract Calibrate Sand	22-Aug-2002	1	22-Aug-2002	1	0	0.00 %
22-Aug-2002	Contract Veneer Sand	29-Aug-2002	7	26-Aug-2002	1	6	85.71 %
22-Aug-2002	Contract Veneer Sand	28-Aug-2002	6	23-Aug-2002	1	5	83.33 %
22-Aug-2002	Shaker Doors	6-Sep-2002	14	26-Aug-2002	4	10	71.43 %

Table F.2 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 20 *minutes.*

		LWC		Tabu			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
23-Aug-2002	Contract Spray Lacquer Top and Base Coat	29-Aug-2002	6	26-Aug-2002	1	5	83.33 %
23-Aug-2002	Poster Box	28-Aug-2002	5	24-Aug-2002	3	2	40.00 %
23-Aug-2002	Poster Box	28-Aug-2002	5	24-Aug-2002	3	2	40.00 %
23-Aug-2002	Contract Calibrate Sand	31-Aug-2002	8	24-Aug-2002	2	6	75.00 %
23-Aug-2002	Contract Veneer Sand	31-Aug-2002	8	24-Aug-2002	2	6	75.00 %
23-Aug-2002	Contract Calibrate Sand	29-Aug-2002	6	24-Aug-2002	2	4	66.67 %
23-Aug-2002	Contract Veneer Sand	29-Aug-2002	6	24-Aug-2002	2	4	66.67 %
23-Aug-2002	Contract Calibrate Sand	28-Aug-2002	5	24-Aug-2002	2	3	60.00 %
23-Aug-2002	Contract Veneer Sand	28-Aug-2002	5	24-Aug-2002	2	3	60.00 %
23-Aug-2002	Contract Veneer Sand	28-Aug-2002	5	29-Aug-2002	2	3	60.00 %
23-Aug-2002	Contract Calibrate Sand	29-Aug-2002	6	24-Aug-2002	2	4	66.67 %
23-Aug-2002	Veneer Over Edge	11-Sep-2002	16	24-Aug-2002	6	10	62.50 %
24-Aug-2002	Unique	29-Aug-2002	5	24-Aug-2002	1	4	80.00 %
24-Aug-2002	Contract Calibrate Sand	28-Aug-2002	4	26-Aug-2002	1	3	75.00 %
24-Aug-2002	Contract Calibrate Sand	30-Aug-2002	6	26-Aug-2002	1	5	83.33 %
26-Aug-2002	Contract Calibrate Sand	26-Aug-2002	1	27-Aug-2002	1	0	0.00 %
26-Aug-2002	Contract Calibrate Sand	30-Aug-2002	5	27-Aug-2002	1	4	80.00 %
27-Aug-2002	Contract Calibrate Sand	2-Sep-2002	6	27-Aug-2002	1	5	83.33 %
27-Aug-2002	Contract Veneer Sand	2-Sep-2002	6	29-Aug-2002	1	5	83.33 %
27-Aug-2002	Contract Calibrate Sand	2-Sep-2002	6	29-Aug-2002	1	5	83.33 %
27-Aug-2002	Shaker Doors	12-Sep-2002	14	28-Aug-2002	3	11	78.57 %
27-Aug-2002	Shaker Doors	12-Sep-2002	14	29-Aug-2002	3	11	78.57 %
28-Aug-2002	Contract Edging	31-Aug-2002	4	29-Aug-2002	1	3	75.00 %
28-Aug-2002	Contract Calibrate Sand	29-Aug-2002	2	29-Aug-2002	2	0	0.00 %
28-Aug-2002	Contract Calibrate Sand	3-Sep-2002	6	29-Aug-2002	2	4	66.67 %
28-Aug-2002	Contract Calibrate Sand	3-Sep-2002	6	29-Aug-2002	2	4	66.67 %
28-Aug-2002	Contract Calibrate Sand	3-Sep-2002	6	29-Aug-2002	2	4	66.67 %
28-Aug-2002	Contract Calibrate Sand	30-Aug-2002	3	29-Aug-2002	2	1	33.33 %
28-Aug-2002	Contract Veneer Sand	3-Sep-2002	6	29-Aug-2002	2	4	66.67 %
28-Aug-2002	Contract Cut	17-Sep-2002	16	29-Aug-2002	2	14	87.50 %
28-Aug-2002	Board Components	17-Sep-2002	16	28-Aug-2002	2	14	87.50 %
28-Aug-2002	Shaker Doors	10-Sep-2002	11	29-Aug-2002	2	9	81.82 %
28-Aug-2002	Contract Cut and Edge	10-Sep-2002	11	29-Aug-2002	1	10	90.91 %
28-Aug-2002	Contract Calibrate Sand	3-Sep-2002	6	29-Aug-2002	2	4	66.67 %
28-Aug-2002	Contract Calibrate Sand	3-Sep-2002	6	29-Aug-2002	2	4	66.67 %
28-Aug-2002	Contract Spray Lacquer Top and Base Coat	4-Oct-2002	30	29-Aug-2002	2	28	93.33 %
29-Aug-2002	Contract Spray: Stain Top Coat	31-Aug-2002	3	29-Aug-2002	1	2	66.67 %
29-Aug-2002	Contract Spray Lacquer Top and Base Coat	4-Sep-2002	6	29-Aug-2002	1	5	83.33 %
29-Aug-2002	Contract Spray Lacquer Top and Base Coat	20-Sep-2002	18	29-Aug-2002	1	17	94.44 %
29-Aug-2002	Contract Veneer Sand	5-Sep-2002	7	29-Aug-2002	1	6	85.71 %
29-Aug-2002	Contract Veneer Sand	4-Sep-2002	6	29-Aug-2002	1	5	83.33 %
29-Aug-2002	Contract Veneer Sand	4-Sep-2002	6	30-Aug-2002	1	5	83.33 %
29-Aug-2002	Contract Calibrate Sand	4-Sep-2002	6	31-Aug-2002	1	5	83.33 %
29-Aug-2002	Shaker Doors	16-Sep-2002	14	2-Sep-2002	2	12	85.71 %
31-Aug-2002	Contract Calibrate Sand	31-Aug-2002	1	2-Sep-2002	1	0	0.00 %
2-Sep-2002	Contract Calibrate Sand	30-Sep-2002	22	2-Sep-2002	1	21	95.45 %
2-Sep-2002	Contract Calibrate Sand	30-Sep-2002	22	2-Sep-2002	1	21	95.45 %
2-Sep-2002	Contract Calibrate Sand	30-Sep-2002	22	2-Sep-2002	1	21	95.45 %
2-Sep-2002	Contract Calibrate Sand	2-Sep-2002	1	3-Sep-2002	1	0	0.00 %
2-Sep-2002	Contract Calibrate Sand	2-Sep-2002	1	5-Sep-2002	1	0	0.00 %
3-Sep-2002	Contract Calibrate Sand	30-Sep-2002	21	10-Sep-2002	1	20	95.24 %
3-Sep-2002	Poster Box	23-Sep-2002	16	4-Sep-2002	3	13	81.25 %
3-Sep-2002	Veneer Over Edge	20-Sep-2002	14	11-Sep-2002	6	8	57.14 %
3-Sep-2002	Contract Cut and Edge	16-Sep-2002	10	4-Sep-2002	2	8	80.00 %
4-Sep-2002	Veneer Over Edge	30-Sep-2002	20	5-Sep-2002	6	14	70.00 %
4-Sep-2002	Contract Calibrate Sand	23-Sep-2002	15	4-Sep-2002	1	14	93.33 %
4-Sep-2002	Poster Box	23-Sep-2002	15	4-Sep-2002	2	13	86.67 %
4-Sep-2002	Contract Calibrate Sand	10-Sep-2002	5	4-Sep-2002	1	4	80.00 %
4-Sep-2002	Contract Calibrate Sand	10-Sep-2002	5	4-Sep-2002	1	4	80.00 %
4-Sep-2002	Contract Calibrate Sand	6-Sep-2002	3	4-Sep-2002	1	2	66.67 %
4-Sep-2002	Contract Calibrate Sand	10-Sep-2002	5	5-Sep-2002	1	4	80.00 %
4-Sep-2002	Contract Calibrate Sand	10-Sep-2002	5	10-Sep-2002	1	4	80.00 %
4-Sep-2002	Unique	16-Sep-2002	9	12-Sep-2002	2	7	77.78 %
4-Sep-2002	Veneer Over Edge	18-Oct-2002	35	11-Sep-2002	5	30	85.71 %
5-Sep-2002	Veneer Over Edge	30-Sep-2002	19	5-Sep-2002	6	13	68.42 %

Table F.2 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 20 *minutes.*

		LWC		**Tabu**			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
5-Sep-2002	Veneer Over Edge	27-Sep-2002	18	5-Sep-2002	5	13	72.22 %
5-Sep-2002	Contract Calibrate Sand	12-Sep-2002	6	5-Sep-2002	1	5	83.33 %
5-Sep-2002	Contract Veneer Sand	11-Sep-2002	5	6-Sep-2002	1	4	80.00 %
5-Sep-2002	Contract Calibrate Sand	5-Sep-2002	1	6-Sep-2002	1	0	0.00 %
6-Sep-2002	Contract Plane all Round(PAR)	23-Sep-2002	13	6-Sep-2002	1	12	92.31 %
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Veneer Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Veneer Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Veneer Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002	5	6-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Calibrate Sand	12-Sep-2002	5	12-Sep-2002	1	4	80.00 %
6-Sep-2002	Contract Calibrate Sand	6-Sep-2002	1	12-Sep-2002	1	0	0.00 %
9-Sep-2002	Contract Calibrate Sand	30-Sep-2002	17	11-Sep-2002	4	13	76.47 %
9-Sep-2002	Shaker Doors	23-Sep-2002	12	12-Sep-2002	4	8	66.67 %
9-Sep-2002	Contract Calibrate Sand	23-Sep-2002	12	11-Sep-2002	3	9	75.00 %
9-Sep-2002	Contract Calibrate Sand	13-Sep-2002	5	12-Sep-2002	4	1	20.00 %
9-Sep-2002	Contract Veneer Sand	13-Sep-2002	5	11-Sep-2002	3	2	40.00 %
9-Sep-2002	Contract Calibrate Sand	13-Sep-2002	5	12-Sep-2002	4	1	20.00 %
9-Sep-2002	Contract Veneer Sand	12-Sep-2002	4	11-Sep-2002	3	1	25.00 %
9-Sep-2002	Contract Calibrate Sand	13-Sep-2002	5	10-Sep-2002	4	1	20.00 %
9-Sep-2002	Contract Veneer Sand	9-Sep-2002	1	10-Sep-2002	3	-2	-200.00 %
9-Sep-2002	Contract Calibrate Sand	9-Sep-2002	1	11-Sep-2002	2	-1	-100.00 %
9-Sep-2002	Contract Calibrate Sand	13-Sep-2002	5	10-Sep-2002	2	3	60.00 %
10-Sep-2002	Unique	30-Sep-2002	16	10-Sep-2002	2	14	87.50 %
10-Sep-2002	Unique	30-Sep-2002	16	10-Sep-2002	1	15	93.75 %
10-Sep-2002	Contract Plane all Round(PAR)	30-Sep-2002	16	11-Sep-2002	1	15	93.75 %
10-Sep-2002	Contract Spray: Stain Top Coat	30-Sep-2002	16	10-Sep-2002	1	15	93.75 %
10-Sep-2002	Contract Calibrate Sand	16-Sep-2002	5	11-Sep-2002	2	3	60.00 %
10-Sep-2002	Contract Calibrate Sand	16-Sep-2002	5	10-Sep-2002	1	4	80.00 %
10-Sep-2002	Contract Calibrate Sand	16-Sep-2002	5	10-Sep-2002	2	3	60.00 %
10-Sep-2002	Contract Calibrate Sand	30-Sep-2002	16	16-Sep-2002	1	15	93.75 %
10-Sep-2002	Contract Edging	13-Sep-2002	4	11-Sep-2002	1	3	75.00 %
10-Sep-2002	Veneer Over Edge	12-Sep-2002	3	11-Sep-2002	5	-2	-66.67 %
10-Sep-2002	Contract Calibrate Sand	11-Sep-2002	2	11-Sep-2002	2	0	0.00 %
11-Sep-2002	Contract Spray Lacquer Top and Base Coat	30-Sep-2002	15	12-Sep-2002	1	14	93.33 %
11-Sep-2002	Contract Spray Lacquer Top and Base Coat	30-Sep-2002	15	13-Sep-2002	1	14	93.33 %
11-Sep-2002	Shaker Doors	26-Sep-2002	13	11-Sep-2002	2	11	84.62 %
11-Sep-2002	Unique	26-Sep-2002	13	12-Sep-2002	3	10	76.92 %
11-Sep-2002	Contract Calibrate Sand	30-Sep-2002	15	11-Sep-2002	1	14	93.33 %
11-Sep-2002	Contract Calibrate Sand	11-Sep-2002	1	11-Sep-2002	2	-1	-100.00 %
11-Sep-2002	Contract Spray Lacquer Top and Base Coat	17-Sep-2002	5	11-Sep-2002	1	4	80.00 %
11-Sep-2002	Contract Spray Lacquer Top and Base Coat	17-Sep-2002	5	13-Sep-2002	1	4	80.00 %
11-Sep-2002	Contract Cut	12-Sep-2002	2	11-Sep-2002	1	1	50.00 %
11-Sep-2002	Contract Cut	12-Sep-2002	2	16-Sep-2002	3	-1	-50.00 %
11-Sep-2002	Contract Spray Lacquer Top and Base Coat	7-Oct-2002	20	16-Sep-2002	1	19	95.00 %
12-Sep-2002	Shaker Doors	30-Sep-2002	14	12-Sep-2002	3	11	78.57 %
12-Sep-2002	Shaker Doors	20-Sep-2002	7	12-Sep-2002	3	4	57.14 %
12-Sep-2002	Contract Calibrate Sand	18-Sep-2002	5	12-Sep-2002	1	4	80.00 %
12-Sep-2002	Contract Calibrate Sand	18-Sep-2002	5	12-Sep-2002	1	4	80.00 %
12-Sep-2002	Contract Veneer Sand	17-Sep-2002	4	12-Sep-2002	1	3	75.00 %
12-Sep-2002	Contract Calibrate Sand	18-Sep-2002	5	12-Sep-2002	1	4	80.00 %
12-Sep-2002	Contract Calibrate Sand	18-Sep-2002	5	12-Sep-2002	1	4	80.00 %
12-Sep-2002	Contract Calibrate Sand	18-Sep-2002	5	12-Sep-2002	1	4	80.00 %
12-Sep-2002	Contract Calibrate Sand	16-Sep-2002	3	12-Sep-2002	1	2	66.67 %
12-Sep-2002	Contract Calibrate Sand	12-Sep-2002	1	12-Sep-2002	1	0	0.00 %
12-Sep-2002	Contract Calibrate Sand	18-Sep-2002	5	12-Sep-2002	1	4	80.00 %
12-Sep-2002	Contract Calibrate Sand	16-Sep-2002	3	13-Sep-2002	1	2	66.67 %

