

## *Chapter 4*

# **APPLICATION**

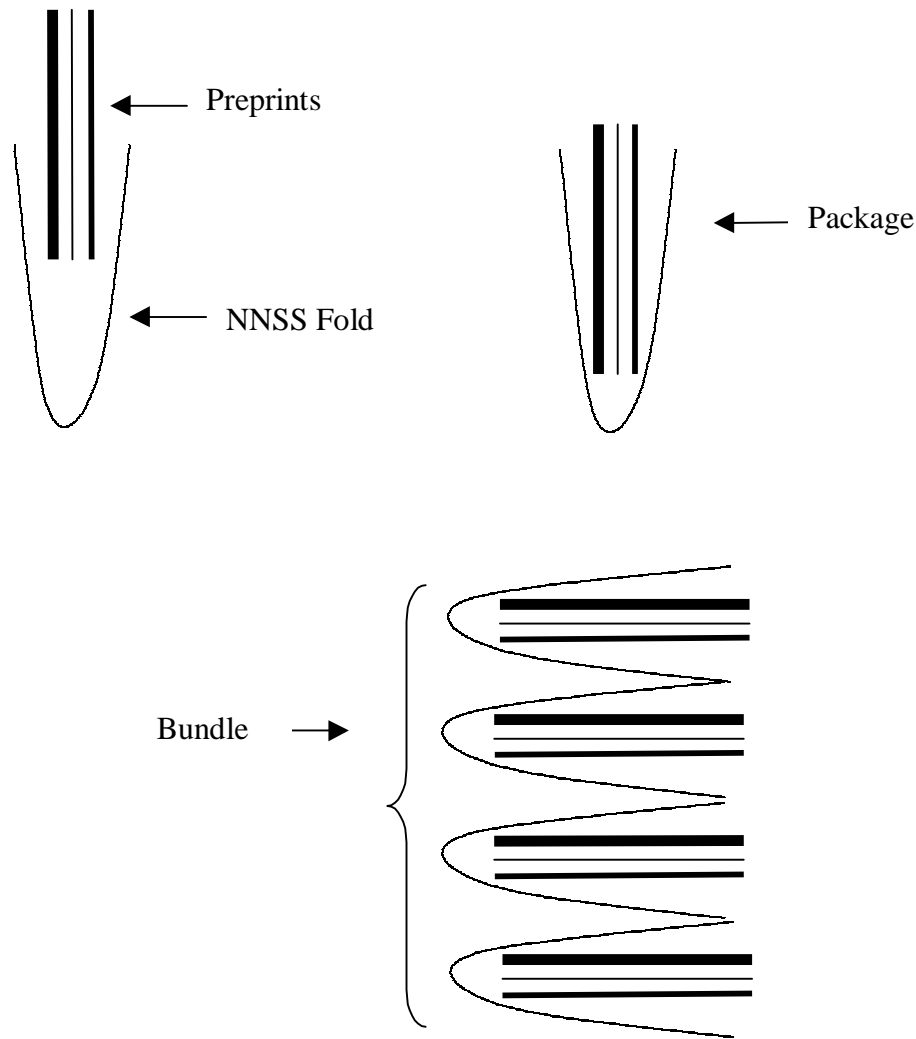
The application of the methodology developed in Chapter 3 is presented in this chapter. The theoretical concepts proposed and developed in this thesis are applied to a real-world manufacturing environment. Specifically, the proposed performance evaluation methodology is applied to a packaging line of a leading American newspaper's preprint insertion process. First, the overview of the process is outlined. Second, the packaging line is described. Third, the definitions of the inputs and outputs and their bounds, the global input and output targets and their bounds, and the conceptual model are provided. And, finally, the framework for the mathematical programming model proposed to measure and evaluate the efficiency of the packaging line in a fuzzy environment is presented.

### **4.1 OVERVIEW OF THE NEWSPAPER PREPRINT INSERTION PROCESS**

The newspaper preprint insertion process (NPIP) consists of inserting commercial preprinted material or preprints into the newspaper folds and assembling the merged packages into bundles for delivery to distributors. Statistics reveal that over the past three decades US newspapers generate a significant portion of their revenue from the preprint insert business and forecasts for the short term show continued increase. This phenomenon is simple to understand. Advertisers use preprint inserts to reach target audiences across geographic and economic spectrums. Preprint inserts can be tailored to meet audience (reader) demands in different distribution territories. Accordingly, this revenue stream is an important consideration for newspapers. The study of the performance of the newspaper preprint insertion process is thus very significant.

### 4.1.1 The Newspaper and NPIP Elements

Newspapers are typically divided into two parts: (i) the news-sensitive section (NSS) and (ii) the non-news sensitive section (NNSS). The NSS section comprises the headsheet and the local, national and international news. The NNSS section comprises supplements on healthcare, travel, real estate, recreation, classifieds, etc. The NSS is more sizeable than the NNSS and forms the body of the newspaper.



