Proceedings of the World Congress on Engineering 2013 Vol I,
WCE 2013, July 3 - 5, 2013, London, U.K.

Stochastic Multi-item Lot Sizing for the Shareholder Wealth Maximisation

X. J. Wang, S. H. Choi

***Abstract*—The multi-item stochastic lot sizing issue is pivotal to batch manufacturing. Despite recent advances made in this field, the optimisation result is often rendered impractical, for little attention has been paid to corporate capital structures and the overall business goal—shareholder wealth maximisation. We attempt to address this issue by focusing on stochastic multi-item lot sizing for manufacturing in a complex yet realistic capital structure to realize the overall business objective. Our study considers an array of economical parameters for maximisation of the shareholder wealth, and also examines the impact of capital structure. Computational studies are presented to demonstrate the important implications of our proposed model on gaining corporate wealth in a practical capital structure.**

***Index Terms* — stochastic, lot sizing, queuing, shareholder wealth, capital structure**

I. Introduction

THE core mindset of modern corporate governance of most businesses in competitive markets is to maximise the interest of their stakeholders—the shareholder value [1, 2]. This paper attempts to address this issue by proposing an extended optimisation approach that deals with the common critical business concern. Our proposed model distinguishes from some current research works in the following aspects.

A. Sustainable Long-term Profitability

Firstly, we aim to optimise a firm's sustainable long-term profitability, instead of short-term optimisation objectives, for it can better represent the interests of the firm's shareholders.

Currently, various short-term optimisation objectives have been applied for operational management. For example, Ref. [3] chose to minimise the weighted expected lead time for a stochastic multi-operation, multi-item job shop under a make-to-order environment; Ref. [4] focused on an M/G/1 lot sizing model with an aim to minimise a weighted average of the queuing time, setup cost and inventory cost of finished goods; and Ref. [5] examined the cost minimisation problem with a focus on the cycle time and product volume. Although these works may be useful for operational management, the optimisation objectives do not necessarily align with the overall business goal of pursuing the maximum long-term sustainable profitability by maximising shareholder wealth [6-8]. In some cases, improper choices of objective functions may lead to undesirable consequences. The discrepancy between practical requirement and academic research has recently received considerable attention. Indeed, the research focus, to some extent, has recently been shifted to the interest of shareholders. For example, Ref. [9] attempted to minimise the annualised capital investment plus cash/material inventory minus the benefit to shareholders for an integral production plant model, taking the relevant financial decisions into account. Ref. [10] derived a holistic model for the short-term supply chain management (SCM) for optimising the change in equity. A seemingly better metric, economic value added (EVA), has recently been adopted to optimise an integrated financial-operational lot sizing queuing model for single-item, single-server cases [11].

Despite its conceptual completeness and the increasing attention, the shareholder wealth has seldom been adopted in research work. Among its implementation complexities, it is vital to design an appropriate financial measure that may best reflect the interests of shareholders.

In our model, we solve this issue by adopting the cash flow return on investment (CFROI) to represent the sustainable long-term profitability, that is, the full interests of shareholders. CFROI can be used to measure a firm's sustainable long-term profitability in real purchasing power, regardless of its size. It is considered superior to other measures such as net present value (NPV), return on investment (ROI), and EVA [6, 11-13].

B. Cash Flow Analysis

Currently, most optimisation approaches focus mainly on operational activities, with little consideration of other important corporate activities—financing and investing, which have significant impacts on the firm's capital structure and the shareholder wealth.

Financing activities are essential for a manufacturing firm to fund its daily operations through a variety of financial instruments, while investing excessive cash in financial markets may help shareholders gain additional return. The rapidly developing financial markets today further highlight the importance of these two activities. However, their impacts on the corporate wealth of a manufacturing firm have not been well examined. Apparently, conventional operational optimisation, which tends to focus merely on operational activities without due consideration of financing and investing activities, would be managerially misleading and practically unrealistic.

Manuscript received February 8, 2013.

X. J. Wang is with The Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong, Hong Kong, (e-mail: kxjwang@hku.hk).

S. H. Choi is with The Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong, Hong Kong, (e-mail: shchoi@hku.hk).

ISBN: 978-988-19251-0-7
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

Therefore, our research takes not only operational activities, but also financing and investing activities of a manufacturing firm into consideration for production optimisation. In our proposed model, a firm can invest its excessive cash in financial instruments, such as stocks, bonds, and index futures to earn additional profit; on the other hand, when the firm is in need of cash flow, it can finance its daily operations and future development by a series of financing instruments, such as taking loans from banks or issuing bonds. As such, the total return may arise from two additional sources—financing and investing activities, in addition to the traditional manufacturing operations.