Table F.2 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 20 *minutes.*

		LWC		**Tabu**		**Improve–ment**	**%Improve–ment**
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**		
12-Sep-2002	Contract Calibrate Sand	12-Sep-2002	1	13-Sep-2002	1	0	0.00 %
13-Sep-2002	Contract Spray: Base Coat	18-Sep-2002	4	13-Sep-2002	1	3	75.00 %
13-Sep-2002	Contract Calibrate Sand	19-Sep-2002	5	16-Sep-2002	1	4	80.00 %
13-Sep-2002	Contract Calibrate Sand	13-Sep-2002	1	13-Sep-2002	1	0	0.00 %
16-Sep-2002	Unique	27-Sep-2002	11	16-Sep-2002	1	10	90.91 %
16-Sep-2002	Contract Edging	23-Sep-2002	7	16-Sep-2002	1	6	85.71 %
16-Sep-2002	Contract Veneer Sand	20-Sep-2002	5	16-Sep-2002	1	4	80.00 %
16-Sep-2002	Contract Calibrate Sand	20-Sep-2002	5	16-Sep-2002	1	4	80.00 %
16-Sep-2002	Contract Veneer Sand	30-Sep-2002	12	16-Sep-2002	1	11	91.67 %
16-Sep-2002	Contract Veneer Sand	30-Sep-2002	12	16-Sep-2002	1	11	91.67 %
16-Sep-2002	Contract Calibrate Sand	20-Sep-2002	5	16-Sep-2002	1	4	80.00 %
16-Sep-2002	Contract Calibrate Sand	20-Sep-2002	5	16-Sep-2002	1	4	80.00 %
16-Sep-2002	Contract Calibrate Sand	20-Sep-2002	5	16-Sep-2002	1	4	80.00 %
16-Sep-2002	Contract Veneer Sand	20-Sep-2002	5	16-Sep-2002	1	4	80.00 %
16-Sep-2002	Contract Veneer Sand	20-Sep-2002	5	16-Sep-2002	1	4	80.00 %
16-Sep-2002	Contract Calibrate Sand	20-Sep-2002	5	16-Sep-2002	1	4	80.00 %
16-Sep-2002	Contract Calibrate Sand	20-Sep-2002	5	18-Sep-2002	1	4	80.00 %
16-Sep-2002	Contract Calibrate Sand	16-Sep-2002	1	17-Sep-2002	1	0	0.00 %
17-Sep-2002	Shaker Doors	26-Sep-2002	9	17-Sep-2002	2	7	77.78 %
17-Sep-2002	Contract Calibrate Sand	23-Sep-2002	6	17-Sep-2002	1	5	83.33 %
17-Sep-2002	Contract Spray Lacquer Top and Base Coat	23-Sep-2002	6	17-Sep-2002	1	5	83.33 %
17-Sep-2002	Contract Spray Lacquer Top and Base Coat	20-Sep-2002	4	17-Sep-2002	1	3	75.00 %
17-Sep-2002	Contract Calibrate Sand	23-Sep-2002	6	17-Sep-2002	1	5	83.33 %
17-Sep-2002	Contract Calibrate Sand	23-Sep-2002	6	17-Sep-2002	1	5	83.33 %
17-Sep-2002	Contract Calibrate Sand	23-Sep-2002	6	18-Sep-2002	1	5	83.33 %
17-Sep-2002	Contract Spray Lacquer Top and Base Coat	10-Oct-2002	19	18-Sep-2002	1	18	94.74 %
18-Sep-2002	Contract Cut	27-Sep-2002	9	18-Sep-2002	1	8	88.89 %
18-Sep-2002	Contract Spray Lacquer Top and Base Coat	26-Sep-2002	8	18-Sep-2002	1	7	87.50 %
18-Sep-2002	Contract Calibrate Sand	30-Sep-2002	10	18-Sep-2002	1	9	90.00 %
18-Sep-2002	Contract Calibrate Sand	20-Sep-2002	3	19-Sep-2002	1	2	66.67 %
18-Sep-2002	Contract Calibrate Sand	18-Sep-2002	1	19-Sep-2002	1	0	0.00 %
19-Sep-2002	Contract Spray Lacquer Top and Base Coat	30-Sep-2002	9	19-Sep-2002	1	8	88.89 %
19-Sep-2002	Contract Calibrate Sand	23-Sep-2002	4	19-Sep-2002	1	3	75.00 %
19-Sep-2002	Contract Veneer Sand	26-Sep-2002	7	19-Sep-2002	1	6	85.71 %
19-Sep-2002	Contract Calibrate Sand	30-Sep-2002	9	19-Sep-2002	1	8	88.89 %
19-Sep-2002	Contract Calibrate Sand	26-Sep-2002	7	19-Sep-2002	1	6	85.71 %
19-Sep-2002	Contract Calibrate Sand	26-Sep-2002	7	19-Sep-2002	1	6	85.71 %
19-Sep-2002	Contract Calibrate Sand	19-Sep-2002	1	20-Sep-2002	1	0	0.00 %
19-Sep-2002	Contract Spray Lacquer Top and Base Coat	14-Oct-2002	20	19-Sep-2002	1	19	95.00 %
19-Sep-2002	Shaker Doors	4-Oct-2002	13	24-Sep-2002	2	11	84.62 %
19-Sep-2002	Contract Spray Lacquer Top and Base Coat	4-Oct-2002	13	20-Sep-2002	1	12	92.31 %
20-Sep-2002	Unique	30-Sep-2002	8	20-Sep-2002	4	4	50.00 %
20-Sep-2002	Contract Cut and Edge	23-Sep-2002	3	20-Sep-2002	1	2	66.67 %
20-Sep-2002	Contract Calibrate Sand	20-Sep-2002	1	21-Sep-2002	1	0	0.00 %
20-Sep-2002	Contract Veneer Sand	20-Sep-2002	1	21-Sep-2002	1	0	0.00 %
20-Sep-2002	Contract Cut	4-Oct-2002	12	23-Sep-2002	2	10	83.33 %
21-Sep-2002	Contract Cut	23-Sep-2002	2	24-Sep-2002	1	1	50.00 %
23-Sep-2002	Contract Plane all Round(PAR)	23-Sep-2002	1	23-Sep-2002	1	0	0.00 %
23-Sep-2002	Contract Cut	23-Sep-2002	1	23-Sep-2002	2	-1	-100.00 %
23-Sep-2002	Contract Veneer Sand	30-Sep-2002	6	23-Sep-2002	1	5	83.33 %
23-Sep-2002	Contract Calibrate Sand	27-Sep-2002	5	23-Sep-2002	1	4	80.00 %
23-Sep-2002	Contract Calibrate Sand	27-Sep-2002	5	23-Sep-2002	1	4	80.00 %
23-Sep-2002	Contract Calibrate Sand	27-Sep-2002	5	24-Sep-2002	1	4	80.00 %
23-Sep-2002	Contract Calibrate Sand	26-Sep-2002	4	24-Sep-2002	1	3	75.00 %
23-Sep-2002	Poster Box	17-Oct-2002	20	24-Sep-2002	2	18	90.00 %
23-Sep-2002	Poster Box	17-Oct-2002	20	25-Sep-2002	2	18	90.00 %
23-Sep-2002	Shaker Doors	8-Oct-2002	12	25-Sep-2002	2	10	83.33 %
25-Sep-2002	Contract Spray: Top and Base Coat	26-Sep-2002	2	26-Sep-2002	1	1	50.00 %
26-Sep-2002	Contract Edging	30-Sep-2002	3	26-Sep-2002	1	2	66.67 %
26-Sep-2002	Contract Spray: Stain Top Coat	30-Sep-2002	3	26-Sep-2002	1	2	66.67 %
26-Sep-2002	Contract Calibrate Sand	27-Sep-2002	2	26-Sep-2002	1	1	50.00 %

