**A RELATIONAL DATABASE APPROACH TO A LINEAR PROGRAMMING
BASED DECISION SUPPORT SYSTEM FOR PRODUCTION PLANNING IN
SECONDARY WOOD PRODUCT MANUFACTURING**

By

ROSS FARRELL

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Department of Forestry

The University of British Columbia
Vancouver, Canada

Date 26 Aug /02

ABSTRACT

Secondary manufacturers in the forest products industry face a complex production planning process. Linear programming based applications have addressed this production planning issue. However, most models have been developed for a specific plant configuration and cannot readily be applied to others. A relational database approach was used to create an integrated linear programming based decision support system that can be used to analyze production planning issues in a wide variety of secondary wood product manufacturers. The system was validated at a secondary manufacturing operation in British Columbia. The flexibility of the resultant system indicated the potential to fine-tune operating strategies in the highly dynamic environment characteristic of secondary manufacturers.

TABLE OF CONTENTS

ABSTRACT	II
TABLE OF CONTENTS.....	III
LIST OF TABLES	V
LIST OF FIGURES	VI
ACKNOWLEDGEMENTS.....	VII
1 INTRODUCTION.....	1
IMPORTANCE OF THE SECONDARY MANUFACTURING SECTOR	1
PRODUCTION PLANNING PROCESS	1
COMPLEXITY OF THE PRODUCTION PLANNING PROCESS	2
DEFINITIONS	4
<i>Secondary manufacturing</i>	4
<i>Decision support system (DSS)</i>	4
2 BACKGROUND	6
LINEAR PROGRAMMING APPLICATIONS IN THE FOREST PRODUCTS INDUSTRY	6
IMPORTANCE OF FLEXIBILITY IN MODEL DESIGN	9
3 OBJECTIVES	12
OBJECTIVE	12
MODEL USE	13
STRATEGY	14
4 METHODOLOGY.....	15
RELATIONAL DATABASE	15
USER INTERFACE.....	19
MODEL FORMULATION.....	21
<i>Objective function</i>	23
<i>Raw material constraints</i>	24
<i>Material balance constraints:</i>	24
<i>Production constraints</i>	25
Recovery:	25
Hours	26
<i>Marketing constraints</i>	26
DEFINITIONS	27
<i>Subscripts</i>	27
<i>Variables</i>	28
<i>Cost coefficients</i>	30
<i>Other coefficients</i>	32
<i>Constraints</i>	33
Raw material constraints:	33
Material balance constraints:	34
Production constraints:	35
Recovery	36
Hours.....	37
Marketing constraints:	38

MODEL DEFINITION	39
QUERY STRUCTURE	40
VARIABLE AND CONSTRAINT INDEXING	40
MODEL INSTANTIATION	41
SOLVING THE MODEL	42
REPORTS	42
5 MODEL VALIDATION.....	44
INTRODUCTION.....	44
DATA COLLECTION.....	45
SCENARIO ANALYSIS	46
<i>Introduction</i>	46
<i>Assumptions</i>	47
BASE CASE : #1 FINGER-JOINT LINE	48
<i>Raw material</i>	48
<i>Potential Products</i>	49
<i>Process Flow</i>	50
<i>Problem definition</i>	51
<i>Results and discussion</i>	52
SCENARIO 1 – LOWER PRICED ECONOMY	59
SCENARIO 2 – ADDITIONS TO PROCESS FLOW	62
<i>Raw Material</i>	62
<i>Potential products</i>	63
<i>Process Flow</i>	63
<i>Problem definition</i>	65
<i>Results and discussion</i>	65
SCENARIO 3 – INCREASING BEAM PRICES.....	74
6 CONCLUSION.....	81
7 FUTURE WORK	85
8 LITERATURE CITED.....	86
9 APPENDICES	90
APPENDIX A.....	90
<i>Shadow prices and ranges for machines at their maximum capacity</i>	90
APPENDIX B	91
<i>Reduced costs and ranges for base case raw materials</i>	91
APPENDIX C	92
<i>Lamina lay-up requirements for glulam beams</i>	92
APPENDIX D	93
<i>Kiln charge volume</i>	93
APPENDIX E	94
<i>Component of the relational database</i>	94

LIST OF TABLES

TABLE 1: MACHINE CENTERS AVAILABLE AT STUDY SITE.....	44
TABLE 2: DATA REQUIRED TO SET-UP THE DECISION SUPPORT SYSTEM.	45
TABLE 3: RAW MATERIAL AVAILABILITY FOR BASE CASE AND SCENARIO 1.....	49
TABLE 4: FINANCIAL SUMMARY FOR BASE CASE.	58
TABLE 5: SUMMARY OF RAW MATERIAL PURCHASES (MFBM) FOR BASE CASE AND SCENARIO 1.....	59
TABLE 6: FINANCIAL SUMMARY FOR BASE CASE AND SCENARIO 1.	61
TABLE 7: POTENTIAL RAW MATERIALS AND PRODUCTS FOR SCENARIO 2.....	62
TABLE 8: RANK OF GLULAM BEAMS BASED ON VOLUME RECOVERY FROM RESPECTIVE RAW MATERIALS.	71
TABLE 9: FINANCIAL SUMMARY FOR BASE CASE AND SCENARIO 2.	73
TABLE 10: FINANCIAL SUMMARY FOR SCENARIO 2 AND SCENARIO 3.....	80

LIST OF FIGURES

FIGURE 1: MATERIAL FLOW FOR A GENERIC MACHINE CENTER.....	16
FIGURE 2: COMPONENTS OF THE DECISION SUPPORT SYSTEM AND FLOW OF DATA.....	43
FIGURE 3: BASE CASE PROCESS FLOW.....	51
FIGURE 4: OPTIMAL RAW MATERIAL PURCHASE DISTRIBUTION FOR BASE CASE AND SCENARIO 1.....	53
FIGURE 5: SHADOW PRICES AND FOR BASE CASE RAW MATERIALS.	54
FIGURE 6: REDUCED COSTS FOR BASE CASE RAW MATERIALS.....	55
FIGURE 7: MACHINE AVAILABILITY AND UTILIZATION FOR BASE CASE AND SCENARIO 1...	56
FIGURE 8: MATERIAL SALES DISTRIBUTION FOR BASE CASE AND SCENARIO 1.	57
FIGURE 9: PROCESS FLOW FOR SCENARIO 2 AND 3.....	64
FIGURE 10: OPTIMAL RAW MATERIAL PURCHASE DISTRIBUTION FOR BASE CASE AND SCENARIO 2.....	66
FIGURE 11: MACHINE AVAILABILITY AND UTILIZATION FOR BASE CASE AND SCENARIO 2.	67
FIGURE 12: MATERIAL SALES DISTRIBUTION FOR BASE CASE AND SCENARIO 2.	69
FIGURE 13: PERCENTAGE OF AVAILABLE LAMINA THAT MAY BE UTILIZED IN EACH BEAM.	71
FIGURE 14: OPTIMAL RAW MATERIAL PURCHASE DISTRIBUTION FOR SCENARIO 2 AND SCENARIO 3.....	75
FIGURE 15: MACHINE AVAILABILITY AND UTILIZATION FOR SCENARIO 2 AND SCENARIO 3.	76
FIGURE 16: MATERIAL SALES DISTRIBUTION FOR SCENARIO 2 AND SCENARIO 3.....	78

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1 INTRODUCTION

IMPORTANCE OF THE SECONDARY MANUFACTURING SECTOR

The expansion of the secondary manufacturing industry is a common interest for the major timber producing, importing and exporting regions of the world (Wilson et al., 1999). Governments recognize the potential of the secondary industry to stimulate economic development through job creation and economic diversification in forest dependent economies. Vlosky, & Chance (1996) and Vlosky et al. (1998) provide references to such government strategies in forest abundant regions of the United States. The Forum Consulting Group Ltd (1999), provide a review of government policies to promote investment in secondary manufacturing in 22 separate jurisdictions. Furthermore, rationalization in the primary manufacturing sector has resulted in fewer but larger more efficient sawmills in the ECE region (Europe, North America and the CIS), (UN / ECE Timber Committee, 1999). This has resulted in downward pressure on employment in the primary manufacturing industry, and may exacerbate the need for increased activity in the secondary industry to support these economies.

PRODUCTION PLANNING PROCESS

The production planning process involves the acquisition and allocation of limited resources to production activities to best meet defined objectives in a specified time period. Typically the primary objective is to maximize profit given the limited resources available.

For a secondary wood products manufacturer the production planning process may entail an examination of the available raw materials, processing options, machine capacities and market conditions.

COMPLEXITY OF THE PRODUCTION PLANNING PROCESS

Secondary manufacturers operate in a highly dynamic market environment (Price Waterhouse, 1992 [a]). Furthermore, the ability of wood products manufacturers to respond quickly to changing and divergent customer needs is a key factor in determining their success (Hoff et al., 1997). Secondary manufacturers survive in this dynamic market by employing a wide variety of machine centers that provide a high degree of manufacturing flexibility. This enables them to manufacture a wide array of products, and therefore adapt to the dynamic nature of market demand.

Given the variety of products, the dynamic nature of their market environment, and the number and heterogeneity of raw materials, the production planning process can be highly complex. At any given time there may exist a myriad of feasible production plans. Managers may fail to find the optimal (profit maximizing) operating strategy, as the computational difficulty of such a problem is too great. The interaction of raw materials, with process and marketing factors produce complex interrelationships that require simultaneous analysis in order to find the optimal operating strategy.

In 1970, Faux elaborated on the high level of complexity involved in production planning for a plywood manufacturer. He then described a linear programming based system to aid production managers to develop optimum production plans. Mendoza et al., (1991) highlight decision complexity as the major motivation for a decision support system to aid the manufacturing of hardwood forest products. More recently Muhanna & Pick (1994) indicated that the increasing complexity and competitiveness of today's business world, has produced a greater reliance on computer based operations research / management science models.

A number of linear programming based applications, have been developed to address a variety of production planning issues in secondary manufacturing. However, most models have been developed for a specific application domain to solve a particular problem. Typically, the use of these models is restricted to the problem set that they were designed to solve, and are difficult to adapt to changes in plant configuration. Consequently, these plant specific models are limited both in their range of application, and in their ability to adapt to changes in a given manufacturing system.

The inherent flexibility of secondary manufacturers requires a modeling approach that can easily be used to solve a wide variety of production planning problems and is not dependent on a particular plant configuration. This work will present a mixed integer linear programming based decision support system for production planning purposes that can be adapted to model a wide variety of secondary wood product manufacturers.

DEFINITIONS

In the interest of clarity, the terms secondary manufacturing and decision support system will be defined to specify the context of their use in this research.

Secondary manufacturing

Secondary manufacturing relates to a wide range of wood product manufacturers who process primary wood-based materials into semi-finished or finished products (Wilson et al., 1999). A useful classification developed by Price Waterhouse (1992 [b]) identifies seven major categories:

- 1) Remanufactured products
- 2) Engineered building components
- 3) Millwork
- 4) Cabinets
- 5) Furniture
- 6) Pallets & Containers
- 7) Other wood products.