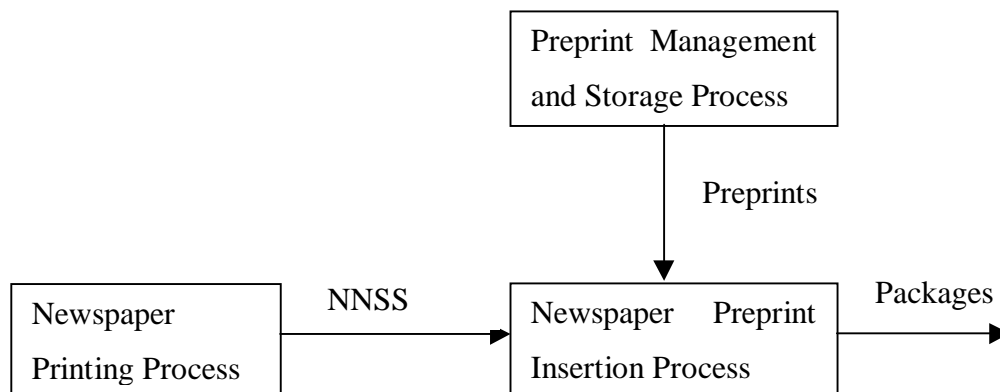
**Figure 4.1** NPIP Elements

The commercial preprints or inserts are inserted into the NNSS fold. A *package* refers to a set of preprints inserted into a NNSS fold. The preprints have different shapes, sizes, color, texture and designs depending on the advertiser. Finally, the packages are wrapped and stacked as bundles. The NNSS with the inserted preprints and the NSS are merged before delivery to the customer.

#### 4.1.2 The Newspaper Preprint Insertion Process (NPIP)

Most newspapers engage in preprint insertion one, two or three times a week. The NPIP model and the data used in this thesis were derived from Girod's (1996) research and represent the NPIP occurring once a week for a period of forty-eight weeks. The main reason for using the same data is the availability of operational information regarding the data for the analysis of results obtained from this research.

The NPIP forms one part of a larger operation in a newspaper production facility. Consequently, the NPIP is dependent on two external processes: (i) the newspaper printing process and (ii) the preprint management and storage process. Figure 4.2 depicts this interaction.



**Figure 4.2 Newspaper Preprint Insertion Process**

The merging of the preprints in the NNSS is achieved by completing the following tasks.

- i) Opening the NNSS
- ii) Inserting the preprints
- iii) Closing the NNSS (to obtain a package)
- iv) Stacking the packages (to obtain bundles)

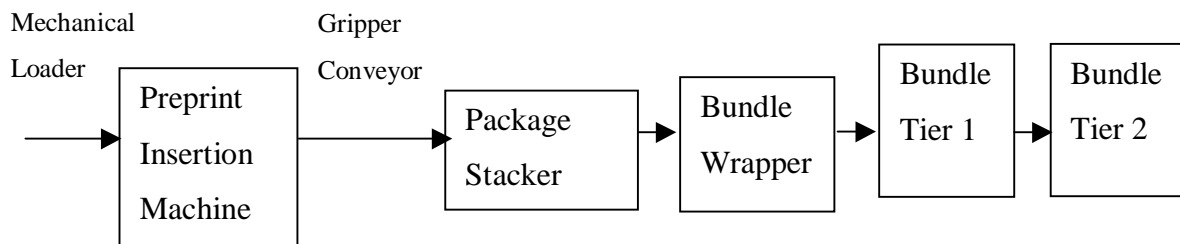
These tasks are completed on several packaging lines. This thesis uses the data from *one* such packaging line that performs the newspaper preprint insertion process. The description of this packaging line is presented in the next section.

## 4.2 THE PACKAGING LINE

The packaging line consists of three components, namely, (i) organization (ii) operation and (iii) fault detection and management.

### 4.2.1 Organization

The organization of the packaging line involves one NNSS Mechanical Loader, one Preprint Insertion Machine (this includes one NNSS Feed Hopper, twelve Preprint Insertion Hoppers and 113 Steel Pockets), one Gripper Conveyor, one Package Stacker, one Bundle Wrapper and two Bundle Tiers. A conceptual flow diagram of the packaging line is illustrated in Figure 4.3.



**Figure 4.3 NPIP Organization Flow Diagram**

### 4.2.2 Operation

The packaging line receives a detailed work order at the beginning of each production day. This work order is divided into production zones. Production zones are subsets of the newspaper distribution area and are categorized according to the advertiser demand. Effectively, each production zone has a unique package content consisting of a different mix of preprint inserts. The packaging line is given the following data for each production zone:

- i) the production or output target *i.e.*, the number of packages or the *batch* size
- ii) the preprint inserts mix

For example, consider a scenario where the packaging line has to insert 13 preprints divided into 11 production zones *i.e.*, there are 11 different package types. The resultant work order could then look as shown in Table 4.1.

**Table 4.1 Example of a Work Order for the Packaging Line**

<b>Production Zone</b>	<b>Batch Size</b>	<b>Preprint Mix</b>
<b>1</b>	<b>3,500</b>	<b>A, C, F, G</b>
<b>2</b>	<b>12,900</b>	<b>B, C, E, F, L, M</b>
<b>3</b>	<b>6,800</b>	<b>C, F, H, K</b>
<b>⋮</b>	<b>⋮</b>	<b>⋮</b>
<b>10</b>	<b>2,000</b>	<b>H, I, K</b>
<b>11</b>	<b>11,500</b>	<b>B, C, D, F, G, J</b>

The packaging line operation involves a significant amount of labor. The labor requirements, however, are a function of the preprint inserts mix. Packages with a higher mix content will require more labor than packages with a lower mix content. The crews that work on the packaging line are made up of hourly employees called operators.