Table F.2 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 20 *minutes.*

		LWC		Tabu			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve-ment**	**%Improve-ment**
26-Sep-2002	Contract Calibrate Sand	26-Sep-2002	1	26-Sep-2002	1	0	0.00 %
26-Sep-2002	Contract Calibrate Sand	2-Oct-2002	5	26-Sep-2002	1	4	80.00 %
26-Sep-2002	Contract Calibrate Sand	30-Sep-2002	3	26-Sep-2002	1	2	66.67 %
26-Sep-2002	Contract Calibrate Sand	3-Oct-2002	6	26-Sep-2002	1	5	83.33 %
26-Sep-2002	Contract Calibrate Sand	3-Oct-2002	6	3-Oct-2002	1	5	83.33 %
26-Sep-2002	Veneer Over Edge	24-Oct-2002	22	27-Sep-2002	6	16	72.73 %
26-Sep-2002	Shaker Doors	10-Oct-2002	11	26-Sep-2002	2	9	81.82 %
26-Sep-2002	Contract Cut	2-Oct-2002	5	2-Oct-2002	1	4	80.00 %
27-Sep-2002	Shaker Doors	30-Oct-2002	26	1-Oct-2002	4	22	84.62 %
27-Sep-2002	Contract Cut	30-Oct-2002	26	2-Oct-2002	3	23	88.46 %
27-Sep-2002	Unique	30-Oct-2002	26	27-Sep-2002	4	22	84.62 %
27-Sep-2002	Board Components	30-Oct-2002	26	8-Oct-2002	1	25	96.15 %
27-Sep-2002	Veneer Over Edge	23-Oct-2002	20	2-Oct-2002	8	12	60.00 %
27-Sep-2002	Unique	23-Oct-2002	20	27-Sep-2002	4	16	80.00 %
27-Sep-2002	Contract Spray Lacquer Top and Base Coat	14-Oct-2002	13	27-Sep-2002	1	12	92.31 %
27-Sep-2002	Contract Veneer Sand	3-Oct-2002	5	2-Oct-2002	1	4	80.00 %
27-Sep-2002	Shaker Doors	4-Oct-2002	6	2-Oct-2002	4	2	33.33 %
30-Sep-2002	Contract Veneer Sand	30-Sep-2002	1	2-Oct-2002	3	-2	-200.00 %
30-Sep-2002	Contract Calibrate Sand	30-Sep-2002	1	1-Oct-2002	3	-2	-200.00 %
30-Sep-2002	Contract Edging	30-Sep-2002	1	2-Oct-2002	2	-1	-100.00 %
30-Sep-2002	Contract Calibrate Sand	30-Sep-2002	1	8-Oct-2002	3	-2	-200.00 %
30-Sep-2002	Veneer Over Edge	30-Sep-2002	1	2-Oct-2002	7	-6	-600.00 %
30-Sep-2002	Board Components	30-Oct-2002	25	2-Oct-2002	3	22	88.00 %
30-Sep-2002	Board Components	14-Oct-2002	12	12-Oct-2002	3	9	75.00 %
30-Sep-2002	Components on Edge	14-Oct-2002	12	2-Oct-2002	11	1	8.33 %
30-Sep-2002	Board Components	14-Oct-2002	12	4-Oct-2002	3	9	75.00 %
30-Sep-2002	Components on Edge	14-Oct-2002	12	2-Oct-2002	5	7	58.33 %
30-Sep-2002	Contract Calibrate Sand	4-Oct-2002	5	2-Oct-2002	3	2	40.00 %
30-Sep-2002	Contract Calibrate Sand	4-Oct-2002	5	2-Oct-2002	3	2	40.00 %
30-Sep-2002	Contract Calibrate Sand	1-Oct-2002	2	2-Oct-2002	3	-1	-50.00 %
30-Sep-2002	Contract Cut	4-Oct-2002	5	30-Sep-2002	3	2	40.00 %
30-Sep-2002	Contract Spray Lacquer Top and Base Coat	7-Oct-2002	6	2-Oct-2002	1	5	83.33 %
1-Oct-2002	Contract Calibrate Sand	1-Oct-2002	1	2-Oct-2002	2	-1	-100.00 %
1-Oct-2002	Contract Veneer Sand	7-Oct-2002	5	2-Oct-2002	2	3	60.00 %
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002	5	2-Oct-2002	2	3	60.00 %
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002	5	2-Oct-2002	2	3	60.00 %
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002	5	2-Oct-2002	2	3	60.00 %
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002	5	2-Oct-2002	2	3	60.00 %
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002	5	1-Oct-2002	2	3	60.00 %
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002	5	2-Oct-2002	1	4	80.00 %
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002	5	2-Oct-2002	2	3	60.00 %
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002	5	2-Oct-2002	2	3	60.00 %
1-Oct-2002	Contract Calibrate Sand	7-Oct-2002	5	2-Oct-2002	2	3	60.00 %
1-Oct-2002	Contract Cut	3-Oct-2002	3	11-Oct-2002	2	1	33.33 %
1-Oct-2002	Components on Edge	3-Oct-2002	3	2-Oct-2002	9	-6	-200.00 %
1-Oct-2002	Poster Box	1-Nov-2002	26	2-Oct-2002	2	24	92.31 %
2-Oct-2002	Contract Calibrate Sand	2-Oct-2002	1	2-Oct-2002	1	0	0.00 %
2-Oct-2002	Contract Calibrate Sand	7-Oct-2002	4	2-Oct-2002	1	3	75.00 %
2-Oct-2002	Contract Calibrate Sand	7-Oct-2002	4	2-Oct-2002	1	3	75.00 %
2-Oct-2002	Contract Calibrate Sand	7-Oct-2002	4	2-Oct-2002	1	3	75.00 %
2-Oct-2002	Contract Calibrate Sand	7-Oct-2002	4	2-Oct-2002	1	3	75.00 %
2-Oct-2002	Contract Calibrate Sand	9-Oct-2002	6	2-Oct-2002	1	5	83.33 %
2-Oct-2002	Contract Edging	2-Oct-2002	1	2-Oct-2002	1	0	0.00 %
2-Oct-2002	Board Components	3-Oct-2002	2	2-Oct-2002	1	1	50.00 %
2-Oct-2002	Contract Cut	3-Oct-2002	2	2-Oct-2002	1	1	50.00 %
2-Oct-2002	Contract Calibrate Sand	2-Oct-2002	1	7-Oct-2002	1	0	0.00 %
3-Oct-2002	Board Components	24-Oct-2002	17	11-Oct-2002	3	14	82.35 %
3-Oct-2002	Veneer Over Edge	24-Oct-2002	17	7-Oct-2002	7	10	58.82 %
3-Oct-2002	Board Components	18-Oct-2002	13	12-Oct-2002	3	10	76.92 %
3-Oct-2002	Veneer Over Edge	18-Oct-2002	13	8-Oct-2002	8	5	38.46 %
3-Oct-2002	Board Components	18-Oct-2002	13	8-Oct-2002	4	9	69.23 %
3-Oct-2002	Contract Spray Lacquer Top and Base Coat	18-Oct-2002	13	11-Oct-2002	4	9	69.23 %
3-Oct-2002	Contract Spray Lacquer Top and Base Coat	14-Oct-2002	9	10-Oct-2002	7	2	22.22 %

Table F.2 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 20 *minutes.*

		LWC		**Tabu**			
			Net		**Net**	**Improve–**	**%Improve–**
Start Date	**Job Type**	**Dispatch**	**Flow Time**	**Dispatch**	**Flow Time**	**ment**	**ment**
3-Oct-2002	Contract Spray Lacquer Top and Base Coat	14-Oct-2002	9	8-Oct-2002	6	3	33.33 %
3-Oct-2002	Contract Calibrate Sand	9-Oct-2002	5	11-Oct-2002	4	1	20.00 %
3-Oct-2002	Contract Veneer Sand	10-Oct-2002	6	8-Oct-2002	7	-1	-16.67 %
3-Oct-2002	Contract Calibrate Sand	9-Oct-2002	5	11-Oct-2002	4	1	20.00 %
3-Oct-2002	Contract Calibrate Sand	10-Oct-2002	6	8-Oct-2002	7	-1	-16.67 %
3-Oct-2002	Contract Calibrate Sand	7-Oct-2002	3	11-Oct-2002	4	-1	-33.33 %
3-Oct-2002	Contract Calibrate Sand	9-Oct-2002	5	7-Oct-2002	7	-2	-40.00 %
3-Oct-2002	Contract Calibrate Sand	7-Oct-2002	3	11-Oct-2002	3	0	0.00 %
3-Oct-2002	Veneer Over Edge	11-Oct-2002	7	7-Oct-2002	7	0	0.00 %
3-Oct-2002	Contract Calibrate Sand	8-Oct-2002	4	10-Oct-2002	3	1	25.00 %
3-Oct-2002	Contract Cut	3-Oct-2002	1	7-Oct-2002	6	-5	-500.00 %
3-Oct-2002	Contract Cut, Veneer Sand and Edging	16-Dec-2002	57	11-Oct-2002	3	54	94.74 %
4-Oct-2002	Unique	18-Oct-2002	12	11-Oct-2002	6	6	50.00 %
4-Oct-2002	Contract Calibrate Sand	4-Oct-2002	1	8-Oct-2002	6	-5	-500.00 %
4-Oct-2002	Contract Veneer Sand	10-Oct-2002	5	11-Oct-2002	3	2	40.00 %
4-Oct-2002	Contract Calibrate Sand	9-Oct-2002	4	8-Oct-2002	6	-2	-50.00 %
4-Oct-2002	Contract Veneer Sand	9-Oct-2002	4	11-Oct-2002	3	1	25.00 %
4-Oct-2002	Contract Calibrate Sand	10-Oct-2002	5	7-Oct-2002	6	-1	-20.00 %
4-Oct-2002	Contract Calibrate Sand	10-Oct-2002	5	8-Oct-2002	2	3	60.00 %
4-Oct-2002	Contract Calibrate Sand	10-Oct-2002	5	11-Oct-2002	3	2	40.00 %
4-Oct-2002	Contract Calibrate Sand	11-Oct-2002	6	8-Oct-2002	6	0	0.00 %
4-Oct-2002	Contract Calibrate Sand	11-Oct-2002	6	7-Oct-2002	3	3	50.00 %
4-Oct-2002	Contract Calibrate Sand	10-Oct-2002	5	12-Oct-2002	2	3	60.00 %
4-Oct-2002	Contract Calibrate Sand	4-Oct-2002	1	11-Oct-2002	7	-6	-600.00 %
4-Oct-2002	Contract Spray Lacquer Top and Base Coat	10-Oct-2002	5	11-Oct-2002	6	-1	-20.00 %
4-Oct-2002	Contract Spray Lacquer Top and Base Coat	10-Oct-2002	5	11-Oct-2002	6	-1	-20.00 %
4-Oct-2002	Contract Spray Lacquer Top and Base Coat	10-Oct-2002	5	11-Oct-2002	6	-1	-20.00 %
7-Oct-2002	Poster Box	17-Oct-2002	10	11-Oct-2002	5	5	50.00 %
7-Oct-2002	Poster Box	17-Oct-2002	10	8-Oct-2002	5	5	50.00 %
7-Oct-2002	Contract Calibrate Sand	10-Oct-2002	4	11-Oct-2002	2	2	50.00 %
7-Oct-2002	Contract Calibrate Sand	8-Oct-2002	2	14-Oct-2002	5	-3	-150.00 %
7-Oct-2002	Poster Box	7-Oct-2002	1	10-Oct-2002	7	-6	-600.00 %
8-Oct-2002	Poster Box	31-Oct-2002	20	12-Oct-2002	3	17	85.00 %
8-Oct-2002	Veneer Over Edge	14-Oct-2002	6	8-Oct-2002	5	1	16.67 %
8-Oct-2002	Contract Veneer Sand	14-Oct-2002	6	11-Oct-2002	1	5	83.33 %
8-Oct-2002	Contract Calibrate Sand	8-Oct-2002	1	8-Oct-2002	4	-3	-300.00 %
8-Oct-2002	Contract Calibrate Sand	11-Oct-2002	4	11-Oct-2002	1	3	75.00 %
8-Oct-2002	Contract Calibrate Sand	14-Oct-2002	6	12-Oct-2002	4	2	33.33 %
8-Oct-2002	Contract Calibrate Sand	14-Oct-2002	6	11-Oct-2002	5	1	16.67 %
8-Oct-2002	Contract Calibrate Sand	14-Oct-2002	6	10-Oct-2002	4	2	33.33 %
9-Oct-2002	Contract Cut	31-Oct-2002	19	11-Oct-2002	2	17	89.47 %
9-Oct-2002	Contract Calibrate Sand	15-Oct-2002	6	11-Oct-2002	3	3	50.00 %
9-Oct-2002	Contract Calibrate Sand	9-Oct-2002	1	11-Oct-2002	3	-2	-200.00 %
9-Oct-2002	Contract Calibrate Sand	9-Oct-2002	1	10-Oct-2002	3	-2	-200.00 %
10-Oct-2002	Contract Spray Lacquer Top and Base Coat	29-Oct-2002	16	12-Oct-2002	1	15	93.75 %
10-Oct-2002	Shaker Doors	29-Oct-2002	16	10-Oct-2002	3	13	81.25 %
10-Oct-2002	Contract Cut	31-Oct-2002	18	11-Oct-2002	1	17	94.44 %
10-Oct-2002	Contract Veneer Sand	23-Oct-2002	11	11-Oct-2002	2	9	81.82 %
10-Oct-2002	Contract Veneer Sand	17-Oct-2002	7	12-Oct-2002	2	5	71.43 %
10-Oct-2002	Contract Calibrate Sand	14-Oct-2002	4	11-Oct-2002	3	1	25.00 %
10-Oct-2002	Contract Calibrate Sand	16-Oct-2002	6	11-Oct-2002	2	4	66.67 %
10-Oct-2002	Contract Calibrate Sand	16-Oct-2002	6	10-Oct-2002	2	4	66.67 %
10-Oct-2002	Contract Calibrate Sand	16-Oct-2002	6	10-Oct-2002	1	5	83.33 %
10-Oct-2002	Contract Plane all Round(PAR)	11-Oct-2002	2	11-Oct-2002	1	1	50.00 %
11-Oct-2002	Board Components	30-Oct-2002	16	17-Oct-2002	1	15	93.75 %
11-Oct-2002	Veneer Over Edge	30-Oct-2002	16	14-Oct-2002	6	10	62.50 %
11-Oct-2002	Shaker Doors	30-Oct-2002	16	15-Oct-2002	3	13	81.25 %
11-Oct-2002	Unique	30-Oct-2002	16	11-Oct-2002	4	12	75.00 %
11-Oct-2002	Contract Cut	30-Oct-2002	16	11-Oct-2002	1	15	93.75 %
11-Oct-2002	Contract Spray Lacquer Top and Base Coat	23-Oct-2002	10	11-Oct-2002	1	9	90.00 %
11-Oct-2002	Contract Spray: Stain Top Coat	23-Oct-2002	10	11-Oct-2002	1	9	90.00 %
11-Oct-2002	Contract Calibrate Sand	16-Oct-2002	5	12-Oct-2002	1	4	80.00 %