Decision support system (DSS)

DSS concepts have evolved from the 1960's to the current day. Following this evolution the way in which a DSS can be categorized and defined has also changed. Power (2000)

provides a comprehensive history of DSS, and suggests a framework to organize and classify modern decision support systems. Five main categories are suggested:

- 1) Communication-driven DSS
- 2) Data-driven DSS
- 3) Document-driven DSS
- 4) Knowledge-driven DSS
- 5) Model-driven DSS

The DSS developed in this research can be categorized as model-driven because fundamentally, decision support is based on solutions to the under-lying linear programming model. However, the relational database approach utilized does exemplify some characteristics of a data-driven DSS, acknowledging the central role of data in the DSS.

The decision support system (DSS) developed in this research will be implemented in a secondary manufacturing operation in British Columbia. The operation can produce a broad range of products that can be best classified as remanufactured products and engineered building components. However, the DSS is designed to be as generic as possible and could theoretically be applied to a wide variety of secondary manufacturing plants.

2 BACKGROUND

LINEAR PROGRAMMING APPLICATIONS IN THE FOREST PRODUCTS INDUSTRY

Historically, there have been many linear programming (LP) applications in forest products manufacturing (Willis, 1998). The first applications of LP were developed in the late 1950's to provide a management tool to aid decision making in the plywood industry. Bethel and Harrell (1957), Koenigsberg (1960), Ramsing, (1968) and Kotak (1976) provide applications concerned with log purchase and veneer peeling decisions to produce a more profitable product mix.

With the emergence of the wood panel industry a number of LP applications have been reported in particleboard manufacturing. Buehlmann (2000) describes an LP based DSS, developed in a spreadsheet environment, to minimize raw material costs considering quality constraints of the end products. Another application provided by Karayilmazlar (2000), was used to determine optimal production, inventory and sale levels of eight different thicknesses of particleboard over a one-year period.

Many applications have been developed for the sawmill industry. The main focus of these applications is log allocation, examined via an analysis of bucking and sawing strategies. Jackson & Smith (1961) develop an LP to optimize lumber sawing strategies. Sampson & Fasick (1970) analyzed the allocation of logs to competing sawing lines, while

Pnevmaticos and Mann (1972) developed a dynamic programming model to optimize log bucking strategies. Maness & Adams (1991) develop an integrated approach combining log bucking and sawing strategies. Norton (1993) examined the impact of multiple time horizons on production planning in a sawmill. Donald (1996) and Willis (1998) provided more recent research in the sawmill sector, focusing on the optimization of integrated manufacturing plants (i.e. plants that incorporate both primary and secondary manufacturing).

There appears to be few LP applications in the secondary manufacturing sector. Mundie (1977) described a basic application of LP to lumber remanufacturing, demonstrating the feasibility of constructing an LP for such a plant. A number of the documented LP's have been designed to solve a specific problem set and / or relate to a fixed plant configuration. For example, Penick (1968) applied an LP to machine loading in a furniture plant. Carino and LeNoir (1988) used LP to determine optimum (least cost) wood procurement policies in cabinet manufacturing. Carino and Foronda (1990) developed a model to minimize blank costs in hardwood furniture manufacturing. Donald (1996) developed a model for maximizing profit in what he defines as a "value-added facility", a term used synonymously with secondary manufacturing in the forest products industry. He described a profit maximizing model that is used to determine optimal production plans, and then explored the influence of secondary manufacturing policies on sawmill production decisions for an integrated manufacturing operation.

The LP's described above have been designed to solve a specific problem set and / or relate to a fixed plant configuration. Consequently, they may be difficult to adapt to a different manufacturing plant due to changes in the plant configuration or indeed the types of machine centers utilized.

Zhang (1990) indicated the need for an application to model the entire furniture making process stressing that current formulations only modeled sub-processes. To address this need a multi time period LP model and user interface was developed for the furniture-manufacturing sector. Two key aspects provide this model with an element of flexibility that is absent from the models previously described.

Firstly, independence from any given plant configuration is achieved by viewing the manufacturing operation as a number of stages that possess generic attributes, rather than focusing on the attributes of specific machine centers themselves. Zhang describes a "general stage" that is used to model material flow throughout the manufacturing process.

Secondly, manufacturing stages are classified into one of three types. A splitting stage describes a process where input materials are split into products; a combining stage a process where input materials are combined into products, and a third stage a process where materials are neither combined nor split. This classification allows one to model a wide variety of machine centers.

In addition, adaptability is further enhanced by a user interface (programmed in Fortran) provided to assist data entry. The interface includes a matrix generator to compose the mathematical model and a report writer to interpret solution results.

Zhang also suggested a number of potential uses for the model:

- 1) To optimize a single process.
- 2) To optimize a number of processes.
- 3) To optimize the whole manufacturing operation.
- 4) To determine whether a new processing stage is profitable.
- 5) To examine profitability of new operations.

One drawback of Zhang's approach is that there is no separation between the mathematical model and the model data. Several authors indicate this is a highly desirable feature for a successful modeling system. Model-data independence provides greater design robustness and clarity (Muhunna & Pick 1994), facilitates data manipulation, and reuse of the same mathematical model in different applications (Geoffrion, 1987, and Atamturk et al. 2000).

IMPORTANCE OF FLEXIBILITY IN MODEL DESIGN

The work presented in this research is similar to that carried out by Zhang in that the manufacturing process is considered in general terms. However, a relational database

approach will be used in an attempt to maximize the flexibility of the resulting decision support system and to facilitate model-data independence.

Srinivasan & Sundaram (2000), and Muhanna & Pick (1994) convey the importance of flexible approaches to model design, in order to broaden the scope of potential applications. Furthermore, Olhager & Rapp (1995) suggest that specific operations research applications may have a short life span due to the highly dynamic nature of the manufacturing environment.

Examples of generic operations research models that incorporate a high degree of application flexibility can be found in a variety of manufacturing environments.

Metaxiotis et al. (2001) used an object oriented approach to develop an adaptable advanced decision support tool. The software package was integrated with a management information system and uses dynamic simulation techniques to support production planning on a daily basis. Fourer (1997) implemented a generic linear programming model via a database system for production planning in the American steel industry, and Gazmuri and Arrate (1995) discuss the development of a system to build optimization models for a variety of applications. They employed a number of software tools from a prototype of a modeling system, and implement a general production-planning model in an appliance manufacturer in Chile.

Database support for mathematical models provide advantages that stem from the data management capability and flexibility (in terms of data manipulation) offered by modern

database systems Geoffrion (1987) and Murphy et al. (1992). Among others, Welch (1987) has observed the analogies between linear programming data and relational database tables. Thus, many authors have suggested the application of relational database structures to mathematical modeling Muller-Merbach (1981 & 1983), Geoffrion (1987), and Blanning (1987). Fourer (1997) indicated that several studies have also investigated a different approach where linear programming features are incorporated into a database management system.

The approach employed in this research presents a direct utilization of relational database technology. A relational database will be designed to efficiently manage the data requirements of the mathematical model. The model design will incorporate a high degree of flexibility providing an adaptable, generic model that will offer decision support for the production planning process in a wide variety of secondary manufacturing plants. Specific applications will be established by inputting data from specific plants, thus users of the model will be mainly concerned with data gathering, entry and maintenance.

3 OBJECTIVES

OBJECTIVE

To develop an adaptable linear programming based DSS using a relational database approach. The DSS should provide secondary manufacturers with a production planning tool that will help determine optimal operating strategies given the raw material supply, manufacturing options and market opportunities specified at a given period in time.

The DSS will provide a short term planning tool that can be used to analyze operational decisions over one future time period. The ideal time period depends on the accuracy of data available and the scenario to be analyzed. Typically, the time period involved would be between one to three months.

The justification of developing a single period production planning model rather than a multi-period model is related to the interests of the collaborating secondary manufacturing company and the time scale available for this research. However, the author acknowledges the additional benefits that would be provided by a multi-period model, and it is proposed that this will be the focus of future work.

MODEL USE

The DSS should be able to aid analyses in the following key decision areas:

- 1) ***Product mix***: Given the myriad of market opportunities and processing options what products should be manufactured in order to use the limited plant resources to create the maximum profit?
- 2) ***Raw material sourcing***: Given current conditions what distribution of raw materials will facilitate a profit maximizing operating strategy?
- 3) ***Production strategies***: What markets should be pursued? What is the impact on mill profitability of focusing on particular markets?
- 4) ***Pricing strategies***: What is the impact of changes in raw material, semi-finished, or finished product prices? What price is acceptable for raw material destined for a specific production run? Are specified products profitable at existing prices?
- 5) ***Resource valuation***: What is the value of additional resources, such as productive capacity, raw materials, and market size?
- 6) ***Capital appropriations requests***: How profitable would it be to add new or upgrade old manufacturing facilities?

STRATEGY

To realize the objective seven main steps were identified:

- 1) Develop a database that will efficiently store and manage data for a wide range of modeling applications in secondary manufacturing.
- 2) Formulate a generic LP that can be applied to a variety of application domains in secondary manufacturing.
- 3) Develop a user interface to facilitate data entry and manipulation.
- 4) Build a number of SQL queries that will create an instance of the LP matrix.
- 5) Develop a number of reports to convey key results back to the user.
- 6) Illustrate the use of the DSS by implementation in a major secondary manufacturing operation in British Columbia.
- 7) Validate the LP by creating a base case scenario that will be compared with the current operating strategy at the manufacturing operation. In addition, experimental scenarios will be tested in order to demonstrate how the system behaves under different conditions.

4 METHODOLOGY

RELATIONAL DATABASE

The readily available database tool Microsoft Access (MS) was used as the development platform for the DSS. The foundation of the DSS is the relational database developed to store and manage all model data. Model-data independence is achieved by the creation of a relational database based on data handling efficiency, rather than the structure of the mathematical model (in terms of variables, constraints and coefficients).

The database was designed for efficient data management, adhering to the principles and fundamentals of database design provided by Riordan (1999). The data stored in the database is discussed further in the user interface section. A component of the relational database showing the data tables concerned with material definition is provided in appendix E.

The database was designed on the fundamental principle that any manufacturing plant may be represented as a system of machine centers, with linkages that facilitate the transfer of material between them. To define any manufacturing plant it is necessary therefore, to first define the machine centers available and the process flow (i.e. the material transfer between them).

Figure 1: Material flow for a generic machine center.

To provide flexibility in the DSS a machine center is viewed as a generic entity having the material flow illustrated in Fig. 1. Input material may enter a machine center from the market, from previous machine centers or a combination of both. The material is then processed into output material/s. Outputs are either transferred to subsequent machine centers for further processing or may leave the manufacturing system to be sold on the market. Chips and rejects may be produced in the transformation of input material to output material.

All machine centers are modeled using the material flow shown in Fig. 1. The database has been designed to handle both, machine centers that combine many inputs into one or more outputs (e.g. edge gluing panels, or pressing glulam beams) and machines that process a single input into one or more outputs (e.g. resaw or a planer).

All machine centers have the same generic attributes however, a distinction has been made for modeling kilns. This machine center is different in that material is processed (dried) in batches. Additional tables relate to the kilns in order to store data concerned with the definition of material groups for kiln drying.