### **4.2.3 Fault Detection and Management**

Faults are classified as *NNSS faults* or *preprint faults* (Girod (1996)). NNSS faults are further classified into *misses*, *multiples*, or *unopened*. Preprint faults are further classified as *misses* or *multiples*. The faults are reviewed in the following subsections as presented by Girod (1996).

#### **4.2.3.1 NNSS Faults**

An NNSS *miss* is defined to occur when the NNSS Feeding Hopper fails to feed the NNSS into the Preprint Insertion Machine. An NNSS *multiple* is defined to take place when the NNSS Feeding Hopper feeds multiple NNSSs into the Preprint Insertion Machine's steel pockets. An NNSS unopened fault is defined to occur when the Preprint Insertion Machine fails to open the NNSS fold for insertion. In case of a *multiple* or *unopened* fault the NNSSs are either recycled for rework if they are in good condition or discarded if they are damaged.

#### **4.2.3.2 Preprint Faults**

A preprint *miss* is defined to occur when one of the twelve Preprint Insertion Hoppers fails to insert a preprint in the NNSS fold. A preprint *multiple* is defined to occur when one of the twelve Preprint Insertion Hoppers drops multiple preprints of the same type in the NNSS fold.

### **4.3 THE PACKAGING LINE MODEL**

The conceptual model proposed to evaluate the performance of the packaging line over the forty-eight week study horizon is presented in this section. The model used here is derived from Girod (1996). Section 4.3.1 states the purpose of the model. The

definitions of the input variables are provided in section 4.3.2 and the definitions of the output variables are provided in section 4.3.3. Section 4.3.4 contains the final formulation of the model applied in this thesis.

### **4.3.1 Purpose**

The purpose of this model is to measure and evaluate the performance of the packaging line described in earlier sections of this chapter. To achieve this, first the model aims to provide a mathematical representation of the packaging line that conforms as closely as possible to the real world. With this representation, the proposed model should serve as a decision-making and performance analysis tool for decision-makers at local and global levels. For the packaging line each production day is the local level while the study period of 48 days is the global level. Global input and output targets are provided by the decision-makers at the global level. Meeting these targets is of greatest importance at the global level. At the local level, maintaining high efficiency might be of more importance than meeting global targets. The proposed model also aims to capture this concept of relative importance attributed to the goals of efficiency and effectiveness specified by a certain level of decision-making. The model formulation allows sensitivity analysis on target achievement of local and global targets for inputs used and output produced by the packaging line for the observed data. The sensitivity analysis can thus be used to set future targets and determine the deviations from the targets acceptable to the decision-maker. The model's ability to achieve these objectives is strongly related to the choice of inputs and outputs as well as the precision of the observed input-output data, the form of the membership functions and the selection of bounds for the satisfaction of the constraints. The definition of the input and output variables and their bounds, the input and output global targets and their bounds and the conceptual model are presented next.

### 4.3.2 Definition of the Input Variables

The conceptual model presented here retains the choice of the inputs and their definitions as in Girod (1996). The three inputs used to evaluate the performance of the packaging line are (i) *Direct Labor* (ii) *Rework* and (iii) *Raw Material*. These inputs are discussed in detail in the following subsections.

#### 4.3.2.1 Direct Labor (DLR)

Direct labor (DLR) is defined as the product of the number of hourly employees (HE), the total production time (PT), and the hourly wage rate of the operator (WR) and is expressed as:

$$DLR = (HE \times PT) \times WR \quad 4.1$$

The hourly wage rate, WR, is crisp and is fixed at \$20 per hour in this research. The total production time, PT, is also crisp and is reported by the management at the end of each production day when the work orders are completed. PT depends on the batch size, the type of preprint mix, and the ability of the packaging line crew to assemble the packages given the complexity associated with the preprint mixes. HE has observed values and corresponding upper bounds that are set by the decision-maker. The HE values are determined by the crew chiefs in charge of the packaging line based on their experience given the production target. However, due to the nature of the newspaper preprint insertion process, in reality, the labor requirements display a dynamic behavior. Therefore, once the production begins the crew chiefs communicate constantly and adjust the labor needs through exchange of operators. Management does not record the labor adjustments and reports constant labor utilization through the production day. Girod (1996) allowed the packaging line to borrow or lend one operator from other lines for a period of half a day. This assumption is adopted in this research too. Now, the observed value and the upper bound on direct labor are discussed below.

*Observed Value:* This is the assumed observed value on the packaging line through the study period for the input *direct labor*.

$$DLR^{ob} = (HE^{ob} \times PT) \times WR \quad 4.2$$

where 'ob' denotes observed value. For this research,  $DLR^{ob}$  is derived with the assumption that  $HE^{ob}$  is the mid-point between the lower and upper bounds of HE employed by Girod (1996).

*Upper Bound:* This is the bound on DLR specified by the decision-maker and is deemed undesirable to attain.

$$DLR^{ub} = (HE^{ub} \times PT) \times WR \quad 4.3$$

where 'ub' denotes upper bound. For this research,  $HE^{ub}$  is maintained as the upper bound as used in Girod (1996) to derive  $DLR^{ub}$ .

$DLR^{ub}$  can be considered as the amount of direct labor with which the production target can be met easily in any circumstance or as a risk-free labor usage. The decision-maker is interested in maintaining the labor usage at levels less than this value. Therefore, the membership function at the upper bound is zero and tends monotonically to one as the value of DLR moves away from  $DLR^{ub}$  and toward zero.