Table F.2 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 20 *minutes.*

		LWC		Tabu			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
11-Oct-2002	Contract Veneer Sand	14-Oct-2002	3	11-Oct-2002	2	1	33.33 %
11-Oct-2002	Contract Calibrate Sand	11-Oct-2002	1	11-Oct-2002	1	0	0.00 %
11-Oct-2002	Contract Calibrate Sand	11-Oct-2002	1	24-Oct-2002	1	0	0.00 %
12-Oct-2002	Contract Cut	31-Oct-2002	16	14-Oct-2002	10	6	37.50 %
14-Oct-2002	Contract Plane all Round(PAR)	17-Oct-2002	4	14-Oct-2002	1	3	75.00 %
14-Oct-2002	Contract Veneer Sand	17-Oct-2002	4	14-Oct-2002	1	3	75.00 %
14-Oct-2002	Contract Cut	15-Oct-2002	2	14-Oct-2002	1	1	50.00 %
14-Oct-2002	Contract Calibrate Sand	18-Oct-2002	5	14-Oct-2002	1	4	80.00 %
14-Oct-2002	Contract Calibrate Sand	18-Oct-2002	5	14-Oct-2002	1	4	80.00 %
14-Oct-2002	Contract Calibrate Sand	18-Oct-2002	5	14-Oct-2002	1	4	80.00 %
14-Oct-2002	Contract Calibrate Sand	18-Oct-2002	5	14-Oct-2002	1	4	80.00 %
14-Oct-2002	Contract Spray: Top and Base Coat	14-Nov-2002	26	14-Oct-2002	1	25	96.15 %
14-Oct-2002	Contract Spray Lacquer Top and Base Coat	12-Nov-2002	24	17-Oct-2002	1	23	95.83 %
14-Oct-2002	Shaker Doors	6-Nov-2002	19	15-Oct-2002	4	15	78.95 %
15-Oct-2002	Contract Cut	31-Oct-2002	14	15-Oct-2002	1	13	92.86 %
15-Oct-2002	Contract Spray Lacquer Top and Base Coat	23-Oct-2002	7	15-Oct-2002	1	6	85.71 %
15-Oct-2002	Contract Plane all Round(PAR)	17-Oct-2002	3	15-Oct-2002	1	2	66.67 %
15-Oct-2002	Contract Plane all Round(PAR)	17-Oct-2002	3	15-Oct-2002	1	2	66.67 %
15-Oct-2002	Contract Calibrate Sand	17-Oct-2002	3	15-Oct-2002	1	2	66.67 %
15-Oct-2002	Contract Calibrate Sand	21-Oct-2002	5	15-Oct-2002	1	4	80.00 %
15-Oct-2002	Contract Calibrate Sand	21-Oct-2002	5	15-Oct-2002	1	4	80.00 %
15-Oct-2002	Contract Calibrate Sand	16-Oct-2002	2	15-Oct-2002	1	1	50.00 %
15-Oct-2002	Contract Calibrate Sand	21-Oct-2002	5	21-Oct-2002	1	4	80.00 %
15-Oct-2002	Veneer Over Edge	6-Nov-2002	18	16-Oct-2002	5	13	72.22 %
16-Oct-2002	Contract Calibrate Sand	16-Oct-2002	1	17-Oct-2002	1	0	0.00 %
16-Oct-2002	Shaker Doors	6-Nov-2002	17	17-Oct-2002	2	15	88.24 %
17-Oct-2002	Contract Cut	31-Oct-2002	12	17-Oct-2002	1	11	91.67 %
17-Oct-2002	Contract Edging	18-Oct-2002	2	17-Oct-2002	1	1	50.00 %
17-Oct-2002	Contract Plane all Round(PAR)	31-Oct-2002	12	17-Oct-2002	1	11	91.67 %
17-Oct-2002	Contract Calibrate Sand	23-Oct-2002	5	17-Oct-2002	1	4	80.00 %
17-Oct-2002	Contract Veneer Sand	23-Oct-2002	5	17-Oct-2002	1	4	80.00 %
17-Oct-2002	Contract Calibrate Sand	23-Oct-2002	5	17-Oct-2002	1	4	80.00 %
17-Oct-2002	Contract Calibrate Sand	23-Oct-2002	5	17-Oct-2002	1	4	80.00 %
17-Oct-2002	Contract Calibrate Sand	23-Oct-2002	5	21-Oct-2002	1	4	80.00 %
17-Oct-2002	Contract Cut	12-Nov-2002	21	18-Oct-2002	3	18	85.71 %
18-Oct-2002	Contract Cut	31-Oct-2002	11	21-Oct-2002	1	10	90.91 %
18-Oct-2002	Unique	18-Oct-2002	1	18-Oct-2002	2	-1	-100.00 %
18-Oct-2002	Contract Veneer Sand	24-Oct-2002	5	18-Oct-2002	1	4	80.00 %
18-Oct-2002	Contract Calibrate Sand	24-Oct-2002	5	18-Oct-2002	1	4	80.00 %
18-Oct-2002	Contract Calibrate Sand	24-Oct-2002	5	18-Oct-2002	1	4	80.00 %
18-Oct-2002	Contract Calibrate Sand	24-Oct-2002	5	21-Oct-2002	1	4	80.00 %
21-Oct-2002	Contract Calibrate Sand	25-Oct-2002	5	23-Oct-2002	1	4	80.00 %
21-Oct-2002	Shaker Doors	8-Nov-2002	16	5-Nov-2002	3	13	81.25 %
21-Oct-2002	Veneer Over Edge	8-Nov-2002	16	21-Oct-2002	13	3	18.75 %
21-Oct-2002	Board Components	8-Nov-2002	16	23-Oct-2002	1	15	93.75 %
21-Oct-2002	Shaker Doors	8-Nov-2002	16	5-Nov-2002	3	13	81.25 %
21-Oct-2002	Veneer Over Edge	8-Nov-2002	16	22-Oct-2002	13	3	18.75 %
22-Oct-2002	Contract Spray: Stain Top Coat	31-Oct-2002	9	23-Oct-2002	1	8	88.89 %
22-Oct-2002	Contract Calibrate Sand	29-Oct-2002	7	23-Oct-2002	2	5	71.43 %
22-Oct-2002	Contract Spray Lacquer Top and Base Coat	29-Oct-2002	7	23-Oct-2002	2	5	71.43 %
22-Oct-2002	Contract Calibrate Sand	28-Oct-2002	6	23-Oct-2002	2	4	66.67 %
22-Oct-2002	Contract Calibrate Sand	28-Oct-2002	6	23-Oct-2002	2	4	66.67 %
22-Oct-2002	Contract Calibrate Sand	22-Oct-2002	1	5-Nov-2002	2	-1	-100.00 %
22-Oct-2002	Veneer Over Edge	5-Nov-2002	12	23-Oct-2002	12	0	0.00 %
23-Oct-2002	Board Components	31-Oct-2002	8	23-Oct-2002	1	7	87.50 %
23-Oct-2002	Contract Calibrate Sand	25-Oct-2002	3	1-Nov-2002	1	2	66.67 %
23-Oct-2002	Veneer Over Edge	14-Nov-2002	19	31-Oct-2002	9	10	52.63 %
23-Oct-2002	Veneer Over Edge	12-Nov-2002	17	21-Nov-2002	8	9	52.94 %
24-Oct-2002	Contract Calibrate Sand	31-Oct-2002	7	19-Nov-2002	23	-16	-228.57 %
24-Oct-2002	Board Components	31-Oct-2002	7	21-Nov-2002	21	-14	-200.00 %
24-Oct-2002	Shaker Doors	31-Oct-2002	7	24-Oct-2002	23	-16	-228.57 %
24-Oct-2002	Contract Edging	28-Oct-2002	4	24-Oct-2002	1	3	75.00 %
24-Oct-2002	Contract Cut	28-Oct-2002	4	24-Oct-2002	1	3	75.00 %
24-Oct-2002	Contract Spray Lacquer Top and Base Coat	28-Oct-2002	4	24-Oct-2002	1	3	75.00 %