Some features of the database design are worthy of note because they provide the DSS with greater flexibility:

- 1) All materials used in the model are defined in terms of thickness (t), width (w), length (l), grade (g), species (s) and material group name (n). The dimension, species and

grade attributes of a material are obvious however, the group name requires further explanation. The group name allows one to distinguish material according to a classification desired by the user. For example, materials of the same dimension, grade and species can be given different group names in order to distinguish between different raw material sources. Another example is the use of group names to identify different types of manufacturing, for example a secondary manufacturer may want to distinguish between custom processing and market processing (i.e. the processing of purchased lumber to produce goods for market).

2) Machine centers are defined by a name and one or more processing functions. The rationale for the function field is based on the recognition that a specific machine center may incur different processing costs depending on the machine set-up, work force or the current processing function. For example, the planer-line at the study site incorporates a split saw and a continuous lumber tester, and therefore can be used for three processing functions, planing, splitting or strength testing. These functions may incur different processing costs. The function field permits the user to define the various functions (and therefore costs) that can be carried out by a particular machine center.

3) A number of methods are provided to model the costs incurred during the operation of the manufacturing plant. Costs can be sub-divided into operating supplies and expenses (OSE), maintenance supplies and expenses (MSE), and an operating cost (OC). Alternatively, they can be combined into one operating cost. Operating costs can be charged on an hourly basis, or on the volume of each input material (i) processed.

Alternatively, an average operating cost may be applied to the total volume of all materials processed by a machine. OSE and MSE can be charged on the total volume processed by a machine, or they can be based on the total hours of operation for that machine. In addition to the above methods kilns may also be charged on the volume of each kiln charge. Further costing details are provided in the formulation. Raw materials are charged on a cost per unit volume. The costing methods available provide an opportunity for the user to select the methods that best model the production costs for the specific machine centers present at the manufacturing plant under study.

4) The database has been designed to handle different unit measurements. A unit table defines all units that can be used in the DSS. Conversion factors are associated with the units in order to permit conversion between different units. This is important when material may be produced for the domestic (North American) market where imperial units are the norm, and export markets where metric units are used (e.g. Japan or Europe).

USER INTERFACE

MS Access forms are developed to provide a user interface that facilitates data entry and manipulation. Forms allow the user to enter or modify data from a number of tables on a single form. In this way the DSS will be easier to use as one need only be concerned with a small number of forms (to view or enter data) rather than navigate the plethora of individual data tables that make up the database. The forms also provide features that can

help minimize data entry error. For example, validation rules can be used to ensure that the species of an output material matches the species of the input material.

Five main forms are provided for data entry:

- 1) **Material definition form** – All (input and output) materials are defined in terms of thickness, width, length, grade, species and group name.
- 2) **Raw material form** – All potential raw materials available for purchase are defined. This includes information pertaining to volume availabilities and price, as well as the primary machine/s that the material may be transferred to.
- 3) **Process data form** – Machines are named and information regarding machine functions, processing costs, available processing time, and downtime is detailed.
- 4) **Process flow data** – The input/s, machine center, and output/s are defined. This includes information on the yield recoveries, machine productivity and the subsequent process or processes that the output/s may be transferred to.
- 5) **Product data** – The price / volume relationships (i.e. demand group prices and volumes) are defined for each market product.

MODEL FORMULATION

Materials used in the model are recognized as input or output materials. Input material/s are processed by a machine center and transformed into output material/s. Output material/s may be transferred from one machine and input to another machine for further processing. In this way outputs (o) from one machine referred to as *source* machine (c), may become inputs (i) for another machine, referred to as *destination* machine (d). For example (o_1) and (o_2) from source machine (c) may become input (i_1) and (i_2) for destination machine (d). Alternatively, output materials (o_1) and (o_2) may exit the manufacturing system to be sold on the market.

In terms of inputs and outputs, machines are identified as one of three types:

- 1) Machines that process one input into one or many outputs (e.g. resaw)
- 2) Machines that combine many inputs into one or many outputs (e.g. beam press).
- 3) Machines that process material in batches (i.e. kilns).

Input materials at a given machine can be processed according to a number of processing options (p). Processing option subscripts are employed in the variable and constraint names to identify related inputs and outputs. The (p) subscripts occur naturally in the relational database as a primary key (unique identifier) that identifies the processing of specific input/s to specific output/s at a given machine. The (p) subscript has a many-to-many relationship with inputs and outputs, and therefore can represent the transformation

of one-or-many inputs to one-or-many outputs at a given machine center. An example of a many-to-many processing option (p_1) would be input materials (i_1), (i_2) and (i_3) processed at machine (m), into output materials (o_1) and (o_2). The (p) subscripts are used in the naming convention to accommodate the different types of machine centers that may be modeled at a secondary manufacturing plant. Identifying the processing option (p) insures that the formulation will correctly model a variety of machine centers irrespective of the number of inputs or outputs in a particular (p). For example, the reject and chip constraints utilize the (p) subscript to prevent creating a constraint for every output when multiple outputs are produced from a given input. This would occur if the subscript (o) were used in the variable and constraint names. The (p) subscript is used to group the multiple outputs (from a single input) together.

Similarly (p) is used to prevent creating market (MKT) and further processing (FUR) variables for each input in a processing option when multiple inputs are combined into an output. Multiple inputs are grouped together for each processing option. Furthermore, the use of processing options in the variable and constraint naming convention ensures that their names are unique even when different processing options may have common inputs and outputs. For example (i_1) could produce outputs (o_1 and o_2) represented by (p_1). Alternatively (i_1) could produce (o_1 and o_3) represented by (p_2). In this example (o_1) is common to both processing options utilizing (i_1). Thus by identifying processing option (p) the generation of conflicting constraint and variable names is prevented.

Kilns are identified as a different type of machine center because they “process” material in batches (kiln charges). For kiln scheduling purposes, charges are modeled as integer variables. It is assumed that kilns must always run at full capacity, and therefore it is not possible to dry a fraction of a kiln charge. However, the user does have the option to change kiln charges to continuous variables if so desired. One might do this if there are no planning concerns with kiln scheduling, and the assumption is made that all material purchases could be dried, providing overall kiln capacity is not exceeded. Furthermore, if a short production-planning period (e.g. one-week) were modeled it would be difficult to use integer kiln charge variables.

All machines are identified by subscript (m). As previously mentioned machine centers have one or more processing functions that incur an associated cost. A machine center is thus defined by both a machine name and one or more processing functions. However, for clarity the subscript (m) has been used in the formulation to denote a particular machine name and processing function. This omits the need to create another subscript for machine processing functions.

Objective function

The objective function is to maximize the profit (total revenue minus total cost) for the secondary manufacturing operation over one future time period. Costs are incurred via raw material purchases, machine operation, maintenance supplies and expenses, and operating supplies and expenses. Revenue is derived from the sale of output material, reject material, and chips.

Maximize:

$$\begin{aligned}
& - \sum_{i=1}^j cRAW_MP_i \times RAW_MP_i \\
& - \sum_{m=1}^M \left[(cOC_TVOL_m \times TVOL_m) - \left(\sum_{i=1}^I cOC_VOL_{im} \times VOL_{im} \right) - (cOC_THRS_m \times THRS_m) \right] \\
& - \sum_{m=1}^M \left[(cMSE_TVOL_m \times TVOL_m) - (cMSE_THRS_m \times THRS_m) \right] \\
& - \sum_{m=1}^M \left[(cOSE_TVOL_m \times TVOL_m) - (cOSE_THRS_m \times THRS_m) \right] \\
& - \sum_{m=1}^M \sum_{t=1}^T \sum_{w=1}^W \sum_{g=1}^G \sum_{s=1}^S cKVOL_{twgsm} \times KVOL_{twgsm} \\
& + \sum_{o=1}^O rTMKT_DG1_o \times TMKT_DG1_o + \sum_{o=1}^O rTMKT_DG2_o \times TMKT_DG2_o \\
& + \sum_{o=1}^O rTMKT_DG3_o \times TMKT_DG3_o \\
& + rCHIP_BDU \times CHIP_BDU \\
& + \sum_{i=1}^I rREJ_i \times TREJ_i
\end{aligned}$$

subject to:

Raw material constraints

$$(1) RAW_MP_i \leq MAX_MP_i \quad (\text{for } i = 1, 2, \dots, j)$$

Material balance constraints:

$$(2) \sum_{m=1}^M RAW_IN_{im} - RAW_MP_i = 0 \quad (\text{for } i = 1, 2, \dots, j)$$

$$(3) \sum_{p=1}^P FUR_{pom} - \sum_{d=1}^D TRN_{ocd} = 0 \quad \forall o, m, c \quad (c = m)$$

$$(4) TRN_{ocd} - T_IN_{icd} = 0 \quad \forall o, i, c, d \quad (o = i)$$

$$(5) \sum_{c=1}^C T_IN_{icd} + RAW_IN_{im} - VOL_{im} = 0 \quad \forall i, d, m \quad (d = m)$$

$$(6) \sum_{p=1}^P PRO_VOL_{ipm} - VOL_{im} = 0 \quad \forall i, m$$

$$(7) \sum_{i=1}^I VOL_{im} - TVOL_m = 0 \quad \forall m$$

$$(8) \sum_{L=1}^I \sum_{n=1}^N VOL_{twLgsm} - KVOL_{twgsm} = 0 \quad \forall t, w, g, s \exists m$$

$$(9) CHRG_CAP_{t,w,g,s,m} \times CHRG_{twgsm} - KVOL_{twgsm} = 0 \quad \forall t, w, g, s \exists m$$

$$(10) \sum_{p=1}^P \sum_{m=1}^M REJ_{ipm} - TREJ_i = 0 \quad \forall i$$

$$(11) \sum_{i=1}^I \sum_{p=1}^P \sum_{m=1}^M CHIP_{ipm} - TCHIP = 0$$

$$(12) (LUM_BDU \times TCHIP) - CHIP_BDU = 0$$

Production constraints

Recovery:

$$(13) LUM_REC_{iopm} \times PRO_VOL_{ipm} - MKT_{pom} - FUR_{pom} = 0 \quad \forall i, p, o, \exists m$$

$$(14) LUM_REJ_{ipm} \times PRO_VOL_{ipm} - REJ_{ipm} = 0 \quad \forall i, p, m$$

$$(15) LUM_CHIP_{ipm} \times PRO_VOL_{ipm} - CHIP_{ipm} = 0 \quad \forall i, p, m$$

$$(16) \begin{aligned} & (IN_LUM_REC_{iopm} \times PRO_VOL_{ipm}) - (OUT_LUM_REC_{iopm} \times MKT_{pom}) - \\ & (OUT_LUM_REC_{iopm} \times FUR_{pom}) = 0 \quad \forall i, p, o, \exists m \end{aligned}$$

Hours

$$(17) PRO_VOL_{ipm} \times [M_RATE_{ipm} \times (1 + D_TIME_m)] - HRS_{ipm} = 0 \quad \forall i, p, \exists m$$

$$(18) KVOL_{mtwgs} \times [M_RATE_{mtwgs} \times (1 + D_TIME_m)] - KHRS_{mtwgs} = 0 \quad \forall t, w, g, s \exists m$$

$$(19) \sum_{i=1}^I \sum_{p=1}^P HRS_{ipm} - THRS_m = 0 \quad \exists m$$

$$(20) \sum_{t=1}^T \sum_{w=1}^W \sum_{g=1}^G \sum_{s=1}^S KHRS_{mtwgs} - THRS_m = 0 \quad \exists m$$

$$(21) THRS_m \leq MAX_THRS_m \quad \forall m$$

Marketing constraints

$$(22) \sum_{p=1}^P \sum_{m=1}^M MKT_{pom} - TMKT_DG1_o - TMKT_DG2_o - TMKT_DG3_o = 0 \quad \forall o$$

$$(23) TMKT_DG1_o - (MAX_DG1_o \times I1_o) \geq 0 \quad \forall o$$

$$(24) TMKT_DG2_o - (MAX_DG2_o \times I1_o) \leq 0 \quad \forall o$$

$$(25) TMKT_DG2_o - (MAX_DG2_o \times I2_o) \geq 0 \quad \forall o$$

$$(26) TMKT_DG3_o - (MAX_DG3_o \times I2_o) \leq 0 \quad \forall o$$

$$(27) TMKT_DG1_o \leq MAX_DG1_o$$

$$(28) I1_o \leq 1$$

$$(29) I2_o \leq 1$$

$I1_o = |\text{Integer}|$

$I2_o = |\text{Integer}|$

$CHRG_{m,t,w,g,s} = |\text{Integer}|$

All variables ≥ 0 .