$DLR^{ob}$  may be efficient or inefficient. The decision-maker specifies an upper bound for DLR (and HE) that is undesirable. The DEA type constraints are used to measure the efficiency of input DLR. The upper bound allows the decision-maker to accept varying degrees of satisfaction for the DEA-type inequality associated with DLR *i.e.*, in the interval  $(DLR^{ob}, DLR^{ub})$ . The degree of satisfaction or the membership function takes the value zero at  $DLR^{ub}$  which is undesirable and takes the value one at  $DLR^{ob}$  or lower depending on whether the direct labor usage is efficient or inefficient.

The observed values and the upper bounds for DLR and HE and the values for PT are listed in Appendix A, Section A.1 for the 48-day study period.

#### 4.3.2.2 Rework (RWK)

Rework (RWK) is defined as the sum of preprint misses (PMIS) and preprint multiples (PMUL), and is expressed as:

$$RWK = PMIS + PMUL \quad 4.4$$

RWK measures the number of packages that have to be reworked in order to produce a good package. This also reflects management's commitment to customer satisfaction which is translated as the customer's right to receive a fault free package *i.e.*, packages without preprint misses and/or preprint multiples.

In the definition for RWK, PMUL is crisp and is recorded accurately by mechanical sensors that are mounted on the Preprint Insertion Hoppers. PMIS has observed values with the corresponding upper bounds set by the decision-maker. The accuracy of PMIS is limited due to dust accumulation on the Preprint Miss Sensor during production. The observed value and the upper bound for rework are discussed below.

*Observed Value:* This is the assumed observed value on the packaging line through the study period for the input *rework*. Here all the preprint misses are assumed to have been recorded accurately by the sensor.

$$RWK^{ob} = PMIS^{ob} + PMUL \quad 4.5$$

where 'ob' denotes observed value. For this research,  $PMIS^{ob}$  is assumed to be the lower bound used by Girod (1996) and utilized to derive  $RWK^{ob}$ .

*Upper Bound:* This is the bound on RWK specified by the decision-maker and is deemed undesirable to attain. Here the PMIS value is adjusted to be three times more than the values recorded by the sensor. This adjustment is made based on empirical knowledge that with these values the resultant RWK values would easily enable the line to produce the required targets and can be said to be the amount of risk-free rework.

$$RWK^{ub} = PMIS^{ub} + PMUL \quad 4.6$$

where 'ub' denotes upper bound. In this research,  $PMIS^{ub}$  is maintained as the upper bound used by Girod (1996), to derive  $RWK^{ub}$ .

The decision-maker is interested in maintaining the amount of rework at levels lower than this upper bound value. Therefore, the membership function at this value is zero and tends monotonically to one as the value of RWK moves away from  $RWK^{ub}$  and toward zero.

$RWK^{ob}$  may be efficient or inefficient. The decision-maker specifies an upper bound for RWK (and PMIS) that is undesirable. The DEA type constraints are used to measure the efficiency of input RWK. The upper bound allows the decision-maker to accept varying degrees of satisfaction for the DEA-type inequality associated with RWK *i.e.*, in the interval  $(RWK^{ob}, RWK^{ub})$ . The degree of satisfaction or the membership function takes the value zero at  $RWK^{ub}$  which is undesirable and takes the value one at  $RWK^{ob}$  or lower depending on whether the magnitude of rework is efficient or inefficient.

The observed values and the upper bounds for RWK and PMIS and the values for PMUL are listed in Appendix A, Section A.2 for the 48-day study period.

### 4.3.2.3 Raw Material (RML)

Raw Material (RML) is defined for the newspaper preprint insertion process in terms of waste. Wastage occurs when NNSS and preprints are rejected due to non-conformance with established standards. Accordingly, minimization of raw material usage implies minimization of raw material wastage. Also, since the newspaper does not incur the cost of preprints it is neglected and only NNSS waste is considered. It is assumed that NNSS waste occurs at only two stages in the packaging line:

- i) Prior to loading at the Mechanical Loader: All defective NNSSs *i.e.*, wrinkled or torn NNSSs are rejected by the operator to prevent NNSS Feeding Hopper jams. The amount of NNSS rejected at this stage is called TRH.
- ii) After completion of the preprint insertion cycle: All NNSSs rejected after completion of the preprint insertion cycle that is considered unfit for use in the NPIP and, thus rejected, is called SCP.

With the variables defined as above, raw material is defined for the present model as:

$$RML = k_{RML} \times (TRH + SCP) \quad 4.7$$

where  $k_{RML}$  is a deterministic correction coefficient with  $k_{RML} \in \mathbb{R}^+$ . This  $k_{RML}$  coefficient is discussed in Section 4.3.3.2.1.

TRH has observed values and upper bounds set by the decision-maker. No record is maintained for the rejected NNSSs that are trashed at the packaging line. It is known empirically that the value of TRH varies between 1% to 5% of the daily preprint insertion machine output (PMOT). For example, if PMOT is equal to 125,000 packages then the NNSSs discarded will range from 1,250 to 6,250. For the purpose of the current model the observed value for TRH is assumed to be 3% of PMOT which is the midpoint of the empirical range reported by Girod (1996) and the upper bound is maintained as 5% of

PMOT as used by Girod (1996). Therefore, if 125,000 packages are to be assembled then the observed value of TRH is 3,750 and the upper bound on TRH is 6,250. Thus, TRH is expressed as:

$$\text{TRH} = F_{\text{PMOT}} \times \text{PMOT} \quad 4.8$$

where  $F_{\text{PMOT}}$  denotes the percentage of NNSSs trashed prior to being fed to the preprint insertion machine.