Table F.2 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 20 *minutes.*

		LWC		Tabu			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
24-Oct-2002	Contract Calibrate Sand	24-Oct-2002	1	19-Nov-2002	1	0	0.00 %
24-Oct-2002	Contract Calibrate Sand	28-Oct-2002	4	24-Oct-2002	21	-17	-425.00 %
24-Oct-2002	Contract Calibrate Sand	30-Oct-2002	6	24-Oct-2002	1	5	83.33 %
24-Oct-2002	Contract Calibrate Sand	30-Oct-2002	6	21-Nov-2002	1	5	83.33 %
24-Oct-2002	Contract Calibrate Sand	24-Oct-2002	1	1-Nov-2002	23	-22	-2200.00 %
24-Oct-2002	Contract Calibrate Sand	24-Oct-2002	1	24-Oct-2002	8	-7	-700.00 %
24-Oct-2002	Contract Spray Lacquer Top and Base Coat	27-Nov-2002	27	31-Oct-2002	1	26	96.30 %
24-Oct-2002	Shaker Doors	20-Nov-2002	22	22-Nov-2002	7	15	68.18 %
24-Oct-2002	Contract Cut	20-Nov-2002	22	1-Nov-2002	24	-2	-9.09 %
24-Oct-2002	Shaker Doors	5-Dec-2002	33	30-Oct-2002	8	25	75.76 %
24-Oct-2002	Veneer Over Edge	5-Dec-2002	33	25-Oct-2002	6	27	81.82 %
25-Oct-2002	Contract Plane all Round(PAR)	29-Oct-2002	4	25-Oct-2002	1	3	75.00 %
25-Oct-2002	Contract Edging	29-Oct-2002	4	22-Nov-2002	1	3	75.00 %
25-Oct-2002	Contract Cut	31-Oct-2002	6	9-Nov-2002	23	-17	-283.33 %
25-Oct-2002	Unique	31-Oct-2002	6	31-Oct-2002	13	-7	-116.67 %
25-Oct-2002	Contract Calibrate Sand	31-Oct-2002	6	30-Oct-2002	6	0	0.00 %
25-Oct-2002	Contract Calibrate Sand	31-Oct-2002	6	31-Oct-2002	5	1	16.67 %
25-Oct-2002	Contract Veneer Sand	31-Oct-2002	6	31-Oct-2002	6	0	0.00 %
25-Oct-2002	Veneer Over Edge	7-Nov-2002	11	31-Oct-2002	6	5	45.45 %
25-Oct-2002	Contract Veneer Sand	5-Dec-2002	32	5-Nov-2002	6	26	81.25 %
26-Oct-2002	Board Components	31-Oct-2002	5	9-Nov-2002	8	-3	-60.00 %
26-Oct-2002	Contract Cut	31-Oct-2002	5	5-Nov-2002	12	-7	-140.00 %
26-Oct-2002	Board Components	31-Oct-2002	5	5-Nov-2002	8	-3	-60.00 %
26-Oct-2002	Contract Cut	31-Oct-2002	5	5-Nov-2002	8	-3	-60.00 %
28-Oct-2002	Contract Spray: Stain Top Coat	31-Oct-2002	4	19-Nov-2002	7	-3	-75.00 %
28-Oct-2002	Board Components	31-Oct-2002	4	9-Nov-2002	18	-14	-350.00 %
28-Oct-2002	Board Components	31-Oct-2002	4	21-Nov-2002	11	-7	-175.00 %
28-Oct-2002	Contract Calibrate Sand	31-Oct-2002	4	31-Oct-2002	20	-16	-400.00 %
28-Oct-2002	Contract Calibrate Sand	31-Oct-2002	4	1-Nov-2002	4	0	0.00 %
28-Oct-2002	Contract Calibrate Sand	31-Oct-2002	4	9-Nov-2002	5	-1	-25.00 %
28-Oct-2002	Contract Calibrate Sand	31-Oct-2002	4	1-Nov-2002	11	-7	-175.00 %
28-Oct-2002	Contract Calibrate Sand	31-Oct-2002	4	31-Oct-2002	5	-1	-25.00 %
28-Oct-2002	Contract Veneer Sand	31-Oct-2002	4	30-Oct-2002	4	0	0.00 %
28-Oct-2002	Contract Calibrate Sand	31-Oct-2002	4	30-Oct-2002	3	1	25.00 %
28-Oct-2002	Contract Spray Lacquer Top and Base Coat	27-Nov-2002	24	28-Oct-2002	3	21	87.50 %
28-Oct-2002	Contract Cut	18-Nov-2002	17	30-Oct-2002	1	16	94.12 %
28-Oct-2002	Contract Calibrate Sand	1-Nov-2002	5	5-Nov-2002	3	2	40.00 %
29-Oct-2002	Veneer Over Edge	29-Oct-2002	1	1-Nov-2002	6	-5	-500.00 %
29-Oct-2002	Contract Calibrate Sand	29-Oct-2002	1	19-Nov-2002	4	-3	-300.00 %
29-Oct-2002	Contract Calibrate Sand	29-Oct-2002	1	5-Nov-2002	17	-16	-1600.00 %
29-Oct-2002	Veneer Over Edge	26-Nov-2002	22	30-Oct-2002	6	16	72.73 %
29-Oct-2002	Contract Cut	21-Nov-2002	19	5-Nov-2002	2	17	89.47 %
29-Oct-2002	Contract Cut	21-Nov-2002	19	31-Oct-2002	6	13	68.42 %
29-Oct-2002	Contract Spray: Lacquer Top and Base Coat and Calibrate and Veneer Sand	12-Nov-2002	12	1-Nov-2002	3	9	75.00 %
30-Oct-2002	Contract Cut	31-Oct-2002	2	5-Nov-2002	3	-1	-50.00 %
30-Oct-2002	Contract Cut	31-Oct-2002	2	22-Nov-2002	5	-3	-150.00 %
30-Oct-2002	Contract Cut	30-Oct-2002	1	15-Nov-2002	19	-18	-1800.00 %
30-Oct-2002	Contract Calibrate Sand	31-Oct-2002	2	31-Oct-2002	14	-12	-600.00 %
30-Oct-2002	Contract Spray Lacquer Top and Base Coat	8-Nov-2002	8	1-Nov-2002	2	6	75.00 %
30-Oct-2002	Contract Spray Lacquer Top and Base Coat	8-Nov-2002	8	30-Oct-2002	3	5	62.50 %
30-Oct-2002	Contract Plane all Round(PAR)	5-Nov-2002	5	11-Nov-2002	1	4	80.00 %
30-Oct-2002	Contract Spray: Stain Top Coat	6-Nov-2002	6	5-Nov-2002	10	-4	-66.67 %
31-Oct-2002	Contract Cut	31-Oct-2002	1	31-Oct-2002	4	-3	-300.00 %
31-Oct-2002	Contract Cut	31-Oct-2002	1	1-Nov-2002	1	0	0.00 %
31-Oct-2002	Contract Edging	31-Oct-2002	1	4-Nov-2002	2	-1	-100.00 %
31-Oct-2002	Contract Calibrate Sand	31-Oct-2002	1	9-Nov-2002	3	-2	-200.00 %
31-Oct-2002	Veneer Over Edge	21-Nov-2002	17	9-Nov-2002	8	9	52.94 %
31-Oct-2002	Shaker Doors	29-Nov-2002	23	8-Nov-2002	8	15	65.22 %
31-Oct-2002	Veneer Over Edge	15-Nov-2002	13	9-Nov-2002	7	6	46.15 %
31-Oct-2002	Contract Cut	21-Nov-2002	17	4-Nov-2002	8	9	52.94 %
31-Oct-2002	Contract Calibrate and Veneer Sand	14-Nov-2002	12	9-Nov-2002	3	9	75.00 %
31-Oct-2002	Veneer Over Edge	11-Nov-2002	9	1-Nov-2002	8	1	11.11 %
31-Oct-2002	Contract Calibrate Sand	6-Nov-2002	5	9-Nov-2002	2	3	60.00 %

Table F.2 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 20 *minutes.*

		LWC		**Tabu**			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
31-Oct-2002	Contract Veneer Sand	6-Nov-2002	5	1-Nov-2002	8	-3	-60.00 %
31-Oct-2002	Contract Calibrate Sand	6-Nov-2002	5	5-Nov-2002	2	3	60.00 %
31-Oct-2002	Contract Calibrate Sand	1-Nov-2002	2	9-Nov-2002	4	-2	-100.00 %
1-Nov-2002	Veneer Over Edge	20-Nov-2002	15	5-Nov-2002	7	8	53.33 %
1-Nov-2002	Contract Calibrate Sand	7-Nov-2002	5	19-Nov-2002	3	2	40.00 %
1-Nov-2002	Contract Cut	6-Nov-2002	4	19-Nov-2002	14	-10	-250.00 %
1-Nov-2002	Contract Cut, Edge and Calibrate Sand	7-Nov-2002	5	1-Nov-2002	14	-9	-180.00 %
1-Nov-2002	Contract Calibrate Sand	5-Nov-2002	3	19-Nov-2002	1	2	66.67 %
1-Nov-2002	Contract Calibrate Sand	4-Nov-2002	2	5-Nov-2002	14	-12	-600.00 %
4-Nov-2002	Contract Calibrate Sand	6-Nov-2002	3	4-Nov-2002	2	1	33.33 %
4-Nov-2002	Contract Cut	6-Nov-2002	3	5-Nov-2002	1	2	66.67 %
4-Nov-2002	Contract Veneer Sand	8-Nov-2002	5	5-Nov-2002	2	3	60.00 %
4-Nov-2002	Contract Calibrate Sand	8-Nov-2002	5	9-Nov-2002	2	3	60.00 %
4-Nov-2002	Contract Calibrate Sand	5-Nov-2002	2	5-Nov-2002	6	-4	-200.00 %
5-Nov-2002	Board Components	13-Nov-2002	8	19-Nov-2002	1	7	87.50 %
5-Nov-2002	Contract Calibrate Sand	11-Nov-2002	6	5-Nov-2002	12	-6	-100.00 %
5-Nov-2002	Contract Veneer Sand	11-Nov-2002	6	5-Nov-2002	1	5	83.33 %
5-Nov-2002	Contract Calibrate Sand	11-Nov-2002	6	9-Nov-2002	1	5	83.33 %
5-Nov-2002	Contract Calibrate Sand	11-Nov-2002	6	19-Nov-2002	5	1	16.67 %
5-Nov-2002	Contract Calibrate Sand	7-Nov-2002	3	5-Nov-2002	12	-9	-300.00 %
5-Nov-2002	Contract Calibrate Sand	6-Nov-2002	2	21-Nov-2002	1	1	50.00 %
5-Nov-2002	Contract Calibrate Sand	5-Nov-2002	1	19-Nov-2002	14	-13	-1300.00 %
6-Nov-2002	Contract Calibrate Sand	6-Nov-2002	1	15-Nov-2002	11	-10	-1000.00 %
6-Nov-2002	Veneer Over Edge	2-Dec-2002	20	22-Nov-2002	9	11	55.00 %
6-Nov-2002	Unique	27-Nov-2002	17	9-Nov-2002	14	3	17.65 %
6-Nov-2002	Contract Calibrate Sand	12-Nov-2002	6	9-Nov-2002	4	2	33.33 %
6-Nov-2002	Contract Calibrate Sand	12-Nov-2002	6	9-Nov-2002	4	2	33.33 %
6-Nov-2002	Contract Calibrate Sand	12-Nov-2002	6	9-Nov-2002	4	2	33.33 %
6-Nov-2002	Contract Calibrate Sand	12-Nov-2002	6	19-Nov-2002	4	2	33.33 %
7-Nov-2002	Contract Veneer Sand	7-Nov-2002	1	21-Nov-2002	10	-9	-900.00 %
7-Nov-2002	Contract Calibrate Sand	7-Nov-2002	1	12-Nov-2002	12	-11	-1100.00 %
7-Nov-2002	Components on Edge	28-Nov-2002	17	7-Nov-2002	5	12	70.59 %
7-Nov-2002	Contract Edging	28-Nov-2002	17	9-Nov-2002	1	16	94.12 %
7-Nov-2002	Board Components	27-Nov-2002	16	9-Nov-2002	3	13	81.25 %
7-Nov-2002	Shaker Doors	27-Nov-2002	16	9-Nov-2002	3	13	81.25 %
7-Nov-2002	Contract Cut	8-Nov-2002	2	9-Nov-2002	3	-1	-50.00 %
7-Nov-2002	Contract Cut	15-Nov-2002	8	7-Nov-2002	3	5	62.50 %
7-Nov-2002	Contract Spray Lacquer Top and Base Coat	13-Nov-2002	6	9-Nov-2002	1	5	83.33 %
7-Nov-2002	Shaker Doors	4-Dec-2002	21	19-Nov-2002	3	18	85.71 %
8-Nov-2002	Veneer Over Edge	28-Nov-2002	16	19-Nov-2002	9	7	43.75 %
8-Nov-2002	Veneer Over Edge	28-Nov-2002	16	19-Nov-2002	9	7	43.75 %
8-Nov-2002	Veneer Over Edge	28-Nov-2002	16	8-Nov-2002	9	7	43.75 %
8-Nov-2002	Contract Spray Lacquer Top and Base Coat	21-Nov-2002	11	8-Nov-2002	1	10	90.91 %
8-Nov-2002	Contract Cut	12-Nov-2002	4	9-Nov-2002	1	3	75.00 %
8-Nov-2002	Contract Cut and Spray	15-Nov-2002	7	9-Nov-2002	2	5	71.43 %
8-Nov-2002	Contract Calibrate Sand	14-Nov-2002	6	19-Nov-2002	2	4	66.67 %
8-Nov-2002	Contract Calibrate Sand	14-Nov-2002	6	9-Nov-2002	9	-3	-50.00 %
8-Nov-2002	Contract Calibrate Sand	14-Nov-2002	6	9-Nov-2002	2	4	66.67 %
8-Nov-2002	Contract Veneer Sand	12-Nov-2002	4	9-Nov-2002	2	2	50.00 %
8-Nov-2002	Contract Veneer Sand	12-Nov-2002	4	21-Nov-2002	2	2	50.00 %
8-Nov-2002	Contract Calibrate Sand	14-Nov-2002	6	14-Nov-2002	11	-5	-83.33 %
9-Nov-2002	Contract Calibrate and Veneer Sand	12-Nov-2002	3	13-Nov-2002	5	-2	-66.67 %
11-Nov-2002	Poster Box	27-Nov-2002	13	19-Nov-2002	3	10	76.92 %
11-Nov-2002	Veneer Over Edge	14-Nov-2002	4	11-Nov-2002	7	-3	-75.00 %
11-Nov-2002	Contract Edging	15-Nov-2002	5	15-Nov-2002	1	4	80.00 %
11-Nov-2002	Contract Spray: Top and Base Coat	13-Nov-2002	3	19-Nov-2002	5	-2	-66.67 %
11-Nov-2002	Contract Cut	11-Nov-2002	1	19-Nov-2002	7	-6	-600.00 %
11-Nov-2002	Contract Spray Lacquer Top and Base Coat	11-Nov-2002	1	19-Nov-2002	7	-6	-600.00 %
11-Nov-2002	Contract Spray: Stain Top Coat	14-Nov-2002	4	19-Nov-2002	7	-3	-75.00 %
11-Nov-2002	Contract Calibrate Sand	15-Nov-2002	5	18-Nov-2002	7	-2	-40.00 %
11-Nov-2002	Contract Calibrate Sand	15-Nov-2002	5	11-Nov-2002	6	-1	-20.00 %
11-Nov-2002	Contract Calibrate Sand	15-Nov-2002	5	15-Nov-2002	1	4	80.00 %
11-Nov-2002	Contract Calibrate Sand	15-Nov-2002	5	19-Nov-2002	5	0	0.00 %
11-Nov-2002	Contract Veneer Sand	15-Nov-2002	5	18-Nov-2002	7	-2	-40.00 %
11-Nov-2002	Contract Veneer Sand	15-Nov-2002	5	19-Nov-2002	6	-1	-20.00 %