DEFINITIONS

Subscripts

(i) = Input material defined by thickness (t), width (w), length (l), grade (g), species (s) and group name (n).

(o) = Output material also defined by (t,w,l,g,s,n).

(p) = Identifies a specific processing option where an input is transformed into an output at a particular machine. The inputs and outputs can be singular or multiple, depending on the type of machine. For example, a glulam beam press combines multiple inputs into a single output, whereas a resaw transforms a single input into multiple outputs. Processing options recognize that input material/s have may have different processing options (and therefore output/s) at a given machine center.

(m) = Machine center defined by a machine name and one or more process functions

(*c*) = Source machine represents a previous machine, i.e. (*m-1*) from which material may be transferred to another (destination) machine.

(*d*) = Destination machine represents a machine that receives (input) material (output) from a previous machine (i.e. a source machine).

There are a total of (*I*) materials, (*j*) of which are defined as raw materials and are available for purchase from the market.

Variables

$CHIP_{ipm}$	Volume of chips produced from input material (<i>i</i>) processed by process option (<i>p</i>) at machine (<i>m</i>).
$CHIP_BDU$	Bone-dry units of chips produced.
$CHRG_{twgsm}$	Number of charges (integer) of kiln material group (<i>t,w,g,s</i>) into kiln (<i>m</i>).
FUR_{pom}	Volume of output material (<i>o</i>) manufactured via processing option (<i>p</i>) at machine (<i>m</i>) to be further processed at another machine.
HRS_{ipm}	Hours used processing input material (<i>i</i>) via processing option (<i>p</i>) at machine (<i>m</i>).
$I1_o$	Indicator variable for demand group 1.

$I2_o$	Indicator variable for demand group 2.
$KHRS_{twgsm}$	Hours used processing kiln material group (t,w,g,s) at kiln (m) .
$KVOL_{twgsm}$	Total volume of kiln group (t,w,g,s) to be dried at kiln (m) .
MKT_{pom}	Volume of output material (o) manufactured via processing option (p) for sale on the market after processing at machine (m) .
PRO_VOL_{ipm}	Volume of input material (i) to be processed according to processing option (p) by machine (m) .
RAW_IN_{im}	Volume of raw material (i) into machine (m) .
RAW_MP_i	Volume of raw material (i) purchased.
REJ_{ipm}	Volume of input material (i) rejected through processing option (p) at machine (m) .
$TREJ_i$	Total volume of input material (i) rejected.
$TCHIP$	Total volume of chips produced.
T_IN_{icd}	Volume of input material (i) transferred from source machine (c) to destination machine (d) .
$THRS_m$	Total hours used by machine (m) .

$TMKT_DG1_o$	Total volume of output material (o) sold to market in demand group 1.
$TMKT_DG2_o$	Total volume of output material (o) sold to market in demand group 2.
$TMKT_DG3_o$	Total volume of output material (o) sold to market in demand group 3.
TRN_{ocd}	Total volume of output material (o) transferred from source machine (c) to destination machine (d).
$TVOL_m$	Total volume of material processed at machine (m).
VOL_{im}	Total volume of input material (i) to be processed by machine (m).
$VOL_{twlgsnm}$	Total volume of material defined by thickness (t), width (w), length (l), grade (g), species (s) and material group name (n) to be processed at machine (m). This is identical to VOL_{im} only (i) has been expanded into its constituent attributes.
Cost coefficients	
$cMSE_THRS_m$	Average cost of maintenance supplies and expenses per hour of operation at machine (m).
$cMSE_TVOL_m$	Average cost of maintenance supplies and expenses per unit volume processed at machine (m).
cOC_THRS_m	Average operating cost of processing material at machine (m) (per hour of operation).

cOC_TVOL_m	Average operating cost of processing material at machine (m) (per unit volume).
cOC_VOL_{im}	Operating cost of processing material (i) at machine (m) (per unit volume).
$cOSE_THRS_m$	Average cost of operating supplies and expenses per hour of operation at machine (m).
$cOSE_TVOL_m$	Average cost of operating supplies and expenses per unit volume processed at machine (m).
$cKVOL_{twgsm}$	Cost of drying a charge of (t,w,g,s) at kiln (m).
$cRAW_MP_i$	Cost per unit volume of procuring raw material (i).
$rCHIP_BDU$	Revenue (per bone dry unit) for selling chips.
$rREJ_i$	Revenue (per unit volume) for selling reject material (i).
$rTMKT_DG1_o$	Revenue (per unit volume) for selling output material (o) in demand group 1.
$rTMKT_DG2_o$	Revenue (per unit volume) for selling output material (o) in demand group 2.
$rTMKT_DG3_o$	Revenue (per unit volume) for selling output material (o) in demand group 3.

Other coefficients

$CHRG_CAP_{twgsm}$	Kiln charge capacity for kiln group (t, w, g, s) at kiln (m).
D_TIME_m	Percentage downtime for machine (m).
$IN_LUM_REC_{iom}$	Percentage of input material (i) recovered as part of output material (o) at machine (m). Applicable to processes that combine many inputs into one or many outputs.
LUM_BDU	Converts solid wood equivalent of lumber chipped to bone-dry units of chips produced.
LUM_CHIP_{ipm}	Percentage of input material (i) chipped when processed via processing option (p) at machine (m).
LUM_REC_{iom}	Percentage of input material (i) recovered as output material (o) at machine (m). Applicable to single input or kiln machines.
LUM_REJ_{ipm}	Percentage of input material (i) rejected when processed via processing option (p) at machine (m).
MAX_DG1_o	Maximum volume of output material (o) that can be sold on the market in demand group 1.
MAX_DG2_o	Maximum volume of output material (o) that can be sold on the market in demand group 2.
MAX_DG3_o	Maximum volume of output material (o) that can be sold on the market in demand group 3.
MAX_MP_i	Maximum volume of raw material (i) available for purchase.

MAX_THRS_m	Maximum operational hours available for machine (m).
M_RATE_{ipm}	Machine hours required per unit volume of input material (i) processed via processing option (p) at machine (m).
K_RATE_{twgsm}	Kiln hours required per unit volume of kiln material group (t,w,g,s) dried at kiln (m).
$OUT_LUM_REC_{iom}$	Percentage of input material (i) required in output material (o) at machine (m). Applicable to processes that combine many inputs into one or many outputs.

Constraints

Some constraints in the LP apply only to one type of machine center. For example constraint (14) is used when modeling single input and batch input machines (e.g. resaw and kilns respectively). This constraint is replaced by constraint (17) for machines that combine multiple inputs (e.g. glulam beam press). In addition constraints (8,9,19,21) apply only to kiln machines, whilst constraint 18 applies only to single input machines. All other constraints are generic and apply to all machine types.

Raw material constraints:

[1] Defines the volume of all (j) raw materials available for purchase.

Material balance constraints:

These constraints are used to sum volumes of material and to ensure that total inputs equal the total outputs.

[2] The total volume of raw material (i) input to all machine centers must equal the total volume of raw material (i) purchased.

[3] The total volume of output material (o), from all processing options at machine (m) that will be further processed at another machine must equal the total volume of (o) transferred from this source machine (c) to the possible destination machines (d).

[4] Volume of output material (o) that is transferred from source machine (c) to destination machine (d) must equal the volume input to destination machine (d) from source machine (c). The output from the source machine becomes the input for the destination machine.

[5] Total volume of material (i) input to a machine is equal to the volume of raw material (i) purchased for that machine added to the total volume of material (i) transferred from all source machines (c).

[6] The total volume of material (i) processed by all processing options (p), at machine (m), must equal the total volume of material (i) input to machine (m).

[7] Total volume of all materials into machine (m) must equal the total volume processed by machine (m).

[8] Sums material by length (l), and material group name (n), to define the total volume of each kiln charge group (t, w, g, s) to be dried in a particular kiln.

[9] The kiln charge capacity for (t, w, g, s) at kiln (m) multiplied by the number of (integer) charges for that kiln material group at kiln (m) must equal the total volume of material to be dried at kiln (m).

[10] Sums the total volume of reject material (i) produced.

[11] Sums the total (solid wood equivalent) volume of chips produced.

[12] Converts the total (solid wood equivalent) volume of chips produced to bone-dry units.

Production constraints:

Two types of production constraints are identified, recovery constraints and hour constraints.

Recovery

Recovery constraints define the recovery of outputs from inputs according to processing option (p).

[13] Defines the percentage of input material (i) that is recovered as output (o) at machine (m), according to processing option (p). The output material may be sold on the market or may be transferred to another machine for further processing. This constraint applies to machines that process a single input into one or more outputs (e.g. resaw) and to batch machines (e.g. kilns).

[14] Defines the percentage of input material (i) that is rejected at machine (m) when processed via processing option (p).

[15] Defines the percentage of input material (i) that is chipped at machine center (m) when processed via processing option (p). When this constraint is initiated by the appropriate query the volume of lumber to be chipped is adjusted from nominal to actual volume. Thus, chip volumes are based on actual dimensions (of lumber chipped) rather than nominal. In this way chip volumes are not over-estimated.

[16] Defines the percentage of input material (i) that is recovered when manufactured into output (o), and the percentage of input material (i) that is required in output material (o), for processing option (p). This constraint is similar to constraint [13] however, [16]

applies only to machines that combine many inputs into one or many outputs (e.g. glulam beam press).

Hours

These constraints are concerned with the hours consumed by machine centers during the operation of the manufacturing plant.

[17] Defines the hours utilized processing input material (i) according to processing option (p) at machine (m). The processing rate (hours per unit volume) is adjusted according to the downtime figure. Consequently, downtime has a direct (negative) effect on machine productivity. This constraint applies only to single and multiple input machine types.

[18] Defines the hours utilized drying kiln material group (t,w,g,s) at kiln (m).

[19] Defines the total hours operated by machine (m).

[20] Defines the total hours operated by kiln (m).

[21] The total operating hours of machine (m) cannot be greater than the maximum available operating hours for machine (m).