The upper bound on TRH is specified by the decision-maker and is deemed undesirable to attain. It is implied that with this empirical value for TRH the production targets are easily met. This upper bound can be considered as the risk-free amount of TRH.

SCP also has observed values and upper bounds set by the decision-maker. No record is maintained for the scrapped NNSSs at the completion of the preprint insertion cycle. It is known empirically (Girod (1996)), however, that the value of SCP varies between 10% to 50% of the rejected NNSSs (REJ). For the purpose of the current model the observed value for SCP is assumed to be 30% of REJ which is the midpoint of the empirical range reported and the upper bound is maintained as 50% of REJ as used by Girod (1996). Thus, SCP is expressed as:

$$\text{SCP} = F_{\text{REJ}} \times \text{REJ} \quad 4.9$$

where  $F_{\text{REJ}}$  denotes the percentage of packages that is rejected.

The upper bound on SCP is specified by the decision-maker and is deemed undesirable to attain. It is implied that with this empirical value for SCP the production targets are easily met. This upper bound can be considered as the risk-free amount of SCP.

REJ also has observed values and upper bounds set by the decision-maker. Accurate data on the number of rejected packages is not available since multiple NNSSs fed by the NNSS Feeding Hopper into the steel pockets can refer to two or three NNSSs. It is known empirically (Girod (1996)) that the probability of encountering multiples more than three is very insignificant. REJ is expressed as:

$$REJ = (N_{MUL} \times MUL) + UON \quad 4.10$$

where UON denotes the occurrence of unopened NNSSs and MUL denotes the occurrence of multiple NNSS feeds.  $N_{MUL}$  represents the number of multiple NNSSs for each occurrence of MUL. For the purpose of the current model the observed value for  $N_{MUL}$  is assumed to be two and the upper bound is taken as three.

The upper bound on  $N_{MUL}$  is specified by the decision-maker and is deemed undesirable to attain. It is implied that with this empirical value for  $N_{MUL}$  the production targets are easily met. This upper bound can be considered as the risk-free value for  $N_{MUL}$ .

Now RML can be rewritten as:

$$RML = \{k_{RML} \times (F_{PMOT} \times PMOT)\} + \{F_{REJ} \times ((N_{MUL} \times MUL) + UON)\} \quad 4.11$$

The observed value and the upper bound for RML are discussed below.

*Observed Value:* This is the assumed observed value on the packaging line for the input RML. Here 3% of the preprint insertion machine output is trashed and 30% of the rejected material is scrapped. Further, each multiple NNSS feed is assumed to amount to two NNSSs in the steel pocket (lower bound used by Girod (1996)). The assumed observed value is expressed as:

$$RML^{ob} = \{k_{RML} \times (F_{PMOT}^{ob} \times PMOT)\} + \{F_{REJ} \times ((N_{MUL}^{ob} \times MUL) + UON)\} \quad 4.12$$

where 'ob' denotes observed value.

*Upper Bound:* This is the bound on RML specified by the decision-maker and is deemed undesirable to attain. Here 5% of the preprint insertion machine output is trashed and 50% of the rejected material is scrapped. Further, each multiple NNSS feed is assumed to amount to three NNSSs in the steel pocket (upper bound used by Girod (1996)). The upper bound is expressed as:

$$RML^{ub} = \{k_{RML} \times (F_{PMOT}^{ub} \times PMOT)\} + \{F_{REJ} \times ((N_{MUL}^{ub} \times MUL) + UON)\} \quad 4.13$$

where 'ub' denotes the upper bound.

The upper bound value for RML is the amount of raw material usage with which the production targets can be met easily and can be considered to be the risk-free value. The decision-maker is interested in maintaining the amount of raw material consumption at levels less than this upper bound value. Therefore, the membership function at this value is zero and tends monotonically to one as the value of RML moves away from  $RML^{ub}$  and toward zero.

$RML^{ob}$  may be efficient or inefficient. The decision-maker specifies an upper bound for RML that is undesirable. The DEA type constraints are used to measure the efficiency of input RML. The upper bound allows the decision-maker to accept varying degrees of satisfaction for the DEA-type inequality associated with RML *i.e.*, in the interval  $(RML^{ob}, RML^{ub})$ . The degree of satisfaction or the membership function takes the value zero at  $RML^{ub}$  which is undesirable and takes the value one at  $RML^{ob}$  or lower depending on whether the raw material usage is efficient or inefficient.

The observed values and the upper bounds for RML, PMOT, MUL and UON are listed in Appendix A, Section A.3 for the 48-day study period.

### 4.3.3 Definition of the Output Variable

The model developed by Girod (1996), and used for the application in this research, employs one output variable. This output variable is the number of packages (PP) produced multiplied by a complexity factor (CF), and is denoted as PCF (PP x CF). The complexity factor represents the complexity involved in assembling the packages and helps to compare the amount of packages produced after accounting for the inherent complexity. The variable, PP, and the complexity factor CF are discussed in subsequent sections.