Table F.2 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 20 *minutes.*

		LWC		**Tabu**			
			Net		**Net**	**Improve–**	**%Improve–**
Start Date	**Job Type**	**Dispatch**	**Flow Time**	**Dispatch**	**Flow Time**	**ment**	**ment**
11-Nov-2002	Contract Veneer Sand	15-Nov-2002	5	18-Nov-2002	7	-2	-40.00 %
11-Nov-2002	Contract Calibrate Sand	15-Nov-2002	5	19-Nov-2002	6	-1	-20.00 %
11-Nov-2002	Contract Calibrate Sand	15-Nov-2002	5	21-Nov-2002	7	-2	-40.00 %
11-Nov-2002	Contract Calibrate Sand	15-Nov-2002	5	19-Nov-2002	9	-4	-80.00 %
11-Nov-2002	Contract Calibrate Sand	15-Nov-2002	5	18-Nov-2002	7	-2	-40.00 %
11-Nov-2002	Contract Veneer Sand	3-Dec-2002	17	11-Nov-2002	6	11	64.71 %
11-Nov-2002	Contract Veneer Sand	3-Dec-2002	17	19-Nov-2002	1	16	94.12 %
11-Nov-2002	Contract Veneer Sand	3-Dec-2002	17	21-Nov-2002	7	10	58.82 %
11-Nov-2002	Board Components	10-Dec-2002	23	19-Nov-2002	9	14	60.87 %
11-Nov-2002	Shaker Doors	10-Dec-2002	23	19-Nov-2002	7	16	69.57 %
11-Nov-2002	Shaker Doors	13-Dec-2002	26	19-Nov-2002	7	19	73.08 %
11-Nov-2002	Board Components	13-Dec-2002	26	14-Nov-2002	7	19	73.08 %
11-Nov-2002	Shaker Doors	13-Dec-2002	26	19-Nov-2002	4	22	84.62 %
11-Nov-2002	Veneer Over Edge	4-Dec-2002	18	21-Nov-2002	7	11	61.11 %
11-Nov-2002	Contract Calibrate and Veneer Sand	14-Nov-2002	4	19-Nov-2002	9	-5	-125.00 %
11-Nov-2002	Poster Box	3-Dec-2002	17	18-Nov-2002	7	10	58.82 %
12-Nov-2002	Contract Calibrate Sand	12-Nov-2002	1	13-Nov-2002	5	-4	-400.00 %
12-Nov-2002	Contract Cut	15-Nov-2002	4	19-Nov-2002	2	2	50.00 %
12-Nov-2002	Contract Veneer Sand	18-Nov-2002	5	19-Nov-2002	6	-1	-20.00 %
12-Nov-2002	Contract Veneer Sand	18-Nov-2002	5	19-Nov-2002	6	-1	-20.00 %
12-Nov-2002	Contract Veneer Sand	18-Nov-2002	5	19-Nov-2002	6	-1	-20.00 %
12-Nov-2002	Contract Veneer Sand	18-Nov-2002	5	19-Nov-2002	6	-1	-20.00 %
12-Nov-2002	Contract Veneer Sand	18-Nov-2002	5	19-Nov-2002	6	-1	-20.00 %
12-Nov-2002	Contract Veneer Sand	18-Nov-2002	5	19-Nov-2002	6	-1	-20.00 %
12-Nov-2002	Contract Veneer Sand	18-Nov-2002	5	19-Nov-2002	6	-1	-20.00 %
12-Nov-2002	Contract Veneer Sand	18-Nov-2002	5	21-Nov-2002	6	-1	-20.00 %
12-Nov-2002	Contract Calibrate Sand	18-Nov-2002	5	19-Nov-2002	8	-3	-60.00 %
12-Nov-2002	Contract Calibrate Sand	18-Nov-2002	5	19-Nov-2002	6	-1	-20.00 %
12-Nov-2002	Contract Calibrate Sand	18-Nov-2002	5	13-Nov-2002	6	-1	-20.00 %
13-Nov-2002	Contract Plane all Round(PAR)	21-Nov-2002	7	14-Nov-2002	1	6	85.71 %
13-Nov-2002	Contract Cut and Edge	26-Nov-2002	10	14-Nov-2002	2	8	80.00 %
13-Nov-2002	Contract Cut	15-Nov-2002	3	13-Nov-2002	2	1	33.33 %
13-Nov-2002	Contract Spray Lacquer Top and Base Coat	29-Nov-2002	13	19-Nov-2002	1	12	92.31 %
13-Nov-2002	Contract Veneer Sand	19-Nov-2002	5	19-Nov-2002	5	0	0.00 %
13-Nov-2002	Contract Veneer Sand	20-Nov-2002	6	19-Nov-2002	5	1	16.67 %
13-Nov-2002	Contract Veneer Sand	19-Nov-2002	5	21-Nov-2002	5	0	0.00 %
13-Nov-2002	Contract Calibrate Sand	20-Nov-2002	6	19-Nov-2002	7	-1	-16.67 %
13-Nov-2002	Shaker Doors	17-Dec-2002	26	19-Nov-2002	5	21	80.77 %
14-Nov-2002	Shaker Doors	28-Nov-2002	11	19-Nov-2002	4	7	63.64 %
14-Nov-2002	Contract Spray Lacquer Top and Base Coat	18-Nov-2002	3	14-Nov-2002	4	-1	-33.33 %
14-Nov-2002	Contract Spray Lacquer Top and Base Coat	18-Nov-2002	3	21-Nov-2002	1	2	66.67 %
14-Nov-2002	Contract Calibrate Sand	15-Nov-2002	2	19-Nov-2002	6	-4	-200.00 %
14-Nov-2002	Shaker Doors	16-Dec-2002	24	19-Nov-2002	4	20	83.33 %
14-Nov-2002	Shaker Doors	10-Dec-2002	20	21-Nov-2002	4	16	80.00 %
14-Nov-2002	Board Components	10-Dec-2002	20	19-Nov-2002	6	14	70.00 %
14-Nov-2002	Shaker Doors	10-Dec-2002	20	19-Nov-2002	4	16	80.00 %
14-Nov-2002	Board Components	10-Dec-2002	20	21-Nov-2002	4	16	80.00 %
14-Nov-2002	Contract Spray: Base Coat	10-Dec-2002	20	15-Nov-2002	6	14	70.00 %
15-Nov-2002	Unique	27-Nov-2002	9	19-Nov-2002	1	8	88.89 %
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002	5	19-Nov-2002	3	2	40.00 %
15-Nov-2002	Contract Veneer Sand	21-Nov-2002	5	19-Nov-2002	3	2	40.00 %
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002	5	18-Nov-2002	3	2	40.00 %
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002	5	19-Nov-2002	2	3	60.00 %
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002	5	18-Nov-2002	3	2	40.00 %
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002	5	19-Nov-2002	2	3	60.00 %
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002	5	18-Nov-2002	3	2	40.00 %
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002	5	19-Nov-2002	2	3	60.00 %
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002	5	19-Nov-2002	3	2	40.00 %
15-Nov-2002	Contract Calibrate Sand	20-Nov-2002	4	21-Nov-2002	3	1	25.00 %
15-Nov-2002	Contract Calibrate Sand	21-Nov-2002	5	19-Nov-2002	5	0	0.00 %
18-Nov-2002	Contract Calibrate Sand	18-Nov-2002	1	19-Nov-2002	2	-1	-100.00 %
18-Nov-2002	Contract Calibrate Sand	18-Nov-2002	1	19-Nov-2002	2	-1	-100.00 %
18-Nov-2002	Contract Spray Lacquer Top and Base Coat	22-Nov-2002	5	18-Nov-2002	2	3	60.00 %
18-Nov-2002	Contract Spray Lacquer Top and Base Coat	21-Nov-2002	4	19-Nov-2002	1	3	75.00 %