Marketing constraints:

These constraints compose market demand into three different demand groups (DG1, DG2, and DG3). These demand groups can be used to model a variable market price, when price is dependent on the volume produced. For example, small volumes of material may be difficult to sell and therefore price per unit volume may be low. Above this threshold volume there may exist a range where a premium price can be obtained. Surplus production beyond this range may cause or necessitate a price decrease. The three demand groups allow the user to define the ranges and market value for each group. Prices can increase or decrease between demand groups, providing flexibility for modeling revenues from the sale of product materials. When DG2 is active, indicator variable ($I1$) must switch to 1 (constraint 24). When indicator variable ($I1$) is equal to 1 DG1 must be at its upper bound (constraint 23). In a similar manner when DG3 is active indicator variable ($I2$) must switch to 1 (constraint 26). When indicator variable ($I2$) is equal to 1, DG2 must be at its upper bound. Constraint 24 prevents DG2 from exceeding its upper bound, whilst constraint 26 prevents DG3 from exceeding its upper bound. Constraint 27 is necessary to prevent DG1 exceeding its upper bound. This set of constraints ensure that material cannot be sold in DG2 or DG3 until DG1 and DG2 demand has been satisfied, respectively.

[22] Composes material for market into market demand groups.

[23-26] Ensure that market material must first enter DG1 until its upper bound is attained, followed by DG2 until its upper bound is attained, followed by DG3.

[27] Places a simple upper bound on demand group 1 (DG1).

[28-29] Causes the (integer) indicator variables to be binary (i.e. 0 or 1).

MODEL DEFINITION

The LP model is defined by constructing a number of queries based on Structured Query Language (SQL). The queries present the model in a pre-defined format that is readable by the model optimizer used to solve the problem. The optimizer used in this application is XA developed by Sunset Software Technology. As is common for a number of optimizers the coefficient matrix is represented using a triplet array, consisting of a column (or variable) index, a row (or constraint) index, and the value of the coefficient.

This is an efficient manner in which to generate the model instance (defined below), as one triplet is produced for every non-zero coefficient. As a result all zero coefficients are ignored, reducing model upload time. This is a useful time saving feature when the coefficient matrix is sparse.

QUERY STRUCTURE

The structure of each query is also important as it has implications in terms of model flexibility. Each query is constructed to define a specific component of a particular constraint (i.e. components of different constraints will not be conjugated in a single query).

In this way each query contains a triplet array representing a particular component of the mathematical model. Consequently, modeling flexibility is enhanced, as it is possible to modify the mathematical model according to the queries that are uploaded to the LP solver (XA). The efficiency of the system is also improved, as redundant constraints need not be initialized. For example, if kilns are not modeled the user may disable the queries associated with this machine center.

The downside of building queries to represent specific components of the model is the increase in query upload time (considering the greater number of queries to be loaded). However, the increase in upload time is more than compensated by the increase in modeling clarity and the resulting flexibility.

VARIABLE AND CONSTRAINT INDEXING

In any LP application it is fundamental that variable and constraint names or indexes are unique. The naming of the variables and constraints is applied in the SQL statements of the queries that define the model. Unique names are ensured by the use of a standardized

naming convention. A feature of relational database theory whereby every record in a data table must have a unique identifier (referred to as a primary key) facilitates the development of such a naming convention.

Another point worthy of noting is that these primary keys allow the model builder to develop succinct variable and constraint names. For example, if a specific material is defined as consisting of a thickness, width, length, grade and species, and group name, then rather than explicitly recording each in the variable or constraint name one can include the primary key or index number that relates to that specific material. Thus, the material is entirely represented by just one index number.

Naming length is important in terms of memory usage, and possibly model debugging. A succinct naming convention reduces the computer memory needed to run a given model. This may be important when solving large models. In terms of debugging, long names may reduce the clarity of the model, making them difficult to comprehend.

MODEL INSTANTIATION

A model instance is a snapshot or realization of the conceptual model at a given time (Murphy et al., 1992). Model instantiation is achieved by running the SQL queries that define the mathematical model. The queries retrieve data from the database in the prescribed format, and generate the model instance based on the records currently present in the database. In this way the size of an instance is entirely independent of the

conceptual model and is determined by the number of records currently stored in the database.

SOLVING THE MODEL

A program XAEZ developed by Andre Schuetz is used to run the SQL queries that generate the model instance. The realization of the model is loaded into the optimizer XA. The model is solved, and the solution written back to pre-defined tables in the database. XAEZ facilitates the transfer of data between the database and the optimizer.

REPORTS

Using MS Access's reporting features a number of key reports are developed to convey the information provided in the model solution to management personnel. Before meaningful reports can be developed the constraint and variable names must be decoded. Another set of queries are constructed to perform this task. The reports are based on these queries and are activated when the reports are initialized. Such queries can be also useful when debugging the model.

Key reports provided include:

- 1) Financial summary
- 2) Optimal lumber purchasing strategy

- 3) Machine utilization
- 4) Lumber sales
- 5) Reject sales
- 6) Chip sales

The reporting features are very flexible and it is relatively easy to customize the reports to meet specific user requirements.

The structure of the DSS and the relationship between the components is summarized in Fig. 2.

Figure 2: Components of the decision support system and flow of data.

5 MODEL VALIDATION

INTRODUCTION

The DSS will be validated by analyzing a number of operating scenarios at a secondary manufacturing operation in British Columbia. This company was selected as a study site due to the wide range of machine centers utilized in the manufacturing process, and the willingness of management personnel to investigate the use of a DSS to assist production planning for their operations. Table 1 shows the range of machine centers available. This is an important as it provides an opportunity to model a wide variety of machines common to many secondary manufacturers.

MACHINE CENTER	PRIMARY FUNCTION
Green Chain	Sticking green lumber for kiln drying
Kilns	Drying lumber to a prescribed moisture content
Planer	Surfacing lumber
Continuous Lumber Tester	Grades lumber by strength
Sorter	Used to sort, stack and package lumber
Finger Jointer	Glues lumber together lengthwise
Beam Press	Glues lumber together one piece on top of the other to produce a glulam beam
Re-saw	Used to split lumber horizontally
Chop-saw	Used to chop defects out along the length of lumber

Table 1: Machine centers available at study site.

DATA COLLECTION

In order to implement the DSS at the study site a range of data was collected regarding materials, manufacturing processes and the market environment. Further details are provided in Table 2.

DATA CATEGORY	DATA DESCRIPTION
Material definition data	Dimensions
	Grades
	Species
	Group names
Raw material data	Available materials
	Volumes available
	Costs
Process data	Manufacturing options
	Process yields (recovery)
	Process rates
	Process capacities
	Costs
Market data	Potential markets
	Forecasted prices
	Forecasted demand

Table 2: Data required to set-up the Decision Support system.

SCENARIO ANALYSIS

Introduction

The objective of this research was to develop an adaptable linear programming based DSS using a relational database approach. The DSS should provide secondary manufacturers with a production planning tool that will help determine optimal operating strategies given the manufacturing technology and marketing conditions prevalent at a given period in time. To assess whether the objective has been achieved a base case and three different operating scenarios will be analyzed with the objective of demonstrating both model validity and flexibility.

As defined by and Fishman and Kiviat (1968), “model validation tests the agreement between the behavior of the model and the real world system being modeled”. The validation process began by analyzing simple scenarios with few raw materials and only a small number of production options. In this way it was easier to analyze the model results, identify any problems with the model formulation, and to calibrate the model parameters. Initial model runs were concerned with calibrating the machine production parameters until accurate production rates and revenues were obtained. Typically, process production rates were over-estimated and it was necessary to reduce these rates to achieve more realistic results.

Model runs were also implemented in order to test and verify the market demand groups. Following a number of runs varying market demand group prices and limits it was found

that the three market demand groups behave as intended. Material may not enter demand group 2 until demand group 1 has been satisfied, and similarly material may not enter demand group 3 until demand group 2 has been satisfied.

The preliminary runs were developed further to establish a base case. The base case was used to determine the optimal raw material purchasing strategy for the #1 finger-joint line at the study site. Scenario 1 was developed from the base case by implementing a change in raw material costs. The optimal operating strategy was then compared with the base case.

Scenario 2 was created to demonstrate that the model could be adapted to changes in the process flow. A number of machines were added to the process flow to include the production of intermediate products (kiln dried material and finger-jointed lamina) that can be sold on the market or further processed into glulam beams. The optimal purchasing and production strategies were then examined. Scenario 3 was developed from scenario 2 with the aim of examining the impact of an increase in glulam beam sale prices. The optimal operating strategy was then compared with scenario 2.

Assumptions

Each scenario is based on a one-month operating period. This is reflected in the machine hours available for each machine center. The assumption has been made that there are no marketing constraints (i.e. the plant may sell all material produced), and that all material

is sold at the one price level irrespective of the volume produced (i.e. only demand group 1 is utilized). The base case and three scenarios were solved and the results examined and discussed to substantiate the validity of the model.

BASE CASE : #1 FINGER-JOINT LINE

Raw material¹

The raw materials for the base case can be aggregated into four main categories (Table 3). All material dimensions are imperial. Thickness is defined in inches, width in inches, and length in feet. Raw materials may be procured from three different sources. Source 1 represents material purchased from the open market, whilst source 2 and 3 indicates material purchased from two specific sawmills that may supply the study site with raw materials. Economy grade material may be purchased from source 1 and source 3, whilst trim block material can be purchased from source 1 and source 2. All materials are spruce.

The price and volume available differ between sources. Source 1 material is consistently cheaper than material from either source 2 or source 3. It is also possible that material from different sources would have different process recovery values. However, this information was not yet available at the study site. Therefore, yield values are assumed to be equal between sources.

¹ Materials are defined in the following format: Thickness x Width x Length _ Grade _ Species _ Source.

RAW MATERIAL CATEGORY	RAW MATERIAL NAME
Wide width trim blocks	2x12x1.67_TrimBlock_S_1
	2x12x1.67_TrimBlock_S_2
	2x10x1.67_TrimBlock_S_1
	2x10x1.67_TrimBlock_S_2
	2x8x1.67_TrimBlock_S_1
	2x8x1.67_TrimBlock_S_2
Narrow width trim blocks	2x6x1.67_TrimBlock_S_1
	2x6x1.67_TrimBlock_S_2
	2x4x1.67_TrimBlock_S_1
	2x4x1.67_TrimBlock_S_2
Wide width economy	2x10x8_Economy_S_1
	2x10x8_Economy_S_3
Narrow width economy	2x6x8_Economy_S_1
	2x6x8_Economy_S_3
	2x4x8_Economy_S_1
	2x4x8_Economy_S_3

Table 3: Raw material availability for base case and scenario 1.

Potential Products

The main finger-jointed products considered in the base case are:

- 1) 2x6 Select
- 2) 2x6 Natural
- 3) 2x4 Select
- 4) 2x4 Natural

Two points should be noted regarding the potential products. First, there is a market premium for the 2x4 product over the 2x6 product. Second, 2x6 material is more efficient in the use of machine time (i.e. a greater volume throughput can be achieved per unit of processing time). Therefore, one of the issues that the model will address is the trade-off between cost of processing and market price.

Process Flow

The process flow varies depending on the input raw material. The basic process flow and machine centers utilized are shown in Fig. 3.