#### 4.3.3.1 Packages (PCF)

The number of packages produced (PP) is defined as the number of complete packages (CP) less the number of incomplete packages (IP) produced per production day. Preprint shortages are the cause of incomplete packages. The number of packages produced (PP) is thus expressed as:

$$PP = CP - IP \quad 4.14$$

CP has observed values and lower bounds set by the decision-maker. Data on the number of complete packages produced by the packaging line are not available accurately due to data recording discrepancies between the preprint insertion machine output (PMOT) for a production zone  $z$  and the packaging line output (PLOT).  $PMOT_z$  is recorded after the assembled packages exit the preprint insertion machine whereas PLOT is recorded after the assembled packages exit the second bundle tier at the end of the packaging line and have completed the production cycle. Theoretically, there should be no accounting discrepancies between the total of PMOT for all production zones  $z$  and PLOT *i.e.*, both values should match. In reality, the sum of PMOT over all zones  $z$  is usually greater than PLOT which can be explained by the packages lost to waste or faults

at stages after the packages leave the preprint insertion machine. The observed value and the lower bound for CP are discussed below.

*Observed Value:* This is the assumed observed value on the packaging line through the study period for the CP. Here the sum of PMOT across all production zones  $z$  is assumed to be equal to the output of the packaging line PLOT.

$$CP^{ob} = \sum_z (PMOT_z) = PLOT \quad 4.15$$

where 'ob' denotes observed value. For this research  $CP^{ob}$  is assumed to be the upper bound used by Girod (1996).

*Lower Bound:* This is the bound on CP specified by the decision-maker and is deemed undesirable to attain. Here the CP value is obtained as the sum of  $PMOT_z$  over all production zones  $z$  minus the sum of absolute differences between PMOT for each zone  $z$  and packaging line output PLOT for each zone  $z$ . This adjusted value of CP is definitely attainable and is thus not desirable to the decision-maker and can be said to be the risk-free value for CP.

$$CP^{lb} = \sum_z (PMOT_z) - \sum_z |PMOT_z - PLOT_z| = PLOT \quad 4.16$$

where 'lb' denotes lower bound. In this research,  $CP^{lb}$  is maintained as the lower bound used by Girod (1996).

The decision-maker is interested in maintaining the amount of CP produced at levels higher than this lower bound. Therefore, the membership function at this value is zero and tends monotonically to one as the value of CP moves away from  $CP^{lb}$  and toward infinity.

Incomplete packages (IP) are a result of preprint shortages (PST). This variable is related to management's commitment to deliver fault-free newspapers to the customers.

Even if the preprint insertion machine produced fault free packages *i.e.*, no occurrence of NNSS misses or multiples, a faulty package could result due to preprint shortages (PST). In the conceptual model used for this research the bounds on IP are defined as in Girod (1996) and are expressed as:

$$IP^{lb} = PST/NoPT \quad 4.17$$

$$IP^{ub} = PST \quad 4.18$$

where NoPT denotes the number of preprint types, 'lb' stands for lower bound and 'ub' stands for upper bound.

$IP^{lb}$  is the event when the amount of preprint shortage is distributed evenly among all preprint types and that shortage of all the preprint types is experienced concurrently.  $IP^{ub}$  is the event when the preprint shortage occurs one preprint at a time. In this research,  $IP^{lb}$  as used by Girod (1996), is assumed to be the observed IP value and  $IP^{ub}$ , as used by Girod (1996), is assumed to be the upper bound on IP.

The observed value and the lower bound for the output PP is discussed next.

*Observed Value:* This is the assumed observed value on the packaging line through the study period for the PP. Here PP is the difference between the observed value of CP and the lower bound for IP.

$$PP^{ob} = CP^{ob} - IP^{ob} \quad 4.19$$

where 'ob' denotes observed value.

*Lower Bound:* This is the bound on PP specified by the decision-maker and is deemed undesirable to attain. Here the PP value is obtained as the difference between the lower bound for CP and the upper bound for IP. This value of PP is definitely attainable, and

thus, is not desirable to the decision-maker and can be said to be the risk-free value for PP.

$$PP^{lb} = CP^{lb} - IP^{ub} \quad 4.20$$

where 'lb' denotes lower bound and 'ub' denotes upper bound.

The decision-maker is interested in maintaining the amount of PP produced at levels higher than this lower bound. Therefore, the membership function at this value is zero and tends monotonically to one as the value of PP moves away from  $PP^{lb}$  and toward infinity.

The observed values and the bounds for PP, CP and IP are listed in Appendix A, Section A.4 for the 48-day study period.

#### **4.3.3.2 Complexity Factor (CF)**

Girod (1996) introduced a complexity factor in the calculation of the output variable PCF to incorporate the level of complexity involved in assembling the packages. This complexity factor is used to depict the production of output *i.e.*, packages accurately and such that varying output levels with varying degrees of complexity can be compared. The complexity factor used is derived from Cooper, Sinha and Sullivan (1992).

The complexity of the work order is a function of the size of the package and the amount of packages to be assembled by a zone *i.e.*, the size of the production zone. In terms of complexity, large packages and small production zones tend toward high complexity while small packages and large production zones tend toward low complexity. Typically, lower complexity would result in less rework and a lower consumption of inputs while higher complexity would result in more rework and higher consumption of inputs.