Table F.2 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 20 *minutes.*

		LWC		**Tabu**		**Improve–ment**	**%Improve–ment**
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**		
18-Nov-2002	Contract Cut	20-Nov-2002	3	19-Nov-2002	2	1	33.33 %
18-Nov-2002	Contract Calibrate Sand	26-Nov-2002	7	21-Nov-2002	2	5	71.43 %
18-Nov-2002	Contract Calibrate Sand	26-Nov-2002	7	19-Nov-2002	4	3	42.86 %
18-Nov-2002	Contract Calibrate Sand	21-Nov-2002	4	19-Nov-2002	2	2	50.00 %
18-Nov-2002	Contract Calibrate Sand	21-Nov-2002	4	19-Nov-2002	2	2	50.00 %
18-Nov-2002	Contract Calibrate Sand	22-Nov-2002	5	19-Nov-2002	2	3	60.00 %
18-Nov-2002	Contract Calibrate Sand	22-Nov-2002	5	19-Nov-2002	2	3	60.00 %
18-Nov-2002	Contract Calibrate Sand	22-Nov-2002	5	19-Nov-2002	2	3	60.00 %
18-Nov-2002	Contract Calibrate Sand	22-Nov-2002	5	19-Nov-2002	2	3	60.00 %
18-Nov-2002	Contract Calibrate Sand	22-Nov-2002	5	21-Nov-2002	2	3	60.00 %
18-Nov-2002	Contract Calibrate Sand	22-Nov-2002	5	19-Nov-2002	4	1	20.00 %
18-Nov-2002	Contract Calibrate Sand	21-Nov-2002	4	19-Nov-2002	2	2	50.00 %
18-Nov-2002	Contract Cut and Assembly	29-Jan-2003	52	18-Nov-2002	2	50	96.15 %
18-Nov-2002	Contract Spray Lacquer Top and Base Coat	12-Dec-2002	20	19-Nov-2002	1	19	95.00 %
19-Nov-2002	Contract Spray: Stain Top Coat	27-Nov-2002	7	19-Nov-2002	1	6	85.71 %
19-Nov-2002	Contract Calibrate Sand	20-Nov-2002	2	19-Nov-2002	1	1	50.00 %
19-Nov-2002	Contract Calibrate Sand	19-Nov-2002	1	19-Nov-2002	1	0	0.00 %
19-Nov-2002	Contract Edging	20-Nov-2002	2	19-Nov-2002	1	1	50.00 %
19-Nov-2002	Board Components	20-Nov-2002	2	19-Nov-2002	1	1	50.00 %
19-Nov-2002	Contract Calibrate Sand	27-Nov-2002	7	19-Nov-2002	1	6	85.71 %
19-Nov-2002	Contract Calibrate Sand	25-Nov-2002	5	21-Nov-2002	1	4	80.00 %
19-Nov-2002	Contract Calibrate Sand	25-Nov-2002	5	19-Nov-2002	3	2	40.00 %
19-Nov-2002	Contract Calibrate Sand	25-Nov-2002	5	21-Nov-2002	1	4	80.00 %
19-Nov-2002	Contract Calibrate Sand	19-Nov-2002	1	26-Nov-2002	3	-2	-200.00 %
19-Nov-2002	Veneer Over Edge	13-Dec-2002	20	25-Nov-2002	6	14	70.00 %
19-Nov-2002	Components on Edge	13-Dec-2002	20	19-Nov-2002	5	15	75.00 %
19-Nov-2002	Board Components	13-Dec-2002	20	21-Nov-2002	1	19	95.00 %
19-Nov-2002	Shaker Doors	5-Dec-2002	13	21-Nov-2002	3	10	76.92 %
20-Nov-2002	Board Components	22-Nov-2002	3	21-Nov-2002	2	1	33.33 %
20-Nov-2002	Contract Veneer Sand	21-Nov-2002	2	21-Nov-2002	2	0	0.00 %
20-Nov-2002	Contract Cut	20-Nov-2002	1	21-Nov-2002	2	-1	-100.00 %
20-Nov-2002	Contract Calibrate Sand	27-Nov-2002	6	21-Nov-2002	2	4	66.67 %
20-Nov-2002	Contract Calibrate Sand	28-Nov-2002	7	21-Nov-2002	2	5	71.43 %
20-Nov-2002	Contract Cut and Spray	5-Dec-2002	12	21-Nov-2002	2	10	83.33 %
20-Nov-2002	Shaker Doors	4-Dec-2002	11	21-Nov-2002	2	9	81.82 %
21-Nov-2002	Contract Calibrate Sand	21-Nov-2002	1	21-Nov-2002	1	0	0.00 %
21-Nov-2002	Contract Calibrate Sand	21-Nov-2002	1	21-Nov-2002	1	0	0.00 %
21-Nov-2002	Contract Calibrate Sand	21-Nov-2002	1	21-Nov-2002	1	0	0.00 %
21-Nov-2002	Contract Calibrate Sand	21-Nov-2002	1	21-Nov-2002	1	0	0.00 %
21-Nov-2002	Contract Spray Lacquer Top and Base Coat	27-Nov-2002	5	21-Nov-2002	1	4	80.00 %
21-Nov-2002	Contract Spray: Stain Top Coat	26-Nov-2002	4	21-Nov-2002	1	3	75.00 %
21-Nov-2002	Contract Plane all Round(PAR)	22-Nov-2002	2	21-Nov-2002	1	1	50.00 %
21-Nov-2002	Contract Plane all Round(PAR)	22-Nov-2002	2	21-Nov-2002	1	1	50.00 %
21-Nov-2002	Contract Calibrate Sand	22-Nov-2002	2	21-Nov-2002	1	1	50.00 %
21-Nov-2002	Contract Calibrate Sand	22-Nov-2002	2	21-Nov-2002	1	1	50.00 %
21-Nov-2002	Contract Edging and Calibrate Sand	21-Nov-2002	1	29-Nov-2002	1	0	0.00 %
21-Nov-2002	Veneer Over Edge	17-Dec-2002	20	29-Nov-2002	7	13	65.00 %
21-Nov-2002	Veneer Over Edge	17-Dec-2002	20	22-Nov-2002	7	13	65.00 %
21-Nov-2002	Shaker Doors	5-Dec-2002	11	21-Nov-2002	2	9	81.82 %
21-Nov-2002	Board Components	5-Dec-2002	11	22-Nov-2002	1	10	90.91 %
22-Nov-2002	Contract Edging	22-Nov-2002	1	22-Nov-2002	1	0	0.00 %
22-Nov-2002	Contract Spray: Stain Top Coat	27-Nov-2002	4	22-Nov-2002	1	3	75.00 %
22-Nov-2002	Contract Calibrate Sand	28-Nov-2002	5	22-Nov-2002	1	4	80.00 %
22-Nov-2002	Contract Calibrate Sand	3-Dec-2002	8	26-Nov-2002	1	7	87.50 %
25-Nov-2002	Contract Calibrate Sand	26-Nov-2002	2	25-Nov-2002	2	0	0.00 %
25-Nov-2002	Contract Calibrate Sand	26-Nov-2002	2	25-Nov-2002	1	1	50.00 %
25-Nov-2002	Contract Calibrate Sand	4-Dec-2002	8	25-Nov-2002	1	7	87.50 %
25-Nov-2002	Contract Calibrate Sand	4-Dec-2002	8	25-Nov-2002	1	7	87.50 %
25-Nov-2002	Contract Calibrate Sand	4-Dec-2002	8	25-Nov-2002	1	7	87.50 %
25-Nov-2002	Contract Calibrate Sand	4-Dec-2002	8	25-Nov-2002	1	7	87.50 %
25-Nov-2002	Contract Calibrate Sand	29-Nov-2002	5	25-Nov-2002	1	4	80.00 %
25-Nov-2002	Contract Calibrate Sand	4-Dec-2002	8	25-Nov-2002	1	7	87.50 %
25-Nov-2002	Contract Calibrate Sand	4-Dec-2002	8	25-Nov-2002	1	7	87.50 %
25-Nov-2002	Contract Calibrate Sand	4-Dec-2002	8	25-Nov-2002	1	7	87.50 %
25-Nov-2002	Contract Calibrate Sand	29-Nov-2002	5	5-Dec-2002	1	4	80.00 %
25-Nov-2002	Veneer Over Edge	17-Dec-2002	18	29-Nov-2002	9	9	50.00 %
26-Nov-2002	Contract Cut	26-Nov-2002	1	26-Nov-2002	4	-3	-300.00 %

Table F.2 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 20 *minutes.*

		LWC		Tabu			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improve–ment**	**%Improve–ment**
26-Nov-2002	Contract Calibrate Sand	27-Nov-2002	2	26-Nov-2002	1	1	50.00 %
26-Nov-2002	Contract Plane all Round(PAR)	28-Nov-2002	3	26-Nov-2002	1	2	66.67 %
26-Nov-2002	Contract Plane all Round(PAR)	28-Nov-2002	3	26-Nov-2002	1	2	66.67 %
26-Nov-2002	Contract Calibrate Sand	28-Nov-2002	3	26-Nov-2002	1	2	66.67 %
26-Nov-2002	Board Components	27-Nov-2002	2	5-Dec-2002	1	1	50.00 %
26-Nov-2002	Veneer Over Edge	27-Nov-2002	2	5-Dec-2002	8	-6	-300.00 %
26-Nov-2002	Veneer Over Edge	27-Nov-2002	2	26-Nov-2002	8	-6	-300.00 %
26-Nov-2002	Contract Cut	26-Nov-2002	1	26-Nov-2002	1	0	0.00 %
26-Nov-2002	Contract Calibrate Sand	4-Dec-2002	7	26-Nov-2002	1	6	85.71 %
26-Nov-2002	Contract Calibrate Sand	5-Dec-2002	8	26-Nov-2002	1	7	87.50 %
26-Nov-2002	Contract Calibrate Sand	5-Dec-2002	8	26-Nov-2002	1	7	87.50 %
26-Nov-2002	Contract Calibrate Sand	3-Dec-2002	6	26-Nov-2002	1	5	83.33 %
26-Nov-2002	Contract Calibrate Sand	13-Dec-2002	15	26-Nov-2002	1	14	93.33 %
26-Nov-2002	Contract Veneer Sand	4-Dec-2002	7	28-Nov-2002	1	6	85.71 %
26-Nov-2002	Shaker Doors	16-Dec-2002	16	5-Dec-2002	3	13	81.25 %
26-Nov-2002	Veneer Over Edge	16-Dec-2002	16	26-Nov-2002	8	8	50.00 %
26-Nov-2002	Contract Spray Lacquer Top and Base Coat	28-Nov-2002	3	26-Nov-2002	1	2	66.67 %
26-Nov-2002	Contract PAR, Rip and Groove	11-Dec-2002	13	26-Nov-2002	1	12	92.31 %
26-Nov-2002	Contract Plane all Round(PAR)	11-Dec-2002	13	5-Dec-2002	1	12	92.31 %
26-Nov-2002	Veneer Over Edge	10-Dec-2002	12	26-Nov-2002	8	4	33.33 %
26-Nov-2002	Contract Spray: Base Coat and Route	10-Dec-2002	12	29-Nov-2002	1	11	91.67 %
27-Nov-2002	Contract Cut	29-Nov-2002	3	29-Nov-2002	3	0	0.00 %
27-Nov-2002	Contract Calibrate Sand	29-Nov-2002	3	29-Nov-2002	3	0	0.00 %
27-Nov-2002	Contract Calibrate Sand	29-Nov-2002	3	29-Nov-2002	3	0	0.00 %
27-Nov-2002	Contract Calibrate Sand	27-Nov-2002	1	29-Nov-2002	3	-2	-200.00 %
27-Nov-2002	Contract Calibrate Sand	27-Nov-2002	1	29-Nov-2002	3	-2	-200.00 %
27-Nov-2002	Shaker Doors	17-Dec-2002	16	29-Nov-2002	3	13	81.25 %
27-Nov-2002	Contract Veneer Sand	4-Dec-2002	6	2-Dec-2002	3	3	50.00 %
27-Nov-2002	Contract Calibrate Sand	3-Dec-2002	5	29-Nov-2002	4	1	20.00 %
27-Nov-2002	Contract Calibrate Sand	3-Dec-2002	5	5-Dec-2002	3	2	40.00 %
27-Nov-2002	Veneer Over Edge	13-Dec-2002	14	27-Nov-2002	7	7	50.00 %
27-Nov-2002	Contract Edging	6-Dec-2002	8	29-Nov-2002	1	7	87.50 %
27-Nov-2002	Contract Cut	6-Dec-2002	8	29-Nov-2002	3	5	62.50 %
28-Nov-2002	Contract Calibrate Sand	6-Dec-2002	7	29-Nov-2002	2	5	71.43 %
28-Nov-2002	Contract Calibrate Sand	6-Dec-2002	7	4-Dec-2002	2	5	71.43 %
28-Nov-2002	Contract Calibrate Sand	6-Dec-2002	7	29-Nov-2002	5	2	28.57 %
28-Nov-2002	Contract Calibrate Sand	4-Dec-2002	5	29-Nov-2002	2	3	60.00 %
29-Nov-2002	Contract Calibrate Sand	29-Nov-2002	1	29-Nov-2002	1	0	0.00 %
29-Nov-2002	Contract Calibrate Sand	6-Dec-2002	6	29-Nov-2002	1	5	83.33 %
29-Nov-2002	Contract Veneer Sand	5-Dec-2002	5	29-Nov-2002	1	4	80.00 %
29-Nov-2002	Contract Veneer Sand	4-Dec-2002	4	3-Dec-2002	1	3	75.00 %
29-Nov-2002	Contract Calibrate Sand	3-Dec-2002	3	5-Dec-2002	3	0	0.00 %
29-Nov-2002	Veneer Over Edge	11-Dec-2002	10	5-Dec-2002	5	5	50.00 %
29-Nov-2002	Board Components	11-Dec-2002	10	29-Nov-2002	5	5	50.00 %
29-Nov-2002	Contract Cut and Edge	3-Dec-2002	3	4-Dec-2002	1	2	66.67 %
29-Nov-2002	Contract Cut	3-Dec-2002	3	8-Dec-2002	4	-1	-33.33 %
2-Dec-2002	Veneer Over Edge	11-Dec-2002	9	5-Dec-2002	6	3	33.33 %
2-Dec-2002	Contract Veneer Sand	13-Dec-2002	11	5-Dec-2002	4	7	63.64 %
2-Dec-2002	Contract Calibrate Sand	5-Dec-2002	4	4-Dec-2002	4	0	0.00 %
2-Dec-2002	Contract Calibrate Sand	3-Dec-2002	2	8-Dec-2002	3	-1	-50.00 %
2-Dec-2002	Veneer Over Edge	12-Dec-2002	10	2-Dec-2002	6	4	40.00 %
2-Dec-2002	Contract Edging	10-Dec-2002	8	5-Dec-2002	1	7	87.50 %
2-Dec-2002	Contract Calibrate and Veneer Sand	3-Dec-2002	2	5-Dec-2002	4	-2	-100.00 %
2-Dec-2002	Contract Calibrate Sand	3-Dec-2002	2	5-Dec-2002	4	-2	-100.00 %
3-Dec-2002	Contract Veneer Sand	13-Dec-2002	10	5-Dec-2002	3	7	70.00 %
3-Dec-2002	Contract Calibrate Sand	13-Dec-2002	10	5-Dec-2002	3	7	70.00 %
3-Dec-2002	Contract Calibrate Sand	11-Dec-2002	8	5-Dec-2002	3	5	62.50 %
3-Dec-2002	Contract Calibrate Sand	11-Dec-2002	8	5-Dec-2002	3	5	62.50 %
3-Dec-2002	Contract Cut and Calibrate Sand	10-Dec-2002	7	5-Dec-2002	3	4	57.14 %
3-Dec-2002	Contract Calibrate Sand	10-Dec-2002	7	5-Dec-2002	3	4	57.14 %
3-Dec-2002	Contract Calibrate Sand	10-Dec-2002	7	5-Dec-2002	3	4	57.14 %
3-Dec-2002	Contract Calibrate Sand	5-Dec-2002	3	3-Dec-2002	3	0	0.00 %
3-Dec-2002	Contract PAR and Edging	5-Dec-2002	3	4-Dec-2002	1	2	66.67 %
3-Dec-2002	Contract Cut	3-Dec-2002	1	4-Dec-2002	2	-1	-100.00 %
3-Dec-2002	Contract Cut and Edge	3-Dec-2002	1	5-Dec-2002	2	-1	-100.00 %
4-Dec-2002	Contract Calibrate Sand	12-Dec-2002	8	5-Dec-2002	2	6	75.00 %
4-Dec-2002	Contract Calibrate Sand	10-Dec-2002	6	4-Dec-2002	2	4	66.67 %
4-Dec-2002	Contract Calibrate Sand	9-Dec-2002	5	4-Dec-2002	1	4	80.00 %