Wide width trim blocks (2x8, 2x10, 2x12) are first split at the #3 resaw. 2x8 trim blocks are split into 2x4's, 2x10 into a 2x4 and a 2x6, and the 2x12's can be split into 2x4's or 2x6's. These narrow width trim blocks (2x4, 2x6) are then finger-jointed into the 2x4 and 2x6 finger-jointed products previously described. A percentage of the finger-jointed material will contain wane (a defect region untouched by the saws). A drop saw on the planer-line is used to remove the wane. 2x6 material with excess wane is ripped back to 2x4, whilst 2x4 material is ripped back to 2x3. Narrow width trim blocks (2x4, 2x6) go directly to the finger-jointer. Once again a small percentage of the finger-jointed material may contain wane that is removed at the planer line.

Figure 3: Base case process flow.

Wide width economy (2x10) is sorted (at the planer line) to remove material not suitable for finger jointing. This material is sold on the market. The “on-grade” material (i.e. material of appropriate quality) is split (at the planer-line), and then sent to the finger-jointer. Narrow width economy (2x4, 2x6) is first sorted into a number of grades at the chop-saw. Grades not suitable for finger jointing are sold on the market. “On-grade” material is chopped at the chop-saw to remove any defects and then sent to the finger-jointer. Material with excess wane is ripped back to the next widest dimension as previously described.

Problem definition

The base case described above indicates a number of raw materials that can be processed into 2x4 or 2x6 finger-jointed products. The production problem is to identify the optimal

(profit maximizing) combination of raw material purchases given the current operating conditions at the study site.

Results and discussion

The optimal raw material purchasing strategy for the base case and scenario 1 is shown in Fig. 4. The optimal raw material purchase strategy for the base case indicates that under the current conditions, maximum profit is achieved by purchasing trim blocks rather than the longer length economy material.

Shadow prices are obtained for raw material constraints that are binding (i.e. at their upper limit). These are given in Fig. 5. The shadow price are marginal valuations that can be interpreted as the effect on the objective function (i.e. profit), of forcing purchases of a raw material down below its upper bound (lowering the objective value) or the effect of increasing purchases beyond the upper bound (increasing the objective value). Due to the proprietary nature of this information the y-axis scale has been omitted. However, the figure has been included to indicate the relative profit contribution of each material. It is noted that the interpretation of the shadow prices is only valid for changes in one constraint at a time.

Figure 4: Optimal raw material purchase distribution for base case and scenario 1.

The shadow prices in Fig 5 show that narrow width trim block materials are more profitable than wide widths. This can be attributed to the additional splitting step at the #3 resaw that takes place when processing wide width material. Although wide width material is purchased at a lower price this does not compensate for the extra cost incurred by the additional processing. From Fig. 5 it is also evident that material from source 1 provides a greater profit contribution than respective material from source 2 or source 3. This is a direct result of the lower purchase price of source 1 material.

Figure 5: Shadow prices and for base case raw materials.

Figure 6 provides the reduced costs for each raw material that was not procured in the optimal raw material purchasing strategy. The reduced costs show the price reductions necessary before each material would be procured in the optimal raw material purchasing plan. In a similar manner to shadow prices these reduced costs are only valid for changes in one raw material price at a time.

An examination of the reduced costs for each raw material demonstrate that source 1 economy material requires a smaller price reduction than economy from source 3. This is explained exactly by the amount (\$10) by which source 1 is cheaper than source 3. We expect this result as the purchase price is the only difference between source 1 and source 3 materials.

Figure 6: Reduced costs for Base Case raw materials.²

An examination of figures 4 and 5, and the machine utilization provided in figure 7 it is possible to explain the results attained. As narrow width trim blocks provide the greatest profit contribution, these materials are purchased until their upper bounds are attained. Following this, wide width materials are purchased in order of profit contribution. 2x12's provide greatest profit, followed by the 2x10's, with 2x8's providing least profit. This trend is explained by the greater volume throughput achieved when processing wider widths. Consequently, wider widths cost less to process per unit volume. Wide width trim blocks are purchased until #3 resaw capacity becomes binding (Fig. 7). This occurs when 74% of the 2x8 trim block material from source 1 is purchased.

² Ranges for these reduced costs are provided in appendix B

Figure 7: Machine availability and utilization for base case and scenario 1.

The exhausted #3 resaw capacity prevents further processing of wide width trim blocks, and as all narrow trim blocks have been utilized further production is constrained. It is evident that chop-saw utilization is zero as no economy material is purchased, and there is slack capacity at the planer and the #1 Finger-jointer. However, it was noted that the #1 finger-jointer is close to maximum capacity. As #3 resaw capacity has been fully utilized a shadow price is obtained for this variable. The shadow price indicates that a further \$116 of profit could be obtained for each additional hour of processing capacity. Conversely, a reduction in #3 resaw capacity would cause a profit loss of \$116 per hour of processing capacity removed. The range for which the shadow price is valid is provided in appendix A.

The majority of lumber sales (Fig. 8) are 2x4 natural and 2x4 select. This is a direct result of the greater availability of 2x4 (trim block) raw material and the existence of a market premium for the 2x4 product over the 2x6 product. Therefore, the model will produce 2x4 material wherever possible. This is evident in the ripping of 2x12 trim blocks at the #3 resaw. The model has the option to produce either 2x4 or 2x6 material. The model produces only the higher value 2x4's.

Figure 8: Material sales distribution for base case and scenario 1.

Table 4 provides a summary of the costs and revenues for the base case.

REVENUES		COSTS	
Material sales	\$446,848	Total operating costs	\$135,001
Chip sales	\$4,032	Raw material purchases	\$212,747
TOTAL REVENUES	\$450,880	TOTAL COSTS	\$347,748
NET REVENUE	\$103,132		

Table 4: Financial summary for base case.

SCENARIO 1 – LOWER PRICED ECONOMY

The purchase price of economy material in the base case was considered above average with respect to previous operating periods. Thus, it was of interest to management personnel to examine the impact of a decrease in the purchase price of such material. Scenario 1 examines the impact of a 20% cost reduction in economy material on the optimal operating plan. All other data remain unchanged.

The reduction in the price of economy material causes a shift in the optimal raw material purchasing strategy. Table 5 shows a reduction in the purchases of wide width trim blocks with an associated increase in purchases of economy material. This shift was anticipated through an examination of the reduced costs for the base case raw materials. The 20 % price reduction implemented exceeded the necessary price reduction shown in Fig. 6. However, it is noted that we cannot use these reduced costs from the base case raw material variables to explain the resultant purchases for scenario 1. The reason for this is that the reduced costs are only valid for changes in one raw material at a time. In contrast, scenario 1 has implemented price reductions on all economy material.

	Wide Width Trim Blocks	Narrow Width Trim Blocks	Wide Width Economy	Narrow Width Economy	Total Volume Purchased
Base Case	387	600	0	0	987
Scenario 1	200	600	200	476	1476

Table 5: Summary of raw material purchases (Mfbm) for base case and scenario 1

Figures 4 and 5 show that the less profitable trim block materials (2x10 trim blocks from source 2 and both sources of 2x8 trim blocks) cease to be procured. This provides additional processing capacity at the #1 finger-jointer that is utilized by the economy purchases.

The 2x10 economy material (from both sources) and 2x6 from source 1 is purchased until their upper bounds are attained. 2x6 economy from source 3 is then purchased until #1 finger-joint capacity becomes binding. This occurs when 51 % of the 2x6 economy from source 3 is purchased. 2x4 economy material is still not purchased as the other economy materials provide a greater profit contribution.

From machine utilization shown in Fig. 7, it is evident that #3 resaw capacity is no longer binding in scenario 1. This is due to the decrease in wide width trim block purchases. The purchase of economy material has resulted in an increase in the utilization of both the chop-saw and the planer-line compared to the base case. Slack processing capacity is available at these machines. #1 finger-joint capacity is exhausted, constraining further production.

The shadow price for the #1 finger-jointer capacity indicates that an additional \$244 of profit could be obtained for each additional hour of processing capacity. Conversely, a profit loss of \$244 would be incurred per hour of processing capacity removed. The ranges for this shadow price are provided in appendix A.

Lumber sales exhibit a shift from 2x4 to 2x6 products. This is reflective of raw material purchases that are now more biased towards 2x6 material. The shift can mostly be attributed to the large volume of 2x6 economy material procured from source 1. As found in the base case the premium for 2x4 material insures that 2x12 trim blocks are resawn into 2x4 products rather than 2x6. The sale of “off-grade” material (i.e. material not suitable for finger-jointing) is also evident in scenario 1. This material is produced from the narrow width economy, as described previously in the process flow.

Table 6 provides the financial summary for scenario 1. Scenario 1 realizes a 9% profit increase over the base case.

REVENUES			COSTS		
	Base Case	Scenario 1		Base Case	Scenario 1
Material sales	\$446,848	\$548,855	Total operating costs	\$135,001	\$153,699
Chip sales	\$4,032	\$10,480	Raw material purchases	\$212,747	\$292,837
TOTAL REVENUES	\$450,880	\$559,335	TOTAL COSTS	\$347,748	\$446,535
PROFIT	\$103,132	\$112,799			

Table 6: Financial summary for base case and scenario 1.

SCENARIO 2 – ADDITIONS TO PROCESS FLOW

To demonstrate the adaptability of the DSS a number of additional machine centers were added to the process flow defined in the base case. In addition to the finger-jointed products manufactured in the base case, scenario 2 can also manufacture glulam beams with the potential to produce a number of semi-finished products in the process.

Raw Material

Three raw material sources are added to the base case scenario. All materials are Fir and are purchased from source 1. Details of the raw materials and their respective products are given in Table 7.

RAW MATERIAL	2x10x16_S4S_F_1 2x5x16_Rough_F_1	2x6x14_Rough_F_1
INTERMEDIATE PRODUCTS	2x5x16_KD_F	2x5x14_KD_F
	2x5x40_FJL160_F	2x6x40_FJL160_F
	2x5x40_FJL140_F	2x6x40_FJL140_F
	2x5x40_FJL125_F	2x6x40_FJL125_F
	2x5x40_FJL90_F	2x6x40_FJL90_F
	2x5x40_FJL80_F	2x6x40_FJL80_F
GLULAM BEAMS	105x360x12_E120F330	120x330x12_E120F330
	105x150x12_E105F300	120x270x12_E120F330

Table 7: Potential raw materials and products for scenario 2.

The raw materials and intermediate materials are given in imperial units (inches x inches x feet), whilst the glulam beams are given in metric units (mm x mm x m).

Potential products

The intermediate products that may be produced (Table 7) are kiln dried (KD) lumber, and machine stress rated finger-jointed lamina (FJL). The FJL material is used to manufacture glulam beams. Five strength grades of lamina can be produced (L160 – L80). The potential glulam beam products added to the base case are destined for the export market and are listed in Table 7 in metric dimensions (i.e. mm x mm x m). Each beam has a different lay-up, consisting of a different percentage of each lamina grade (appendix C).

Process Flow

The process flow for scenario 2 is shown in Fig. 9. The materials and machine centers utilized in the base case are shown in bold. The grey arrows represent the base case process flow. The additions made to the base case to create scenario 2 are now discussed.

Rough material enters the production operation at the green chain. Lumber not suitable for beam production is removed at the green chain and sold on the market. The remaining lumber is stacked for drying in the kilns. When the desired moisture content is attained, the material may leave the production process to be sold on the market, or can be sent to the planer line where a continuous lumber tester is used to assign strength grades to the

dried lumber. Material is sorted into the designated strength grades at the sorter, and defect material is sent to the chop-saw or to the drop-saw on the planer-line for splitting. Defects are removed at the chop-saw and the “on-grade” lamina produced are sent to the #2 finger-jointer.