The complexity factor suggested by Girod (1996) and maintained in this research is expressed as:

$$CF_p = (TPZ_p/14 \times APS_p/4)^{0.39} \quad 4.21$$

where  $TPZ_p$  denotes the total number of production zones activated during the day, and  $APS_p$  denotes the average package size or the average number of preprints per package. The denominators '14' and '4' represent the median observations for the number of production zones and the package size respectively. The power '0.39' ensues that the complexity factor takes values between 0.5 and 1.5. Girod (1996) deduced the median values and the power empirically for the packaging line. It should be noted that while this formulation of the complexity factor is adopted for the packaging line alternate formulations could also be employed. The values for CF are listed in Appendix A, Section A.5 for the 48-day study period.

The observed value and the upper bound on PCF are discussed next.

*Observed Value:* This is the assumed observed value on the packaging line through the study period for PCF. Here PCF is  $PP^{ob}$  multiplied by the  $CF_p$ .

$$PCF^{ob} = PP^{ob} \times CF_p \quad 4.22$$

where 'ob' denotes observed value.

*Lower Bound:* This is the bound on PCF specified by the decision-maker and is deemed undesirable to attain. Here the PCF value is obtained as  $PP^{lb}$  multiplied by the  $CF_p$ . This value of PCF is definitely attainable and is thus not desirable to the decision-maker and can be said to be the risk-free value for PCF.

$$PCF^{lb} = PP^{lb} \times CF_p \quad 4.23$$

where 'lb' denotes lower bound.

The decision-maker is interested in maintaining the amount of PCF produced at levels higher than this lower bound. Therefore, the membership function at this value is zero and tends monotonically to one as the value of PCF moves away from  $PCF^{lb}$  and toward infinity.

The observed values and the lower bounds for PCF along with the respective CFs are listed in Appendix A, Section A.6 for the 48-day study period.

#### 4.3.3.2.1 CF and $k_{RML}$

The mathematical representation of the packaging line developed in this research is driven by the need to measure and evaluate the performance of the packaging line based on input consumption, namely, direct labor, rework and raw material and output production *i.e.*, the amount of packages produced. Under the laws of production theory an increase in the use of input resources will lead to an increase in the production of output. Under the disposability assumption labor and rework are positively correlated with the complexity of the packages to be assembled. However, raw material consumption is independent of the *complexity* of the packages and is directly proportional to the *quantity* of packages to be assembled. Therefore, to model this behavior of the packaging line the following relationship must hold true.

$$CF/k_{RML} = \text{constant} \quad 4.24$$

With this relationship the output *i.e.*, PCF increases as raw material increase and ensures that raw material is also positively correlated to the output similar to direct labor and rework. This relationship is used by Girod (1996) and is retained for the current model.

The complete input and output data set is reported in Appendix A, Section A.7 for the 48-production days.

#### 4.3.4 Definition of the Global Targets

The global targets for the inputs and outputs used in this research are defined for the fuzzy and crisp cases. When the effectiveness constraints are fuzzy the global targets represent maximum satisfaction for the decision-maker. The BCC projections are used to define an ideal benchmark that serves as the global target for each inputs and output. Accordingly, the global targets are expressed as:

$$DLR_{GT} = \Sigma DLR_{BCC-IR \text{ Projections}} \quad 4.24$$

$$RWK_{GT} = \Sigma RWK_{BCC-IR \text{ Projections}} \quad 4.25$$

$$RML_{GT} = \Sigma RML_{BCC-IR \text{ Projections}} \quad 4.26$$

$$PCF_{GT} = \Sigma PCF_{BCC-OI \text{ Projections}} \quad 4.27$$

For the inputs DLR, RWK, and RML the global targets are defined as the sum of the efficient BCC input-reducing (BCC-IR) projections. For the output PCF the global target is defined as the sum of the efficient BCC output-increasing projections (BCC-OI). By definition, these projections can be met simultaneously only in the event that all observations are 100% BCC efficient. This ensures that the all the global targets cannot be achieved simultaneously and provides the decision-maker with ideal benchmarks for achievement. The degree of satisfaction increases as achievement of the effectiveness constraints tends to the global targets. The bounds on the global targets for the fuzzy case are defined next.

The bounds on the inputs and outputs for the fuzzy case are constructed by aggregating the bounds on the observed input and output values defined in Sections 4.3.2-4.3.3. Since these bounds represent the risk-free values for the input/output data it

follows that the sum of the bounds for each input and output represents the risk free global targets for the inputs and output. The decision-maker's objective is to maximize the achievement of global targets away from these bounds and toward the global targets. Consequently, the degree of satisfaction is least at the bounds and maximized at the global targets. The bounds on the global targets are defined as:

$$DLR_{UB} = \Sigma DLR^{ub} \quad 4.28$$

$$RWK_{UB} = \Sigma RWK^{ub} \quad 4.29$$

$$RML_{UB} = \Sigma RML^{ub} \quad 4.30$$

$$PCF_{LB} = \Sigma PCF^{ub} \quad 4.31$$

Due to the unattainable nature of the BCC projections the global targets are redefined for the crisp case. When the effectiveness constraints are crisp the decision-maker needs to define realistic global targets. One possible method to do this is to set the sum of the bounds for the inputs and outputs as the global targets. This maintains the decision-maker's aim to improve achievement of the effectiveness goal by exceeding the global targets. These targets are defined as:

$$DLR_{GT} = \Sigma DLR^{ub} \quad 4.32$$

$$RWK_{GT} = \Sigma RWK^{ub} \quad 4.33$$

$$RML_{GT} = \Sigma RML^{ub} \quad 4.34$$

$$PCF_{GT} = \Sigma PCF^{ub} \quad 4.35$$

The observed values for the global targets and the bounds for the fuzzy and crisp cases are listed in Appendix A, Section A.7.