Table F.2 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 20 *minutes.*

		LWC		Tabu			
Start Date	**Job Type**	**Dispatch**	**Net Flow Time**	**Dispatch**	**Net Flow Time**	**Improvement**	**%Improvement**
4-Dec-2002	Contract Plane all Round(PAR)	4-Dec-2002	1	8-Dec-2002	1	0	0.00 %
5-Dec-2002	Shaker Doors	17-Dec-2002	10	5-Dec-2002	3	7	70.00 %
5-Dec-2002	Contract Calibrate Sand	12-Dec-2002	7	5-Dec-2002	1	6	85.71 %
5-Dec-2002	Contract Calibrate Sand	11-Dec-2002	6	5-Dec-2002	1	5	83.33 %
5-Dec-2002	Contract Calibrate Sand	10-Dec-2002	5	5-Dec-2002	1	4	80.00 %
5-Dec-2002	Contract Calibrate Sand	10-Dec-2002	5	5-Dec-2002	1	4	80.00 %
5-Dec-2002	Contract Calibrate Sand	10-Dec-2002	5	5-Dec-2002	1	4	80.00 %
5-Dec-2002	Contract Calibrate Sand	10-Dec-2002	5	8-Dec-2002	1	4	80.00 %
6-Dec-2002	Contract Calibrate Sand	11-Dec-2002	5	6-Dec-2002	2	3	60.00 %
6-Dec-2002	Contract Calibrate Sand	11-Dec-2002	5	8-Dec-2002	1	4	80.00 %
6-Dec-2002	Contract Calibrate Sand	10-Dec-2002	4	9-Dec-2002	2	2	50.00 %
6-Dec-2002	Shaker Doors	13-Dec-2002	7	12-Dec-2002	3	4	57.14 %
6-Dec-2002	Veneer Over Edge	13-Dec-2002	7	8-Dec-2002	6	1	14.29 %
6-Dec-2002	Board Components	13-Dec-2002	7	11-Dec-2002	2	5	71.43 %
6-Dec-2002	Veneer Over Edge	13-Dec-2002	7	6-Dec-2002	5	2	28.57 %
6-Dec-2002	Contract Calibrate Sand	11-Dec-2002	5	8-Dec-2002	1	4	80.00 %
6-Dec-2002	Contract Calibrate and Veneer Sand	6-Dec-2002	1	9-Dec-2002	2	-1	-100.00 %
8-Dec-2002	Shaker Doors	12-Dec-2002	5	16-Dec-2002	2	3	60.00 %
9-Dec-2002	Veneer Over Edge	17-Dec-2002	7	16-Dec-2002	6	1	14.29 %
9-Dec-2002	Components on Edge	17-Dec-2002	7	16-Dec-2002	6	1	14.29 %
9-Dec-2002	Veneer Over Edge	17-Dec-2002	7	16-Dec-2002	6	1	14.29 %
9-Dec-2002	Components on Edge	17-Dec-2002	7	9-Dec-2002	6	1	14.29 %
9-Dec-2002	Contract Calibrate and Veneer Sand	17-Dec-2002	7	9-Dec-2002	1	6	85.71 %
9-Dec-2002	Contract Veneer Sand	13-Dec-2002	5	9-Dec-2002	1	4	80.00 %
9-Dec-2002	Contract Veneer Sand	13-Dec-2002	5	9-Dec-2002	1	4	80.00 %
9-Dec-2002	Contract Calibrate Sand	13-Dec-2002	5	9-Dec-2002	1	4	80.00 %
9-Dec-2002	Contract Calibrate Sand	13-Dec-2002	5	9-Dec-2002	1	4	80.00 %
9-Dec-2002	Contract Calibrate Sand	11-Dec-2002	3	9-Dec-2002	1	2	66.67 %
9-Dec-2002	Contract PAR, Calibrate and Veneer Sand	10-Dec-2002	2	9-Dec-2002	1	1	50.00 %
9-Dec-2002	Contract Calibrate and Veneer Sand	9-Dec-2002	1	10-Dec-2002	1	0	0.00 %
10-Dec-2002	Contract Spray: Top and Base Coat and Edging	17-Dec-2002	6	13-Dec-2002	1	5	83.33 %
10-Dec-2002	Shaker Doors	17-Dec-2002	6	10-Dec-2002	4	2	33.33 %
10-Dec-2002	Contract Calibrate Sand	12-Dec-2002	3	10-Dec-2002	1	2	66.67 %
10-Dec-2002	Contract Calibrate Sand	12-Dec-2002	3	10-Dec-2002	1	2	66.67 %
10-Dec-2002	Contract Calibrate Sand	12-Dec-2002	3	10-Dec-2002	1	2	66.67 %
10-Dec-2002	Contract Calibrate Sand	12-Dec-2002	3	10-Dec-2002	1	2	66.67 %
10-Dec-2002	Contract Calibrate Sand	19-Dec-2002	8	10-Dec-2002	1	7	87.50 %
10-Dec-2002	Board Components	13-Dec-2002	4	16-Dec-2002	1	3	75.00 %
10-Dec-2002	Veneer Over Edge	11-Dec-2002	2	10-Dec-2002	5	-3	-150.00 %
10-Dec-2002	Contract Groove	10-Dec-2002	1	10-Dec-2002	1	0	0.00 %
10-Dec-2002	Contract Calibrate and Veneer Sand	10-Dec-2002	1	10-Dec-2002	1	0	0.00 %
10-Dec-2002	Contract Calibrate and Veneer Sand	10-Dec-2002	1	16-Dec-2002	1	0	0.00 %
11-Dec-2002	Contract Calibrate Sand	13-Dec-2002	3	12-Dec-2002	4	-1	-33.33 %
11-Dec-2002	Contract Cut	18-Dec-2002	6	16-Dec-2002	2	4	66.67 %
11-Dec-2002	Shaker Doors	17-Dec-2002	5	16-Dec-2002	4	1	20.00 %
11-Dec-2002	Contract Calibrate Sand	11-Dec-2002	1	16-Dec-2002	4	-3	-300.00 %
11-Dec-2002	Shaker Doors	19-Dec-2002	7	16-Dec-2002	4	3	42.86 %
11-Dec-2002	Board Components	19-Dec-2002	7	16-Dec-2002	4	3	42.86 %
11-Dec-2002	Shaker Doors	19-Dec-2002	7	12-Dec-2002	4	3	42.86 %
12-Dec-2002	Contract Edging	12-Dec-2002	1	16-Dec-2002	1	0	0.00 %
12-Dec-2002	Contract Cut	19-Dec-2002	6	16-Dec-2002	3	3	50.00 %
12-Dec-2002	Contract Veneer Sand	13-Dec-2002	2	13-Dec-2002	3	-1	-50.00 %
13-Dec-2002	Contract Calibrate Sand	18-Dec-2002	4	16-Dec-2002	1	3	75.00 %
13-Dec-2002	Contract Calibrate Sand	19-Dec-2002	5	16-Dec-2002	2	3	60.00 %
13-Dec-2002	Contract Calibrate and Veneer Sand	16-Dec-2002	2	16-Dec-2002	2	0	0.00 %
13-Dec-2002	Contract Calibrate Sand	18-Dec-2002	4	16-Dec-2002	2	2	50.00 %
16-Dec-2002	Contract Calibrate Sand	18-Dec-2002	3	16-Dec-2002	1	2	66.67 %
16-Dec-2002	Contract Calibrate Sand	17-Dec-2002	2	17-Dec-2002	1	1	50.00 %
17-Dec-2002	Contract Veneer Sand	17-Dec-2002	1	17-Dec-2002	1	0	0.00 %
17-Dec-2002	Contract Cut	18-Dec-2002	2	17-Dec-2002	1	1	50.00 %

Table F.2 (continued): *The starting and dispatch dates as well as the improvement that the tabu search gave for each job during the run resulting in the best objective function value, assuming a ramp cost of* 20 *minutes.*

Appendix G

Instructions for using Compact Disc

This appendix contains a description of the contents of the compact disc attached to this thesis, and brief instructions for the use of this disc. There are six files on the compact disc, the first file, called `2002 Orders Received.xls` contains the order data from the last six months of 2002, used in Chapters 5 and 6.

The second file, called `SikGrid2221.xls` contains the data sets $S_i(k)$ for machine i and grid–point k with 22 horizontal blocks and 21 vertical blocks.

The third file contains the Layout decision support system, called `Layout.exe`, developed in Microsoft Visual Basic, as discussed in Chapter 7. The decision support system can be launched by double–clicking on the `Layout.exe` file.

The last three files, called `Scheduling.exe`, `JobShopTabuFLWC.exe` and `In.txt` form part of the Scheduling decision support system. The first, is the scheduling decision support system executable, whereas the second file, called `JobShopTabuFLWC.exe`, is the tabu search heuristic, coded in C++. The user inputs the following statement into the DOS command prompt: JobShopTabuFLWC.exe In.txt LWCSched.txt Out1.txt In.txt Out2.txt In.txt Out3.txt In.txt Out4.txt In.txt Out5.txt In.txt Out6.txt In.txt Out7.txt In.txt Out8.txt In.txt Out9.txt In.txt Out10.txt In.txt Out11.txt In.txt Out12.txt In.txt Out13.txt In.txt Out14.txt In.txt Out15.txt In.txt Out16.txt In.txt Out17.txt In.txt Out18.txt In.txt Out19.txt In.txt Out20.txt In.txt Out21.txt In.txt Out22.txt In.txt Out23.txt In.txt Out24.txt In.txt Out25.txt In.txt Out26.txt In.txt Out27.txt In.txt Out28.txt In.txt Out29.txt In.txt Out30.txt In.txt Out31.txt > FinOut.txt. This statement contains the files `In.txt` (which is on the compact disc) and the set of files, `Out1.txt` – `Out31.txt`, which contains the information for the completed tasks during the successive 31 days. These files are read into the decision support system as discussed in Chapter 7 to produce the total schedule for all the jobs processed at the given day.