Figure 9: Process flow for scenario 2 and scenario 3.³

³ Process flow for the base case is highlighted in bold.

Material resawn at the drop-saw on the planer may re-enter the production process depending on the beams being produced. Alternatively, they are sold on the market. The dimensions and grade of the beam being produced dictates what lamina is required by downstream processes.

Lamina of the required strength grades are sent to the #2 finger-jointer (from both the sorter and chop-saw) where they are glued end-wise and cut to the desired length. After finger jointing, the lamina are planed to their target dimensions at the beam moulder. The planed lamina are glued and pressed into rough beams at the beam press. Rough beams are then planed down to their final dimensions at the beam planer and sold on the market. The 2x10 S4S follows a similar set of processing steps once it has been resawn into five-inch widths at #3 resaw.

Problem definition

The problem is to identify the most profitable raw material purchasing strategy and product mix for the operation, considering the #1 finger-joint line, the beam line and the interaction between them.

Results and discussion

The raw material procurement strategy for scenario 2 is provided in figure 10. The new strategy is similar to the base case with respect to purchase of narrow width trim blocks

and economy material for the #1 finger-joint line. However, there are changes in the volume of wide width trim blocks purchased.

It is evident in scenario 2 that there are reductions in both the volume of 2x10 trim blocks purchased from source 2, and the 2x8 trim blocks from source 1. The reason for this is related to the procurement of 2x10 S4S material for the beam-line. The wide width trim blocks compete with the 2x10 S4S, for limited processing capacity at the #3 resaw.

Figure 10: Optimal raw material purchase distribution for base case and scenario 2.

Figure 11 shows that the #3 resaw was fully utilized in both the base case and scenario 2. The 2x10 S4S material purchased provides a greater profit contribution than the 2x10 and 2x8 wide width trim block material. Therefore, the purchase of 2x10 S4S material causes a reduction in the volume of 2x10 and 2x8 trim blocks that can be procured in scenario 2. The reduction in trim block purchases is associated with the lower utilization of the #1 finger-joint line in scenario 2.

Figure 11: Machine availability and utilization for base case and scenario 2.

An interesting question relates to the small volume of the 2x10 trim blocks purchased from source 2. If the 2x10 S4S material is more profitable, why is there still a small volume of the 2x10 trim blocks purchased, considering the availability of 2x10 S4S

material? The explanation is linked to the volume of kiln charges. To dry another charge of material, would force the model to purchase another entire charge volume of the 2x10 S4S raw material. In order to free up additional #3 resaw capacity (to process this material) the purchase of other wide width trim block materials would have to be displaced (because #3 resaw capacity is limiting). It is probable that the profit contribution from the 2x10 S4S material is not large enough to justify this. Consequently, there is available (#3 resaw) capacity to process a small volume of the 2x10 trim blocks from source 2.

The shadow price obtained for the exhausted #3 resaw capacity in scenario 2 is \$144 (ranges are provided in appendix A). This compares to a shadow price of \$116 for the #3 resaw in the base case. The increase in marginal value is explained by the addition of 2x10 S4S material for the beam-line. As stated previously, this material provides a greater profit contribution than the 2x10 and 2x8 wide width trim blocks that utilized #3 resaw capacity in the base case. Therefore, because of the potential profit increase through processing 2x10 S4S material, it is expected that the marginal value of #3 resaw capacity would be greater in scenario 2.

Raw material purchases destined for the beam-line and associated processes include almost all (99%) 2x6 rough material and 40% of the 2x10 S4S material. 2x5 rough material is not procured (Fig. 10). The purchase of 2x10 S4S material is constrained by #3 resaw capacity, while the purchase of 2x6 is constrained by volume availability and the kiln charge volume, (there is not enough material available to fill another kiln charge of the material). Charge volumes for each kiln are provided in appendix D. Kilns 1 to 3

are identical both in terms of charge volume and operating cost, and therefore the difference in their utilization (Fig. 11) is arbitrary. However, Kiln 4 has a smaller charge volume, and is more expensive to operate. The model makes use of the smaller charge volume at this kiln (even though it incurs a greater cost) to better match processing capacity with raw material availability.

Material sales for the base case and scenario 2 are shown in Fig. 12.

Figure 12: Material sales distribution for base case and scenario 2.

In accordance with the decrease in material purchases for the #1 finger-joint line (Fig. 10), and the associated decrease in #1 finger-joint utilization (Fig. 11), scenario 2 sales show a decrease in the sale of materials produced by this line.

Sales of material from the beam-line and associated processes consist of kiln-dried material, machine stress rated finger-jointed lamina and one dimension of glulam beam. The 2x5 KD S4S are produced from the splitting and drying of 2x10 S4S grade material. Considering the four dimensions of glulam beams that can be manufactured in scenario 2, only the 120x330mm beam is produced. Four main factors interact to determine the beam dimensions that should be produced. First, there is the obvious influence of sale price. Second, there are the different processing rates (and therefore costs) associated with processing material of different dimensions. Third, there is the supply of lamina grades produced at the continuous lumber tester, and the grades required in the lay-up of each beam. Finally, there is the influence of recovery volumes that are dependent on the lamina and beam target dimensions, as well as recovery rates in the intermediate processes.

Given that there is very little difference in sale price between the four beam dimensions this factor may be excluded from the discussion. Table 8 shows how each glulam beam ranks relative to the other beams based on volume recovery from respective raw materials. Rank 1 indicates the highest volume recovery. The actual recovery values are not included due to the proprietary nature of this information. Figure 13 shows the volume of each beam that can be produced from the available lamina grades.

GLULAM BEAM	RAW MATERIAL	RECOVERY RANK
105x360mm	2x5 Rough	1
105x360mm	2x10 S4S	2
105x150mm	2x5 Rough	3
120x270mm	2x6 Rough	4
120x330mm	2x6 Rough	5
105x150mm	2x10 S4S	5

Table 8: Rank of glulam beams based on volume recovery from respective raw materials.

Figure 13: Percentage of available lamina that may be utilized in each beam.

The volumes are based on a comparison of the lamina requirements for each beam (provided in appendix C), and the lamina grade out-turn from the continuous lumber tester.

As indicated in table 8 and figure 13 the recovery, and the supply demand relationship for lamina, cannot justify the production of 120mm beams over 105mm beams. 105mm beams have a higher recovery than 120mm beams (Table 8), and the lamina utilization levels are similar. The most probable cause for the production of 120mm beams whilst not producing 105mm beams, may be attributed to the greater volume throughput achieved when processing wider width material. 120mm beams are manufactured from 2x6 raw material, whilst 105mm beams are manufactured from 2x5 raw material. The 2x6 material is less costly to process due to the greater volume throughput achieved when processing wider width materials.

Table 8 and figure13 do help explain the difference in production of 120x330mm and 120x270mm beams. When manufacturing 120x330 beams, 60% of the available lamina can be utilized. While, when manufacturing 120x270mm beams only 48% of the available lamina can be utilized. Consequently, it is possible to produce a greater volume (and therefore profit) when manufacturing 120x330mm beams rather than 120x270mm beams. The greater recovery from 120x270mm beams does not compensate for the lower lamina utilization level.

Further production of 120x330mm beams is constrained by the volume of raw material available. Figure 12 shows the sale of FJL finger-jointed lamina that cannot be utilized in the beams produced. This occurs because there is a discrepancy between the volume of lamina grades produced, and the lamina grades required for glulam beam production.

Table 6 provides a comparison of the financial summary for the base case and scenario 2. The addition of the beam line and associated processes, to the base case realized a 23% increase in profit for scenario 2.

REVENUES			COSTS		
	Base Case	Scenario 2		Base Case	Scenario 2
Material sales	\$446,848	\$1,071,587	Total operating costs	\$135,001	\$336,575
Chip sales	\$4,032	\$22,890	Raw material purchases	\$212,747	\$631,342
TOTAL REVENUES	\$450,880	\$1,094,477	TOTAL COSTS	\$347,748	\$967,917
PROFIT	\$103,132	\$126,559			

Table 9: Financial summary for base case and scenario 2.

SCENARIO 3 – INCREASING BEAM PRICES

Scenario 3 is a market driven scenario that was developed in anticipation of improved market prices for glulam beams. It is of interest to the management personnel at the study site to examine the impact of a price increase on the optimal operating strategy. A 10% increase in prices was applied to the potential glulam beam products identified in scenario 2. All other data remained unchanged.

The optimal raw material purchasing strategy (Fig. 14) shows that material destined for the #1 finger-joint line is similar to scenario 2. All the available narrow width trim blocks are procured, however, a change is observed in the volumes of wide width trim blocks purchased. In scenario 3 it is evident that 2x10 wide width trim blocks cease to be procured. Figure 14 also shows that there is a change in material purchases destined for the beam-line and associated processes. The 2x6 rough material purchases remain at the same level as scenario 2, however, 2x5 rough material is now procured, and there is an increase in the volume of 2x10 S4S material purchased.

The absence of 2x10 wide width trim block purchases may be explained by the planer-line bottleneck that occurs in scenario 3. Figure 15 shows the machine utilization for both scenario 2 and 3. It is observed that the #3 resaw capacity is once again fully utilized, and that planer-line capacity has also been exhausted in scenario 3.

Figure 14: Optimal raw material purchase distribution for scenario 2 and scenario 3.

The increase in planer-line utilization is a result of the 2x5 rough purchases. The 2x5 rough material is strength graded by the continuous lumber tester on the planer-line to produce lamina for manufacturing glulam beams. As the planer-line capacity is limiting, it appears that the model has foregone the purchase of the 2x10 wide width trim blocks in order to release processing capacity at the planer-line. It is recalled from the process flow in the base case, that some material processed at the #1 finger-joint line will contain waste that is removed at the drop saw on the planer-line. Decreasing material purchases for the #1 finger-joint line indirectly provides additional processing capacity at the planer-line.

This in turn allows a greater volume of material to be purchased for the beam-line. Furthermore, the decrease in wide width trim block procurement has permitted an increase in the purchase of 2x10 S4S material due to the release of processing capacity at the #3 resaw. It is noted that the purchase of 2x12 trim blocks are not displaced.

Figure 15: Machine availability and utilization for scenario 2 and scenario 3.

The increase in 2x10 S4S and 2x5 rough purchases results in a greater utilization of the kilns. From figure 15 it is evident that the utilization of kiln 1 and 2 is approximately 95%. Although kiln hours are still available, further kiln drying is effectively constrained because kiln charges are integer, and there are not enough hours remaining to dry another full charge of material. However, there is available capacity at both kiln 3 and 4. As

mentioned in scenario 2, the difference in utilization levels between kilns 1 and 2 and 3 is arbitrary as they use the same charge volume and incur identical operating costs. The utilization level of kiln 4 is related to the smaller charge volume of this kiln.

The shadow prices for fully utilized machines indicate that the marginal value for additional capacity is \$233 for the #3 resaw, and \$371 for the planer-line. The #3 resaw marginal value in scenario 3 is greater than that for the #3 resaw in scenario 2 (\$144).