It should be noted that the above method for estimation of global targets and their bounds is the one found suitable for this research. There are other possibilities to accomplish this data construction and this issue is cited as an area of further research in Chapter 6.

### 4.3.5 Conceptual Model

The model proposed for the efficiency evaluation of the NPIP by Girod (1996) is:

$$PCF_p = f(DLR_p, RWK_p, RML_p) \quad 4.36$$

where  $p$  denotes the  $p$ th production day and  $f$  represents the production frontier. This means that the output production is a function of the inputs specified.

## 4.4 APPLICATION PROCEDURE FOR THE PACKAGING LINE ANALYSIS

The application of the Fuzzy GoDEA model to the packaging line and the subsequent analysis of the results involve the following tasks. First, the data for the model parameters has to be collected to suit the model specifications. This step has been outlined in the discussion of input and output variables in this chapter. Second, the results for the unknown variables (*i.e.*, the activity levels and the membership functions) in the model have to be computed. Third, detailed analysis and interpretation of the results have to be performed on the results obtained from the solution of the model.

### 4.4.1 Model Specification for the Packaging Line

The Fuzzy GoDEA model is developed in this research is presented in this section for the specific application to the NPIP.

#### Fuzzy GoDEA Model

$$\begin{aligned} \mathbf{Max} & \left( \sum_{k=1}^{48} \mu_{DLR^k} \right) + \left( \sum_{k=1}^{48} \mu_{RWK^k} \right) + \left( \sum_{k=1}^{48} \mu_{RML^k} \right) + \left( \sum_{k=1}^{48} \mu_{PCF^k} \right) \\ & + (\mu_{DLR}) + (\mu_{RWK}) + (\mu_{RML}) + (\mu_{PCF}) \end{aligned} \quad 4.37$$

Subject to:

For the DMU representations:

$$\mu_{PCF^c} = \frac{\sum_{k=1}^{48} \lambda_k^c (PCF)_k - (PCF)_{lb}^c}{(PCF)^c - (PCF)_{lb}^c}, \forall c \in \{1, 2, \dots, 48\} \quad 4.38$$

$$\mu_{DLR^c} = \frac{(DLR)_{ub}^c - \sum_{k=1}^{48} \lambda_k^c (DLR)_k}{(DLR)_{ub}^c - (DLR)^c}, \forall c \in \{1, 2, \dots, 48\} \quad 4.39$$

$$\mu_{RWK^c} = \frac{(RWK)_{ub}^c - \sum_{k=1}^{48} \lambda_k^c (RWK)_k}{(RWK)_{ub}^c - (RWK)^c}, \forall c \in \{1, 2, \dots, 48\} \quad 4.40$$

$$\mu_{RML^c} = \frac{(RML)_{ub}^c - \sum_{k=1}^{48} \lambda_k^c (RML)_k}{(RML)_{ub}^c - (RML)^c}, \forall c \in \{1, 2, \dots, 48\} \quad 4.41$$

For the achievement of Global Targets:

$$\mu_{PCF} = \frac{(\sum_{k=1}^{48} \lambda_k^1 (PCF)_k + \dots + \sum_{k=1}^{48} \lambda_k^{48} (PCF)_k) - (PCF)_{LB}}{(PCF)_{GT} - (PCF)_{LB}} \quad 4.42$$

$$\mu_{DLR} = \frac{(DLR)_{UB} - (\sum_{k=1}^{48} \lambda_k^1 (DLR)_k + \dots + \sum_{k=1}^{48} \lambda_k^{48} (DLR)_k)}{(DLR)_{UB} - (DLR)_{GT}} \quad 4.43$$

$$\mu_{RWK} = \frac{(RWK)_{UB} - (\sum_{k=1}^{48} \lambda_k^1 (RWK)_k + \dots + \sum_{k=1}^{48} \lambda_k^{48} (RWK)_k)}{(RWK)_{UB} - (RWK)_{GT}} \quad 4.44$$

$$\mu_{RML} = \frac{(RML)_{UB} - (\sum_{k=1}^{48} \lambda_k^1 (RML)_k + \dots + \sum_{k=1}^{48} \lambda_k^{48} (RML)_k)}{(RML)_{UB} - (RML)_{GT}} \quad 4.45$$

$$\sum_{k=1}^{48} \lambda_k = 1, \quad 4.46$$

$$\lambda_k^c \geq 0, \quad \forall k = \{1, 2, \dots, 48\}, \quad \forall c \quad 4.47$$

$$0 \leq \mu_q \leq 1 \quad 4.48$$

Here the  $\mu$ 's represent the degree of satisfaction of the decision-maker relative to crisp satisfaction of the constraints.

The above model is solved as a linear program to obtain the values for  $\lambda$ 's and  $\mu$ 's. The model was solved using CPLEX. The BCC results were obtained using IDEAS 6.0.2.