This occurs because an increase in #3 resaw in scenario 3 would allow the 2x10 wide width trim block material currently displaced, to re-enter the optimal operating strategy, and therefore increasing profit levels. The shadow prices and their ranges (provided in appendix A) can be used to justify increasing the capacity at these constraining machine centers, through the purchase of additional machine centers, productivity improvements or by increasing the running time available (e.g. schedule 2 shifts rather than one).

Figure 16 shows the material sales from scenario 2 and 3. It is apparent that there is a decrease in the sale of material produced from the # 1 finger-joint line, corresponding to the decrease in wide width trim block purchases and the lower utilization of the #1 finger-joint line in scenario 3. The increase in the sale of 2x5x16 KDS4S is associated with an increase in 2x10 S4S purchases. Figure 16 also shows that a small volume of 2x5 rough material purchases was also sold as KD material. The reason for this can be found from an examination of machine utilization for scenario 3 (Fig. 15). It is evident that planer-line capacity is fully utilized and therefore constrains further production of beam products by downstream machine centers. Consequently, material that cannot be further processed is sold on the market as kiln-dried material.

Figure 16: Material sales distribution for scenario 2 and scenario 3.

The increase in glulam beam sale prices has resulted in higher levels of glulam beam production. Accordingly, figure 15 shows an associated increase in utilization levels for machine centers involved in beam production. Three beam dimensions are manufactured in scenario 3. 120x330 beams sales, and sale of lamina not utilized in beam production are identical to scenario 2. This is expected, as raw material purchases of 2x6 rough material are identical to scenario 2. In addition to the production of 120mm beams, the optimal operating plan for scenario 3 involves the production of a combination of both 105x360mm and 105x150mm beams.

Figure 16 reveals that sales levels of 105x150mm beams are almost double that of 105x360mm beams. An explanation for this may be found in table 8 and figure 13 presented in scenario 2. Figure 13 showed the volume of available lamina that could be

utilized in each glulam beam. Table 8 ranked the potential beams based on the volume recovery from respective raw materials. From these figures it was observed that the 105x150mm beam incurs a greater volume loss than the 105x360mm beam. However, the 105x150mm beam can utilize a greater volume of the available lamina (62% utilization as opposed to 42%). This factor appears to be more salient in deciding what beam to produce, hence the greater production level of 105x150mm beams. This factor was also evident in scenario 2, where 120x330mm beams were produced rather than the (higher recovery) 120x270mm beams. The 120x330mm beams incurred a greater volume loss, but attained higher utilization levels.

The explanation for the production of a combination of the 105x360mm and 105x150mm beams is not obvious due to the complexity of factors involved in this decision process. However, the results indicate that it is more profitable to manufacture a combination of these beams rather than focus on the production of a single glulam beam product.

Figure 16 shows that 2x10 S4S material is resawn, dried and sold as KD lumber rather than being further processed into glulam beams. One may question why this is so, considering that 2x5 rough material was processed into glulam beams. From Table 8 it is evident that a greater volume recovery is possible by processing 2x5 rough raw material rather than 2x10 S4S. Figure 13 shows that a greater utilization of lamina is possible from the 105x150mm beams when processing 2x5 rough raw material. However, this result is reversed for the 105x360mm beams (2x10 S4S raw material provides a greater utilization level). It was concluded that in this case the higher yield recovery from the 2x5 rough

raw material, combined with the greater lamina utilization for 105x150mm beams, favors the 2x5 rough material for beam production. Furthermore, the lower purchase cost of the 2x10 S4S material does not compensate for this result. As noted earlier, the exhausted planer-line capacity constrains further beam production.

The 10% increase in glulam beam market prices in scenario 3 realized a 55% increase in profit over that obtained in scenario 2. The source of the additional profit is the purchase of 2x5 rough material for manufacturing into glulam beams. This has been facilitated by an increase in glulam beam prices. A comparison of the financial summary for scenario 2 and scenario 3 is provided in Table 10.

REVENUES			COSTS		
	Scenario 2	Scenario 3		Scenario 2	Scenario 3
Material sales	\$1071587	\$1,548,051	Total operating costs	\$336,575	\$494,525
Chip sales	\$22,890	\$35,039	Raw material purchases	\$631,342	\$892,016
TOTAL REVENUES	\$1,094,477	\$1,583,090	TOTAL COSTS	\$967,917	\$1,386,541
PROFIT	\$126,559	\$196,549			

Table 10: Financial summary for scenario 2 and scenario 3.

6 CONCLUSION

Production planning in the secondary manufacturing sector is a complex task. The interactions of raw materials, with process and marketing factors produce complex interrelationships that require simultaneous analysis in order to find the optimal operating strategy. An examination of the literature on operations research techniques for production planning in secondary manufacturing revealed the specificity of existing applications. Most models have been designed for specific secondary manufacturing plants or focus on solving specific problems. The decision support system developed in this research can be adapted to model a wide variety of secondary manufacturing facilities, and can be used to address a range of short-term production planning issues.

The decision support system was successfully developed using Microsoft Access. A relational database was used to manage the model data. Access forms facilitate data entry, and SQL queries define the LP. A program (XAEZ) facilitates transfer of the instantiated LP model to the optimizer (XA), and transfer of the optimal solution back to the database. A number of Access reports are generated to convey results back to the user.

Microsoft Access was found to provide an appropriate design environment for building the DSS. The relational database provides an efficient data management tool for handling potentially large data sets. Model data can be easily updated through the appropriate forms, and re-use of common data is facilitated by their storage in the database. For example, once materials have been defined they are stored in a table and can be retrieved

for use in a new problem. There is no need to re-define such data. The Access forms provide a number of advantages for the user interface. Data entry is initiated through a small number of forms rather than directly through the plethora of tables in the database. The data entry forms are designed to allow the user to enter view and update model data in an intuitive manner. The forms provide features that can be used to minimize data entry error. Validation rules are defined for example, to ensure that the species of an output material is the same as the species of the input material.

Model-data independence is provided by a database that manages all model data, and SQL queries that define the mathematical model. As noted by other authors (Muhunna & Pick 1994, Geoffrion, 1987, and Atamturk et al. 2000) model-data independence facilitates data manipulation, reuse of the same mathematical model in different specific modeling applications, and provides greater design robustness and clarity. Furthermore, the use of SQL queries to define the mathematical structure allows the LP to be modified relatively simply by changing the defining queries.

The resultant DSS is flexible in terms of the variety of machine centers that can be modeled, and the adaptability to any plant configuration. However, highly complex flows may be difficult to apply without a more visual user interface to support the text-oriented interface currently developed. This limitation is discussed further in the future work chapter.

System flexibility was achieved primarily through a generic view of the manufacturing process, rather than focusing on the attributes of specific machine centers. Accordingly, a wide range of secondary manufacturing machine centers can be modeled. Flexibility of the system was further enhanced by:

- 1) Model-data independence
- 2) The material naming convention employed (the ability to group materials)
- 3) The ability to handle and convert between different units
- 4) Providing different methods for costing production processes (i.e. on a volume or hourly basis).
- 5) The ability to model revenue from sale of product material through three different demand groups that incur different revenues based on volume sold.

To demonstrate model validity a base case scenario was established for a secondary manufacturing operation in British Columbia. The results attained comply with the findings of management personnel in the manufacturing operation being modeled. A number of scenarios were developed from the base case to demonstrate how the model behaves under varying conditions, and to demonstrate that the model can be adapted to changes in process flow. An examination of the scenario results focusing on the raw material purchasing strategies, machine utilization and product sales showed that the model produces realistic results, and appears to react accordingly to changes in the manufacturing system being modeled.

The scenarios described in this research have presented a narrow example of how the DSS can be used in a secondary manufacturing environment. The DSS has a broad application domain, and can be used to provide insight on decisions concerned with product mix, raw material sourcing, production strategies, pricing strategies, resource valuation and capital appropriations requests.

The scenarios analyzed have been kept relatively simple in order to more clearly demonstrate model behavior, and therefore model validity. More realistic operating scenarios would involve a much greater number of potential raw materials and products. Given the number of variables to analyze, and the interrelationships between raw materials, process rates, process recoveries, process capacities, glulam beam lay-up requirements (where appropriate), and market prices, it is evident that the decision process can become highly complex. The inherent complexity indicates both the need, and the potential of the DSS to provide managers with a production planning tool that will help them fine-tune operating strategies to maximize profit contribution.

Furthermore, the life span of the resultant DSS should be increased through the system flexibility allowing one to model a wide variety of machine centers and providing the ability to adapt to changes in the process flow. This flexibility is a major advantage in a manufacturing sector characterized by a highly dynamic operating environment.

7 FUTURE WORK

Having validated the DSS further work will focus on the successful implementation of the model at the study site.

Additional work could also focus on the development of a more sophisticated user interface. The interface is vital to ensure ease of use, and comprehension of the modeling problem. The DSS developed can model highly complex process flows. However, highly complex problems may be cumbersome to define and understand, using the current (text-oriented) interface. A more visual “drag and drop” style interface, where the user may define the plant layout by a series of interconnected modules (represented by defined shapes), could support the current interface to provide a more comprehensible view of complex process flows.

The decision support system developed in this research is a single period production planning model designed to address production planning issues on a monthly to quarterly basis. The ability to model production over multiple time periods would increase the scope of potential applications. A multi-period model would be achieved by including a set of inventory variables as another destination for material outputs from a machine center. In a multiple time period model inventory would provide a third option for input / output material. Accordingly, material inputs would be sourced from the market, a previous machine center or from inventory in period $(p-1)$. For example, the inventory in period (p) would provide another material source for machine centers in period $(p+1)$.

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9 APPENDICES

APPENDIX A

Shadow prices and ranges for machines at their maximum capacity

SCENARIO	MACHINE	SHADOW PRICE	LOWER RANGE	CURRENT	UPPER RANGE
Base Case	#3 Resaw	\$116	134	153	160
Scenario 1	#1 Finger- jointer	\$244	297	308	317
Scenario 2	#3 Resaw	\$144	149	153	210
Scenario 3	#3 Resaw	\$233	120	153	154
Scenario 3	Planer	\$370	114	153	158

APPENDIX B

Reduced costs and ranges for base case raw materials

RAW MATERIAL	REDUCED COST	LOWER RANGE	UPPER RANGE
2x8x1.67 TrimBlock S 2	-5.00	0	37
2x10x8 Economy S 1	-7.00	0	165
2x10x8 Economy S 3	-17.00	0	165
2x6x8 Economy S 1	-3.00	0	105
2x6x8 Economy S 3	-13.00	0	105
2x4x8 Economy S 1	-4.00	0	80
2x4x8 Economy S 3	-14.00	0	80

APPENDIX C

Lamina lay-up requirements for glulam beams

GLULAM BEAM (Thickness x Width)	LAMINA	% REQUIRED
120x270mm	L140	25%
	L125	0%
	L110	25%
	L90	50%
120x330mm	L140	20%
	L125	20%
	L110	20%
	L90	40%
105x150mm	L140	0%
	L125	40%
	L110	40%
	L90	20%
105x360mm	L140	20%
	L125	40%
	L110	0%
	L90	40%

APPENDIX D

Kiln charge volume

KILN #	CHARGE VOLUME (Mfbm)
1	190
2	190
3	190
4	65

APPENDIX E

Component of the relational database