C. *Manufacturing Model*

Model formulation of manufacturing scenarios is another major concern. We adopt the multi-item lot sizing queuing model to represent a stochastic make-to-order manufacturing environment, because of its widespread application and acceptance in academia and industry. For example, Ref. [14] demonstrated the significant implications of the lot sizing policy on SCM. Ref. [15] explored a multi-item capacitated lot sizing formulation with setup time, safety stock and demand shortage. Ref. [16] further applied another extended multi-product dynamic lot sizing model to a stochastic manufacturing environment.

Nevertheless, a main issue in modelling stochastic manufacturing is that unrealistic assumptions on random variables often lead to impractical results. Ref. [17] argued that factitious assumptions were extremely restrictive and thus not realistic.

In current research, it is common to assume that the inter-arrival time follows a Poisson process, and that the processing time is negative-exponentially distributed. Some studies even perceived certain stochastic parameters as deterministic, in order to simplify the model derivation or to achieve a closed form solution.

Thus, in order to improve the generality as well as the exactness of our proposed model, we choose to characterize random variables by their two statistic merits—expected values (or rates) and standard deviations, rather than by making any assumption on their specific theoretical distributions.

In summary, this paper presents a shareholder wealth maximisation mechanism for stochastic multi-item make-to-order manufacturing, with a primary concern of the sustainable long-term profitability measured by CFROI. This model considers not only operational activities but also financing and investing activities in the real capital structure, in a synergy to increase the shareholder wealth. An uncertain manufacturing environment is formulated as a stochastic multi-item lot sizing queuing mode without any impractical assumption on the relevant random variables.

II. Stochastic Multi-item Lot Sizing Formulation

A. *Supply Chain Description*

Fig. 1 shows the workflow of a stochastic make-to-order multi-item lot sizing manufacturing scenario, in which the sales department gathers individual orders for products. When individual orders accumulate to a batch of lot size Q_i, where $i = 1,2,\ldots,N$ denotes a product type, they are collected and transferred in a batch order for product *i* to the manufacturing department to queue for batch setup and subsequent processing on an individual basis. Afterwards, the batch of finished products leaves the manufacturing department for temporary storage in the warehouse, where the batch is subsequently broken down for deliveries of individual product *i* to customers.

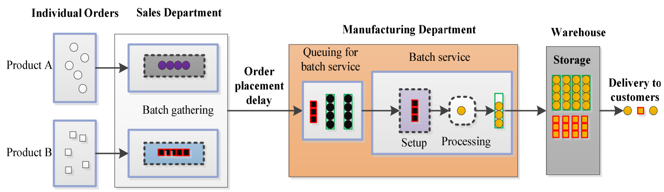

Fig. 1 Make-to-order multi-item lot sizing manufacturing

The market demand for each type of products is assumed mutually independent. In the case of competition for capacitated resources, orders would be served in accordance with the first-come-first-served (FCFS) queuing principle. Without loss of generality, we further assume that each individual order contains only one product item, and that the manufacturer is a price taker in either the perfect or the monopolistic competition environment.

B. *Lead Time Formulation*

As illustrated in Fig. 1, the lead time W_i for an individual order of product *i* is defined as the time that elapses after it arrives at the sales department and before being delivered to the customer, as in:

$$E(W_i) = E(W_i^c) + E(W_i^d) + E(W_i^{WIP}) + E(W_i^{FG}) + E(W_i^t) \quad (1)$$

where

- W_i^c = waiting time that an order spends during the batch gathering stage for product *i*
- W_i^d = order placement delay time from sales department to manufacturing department for an order of product *i*
- W_i^{WIP} = WIPs holding time for an order of product *i*
- W_i^{FG} = inventory holding time for a finished product *i*
- W_i^t = shipping time of a finished product *i* to customer

and the function $E(\,)$ represents the average value that can be expected of the specified random variable in the bracket. For example, $E(W_i)$ means the average lead time that an order can be expected to spend during the entire stochastic work flow for all orders of product *i*.

For a specific individual order with the j^{th} arrival sequence in a batch of lot size Q_i, then $W_{i_j}^c$ denotes the waiting time that this order spends during the batch gathering stage for

ISBN: 978-988-19251-0-7
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

product *i*. Using X_{i_j} to denote the inter-arrival time of this order, $W_{i_j}^c$ can be expressed as:

$$W_{i_j}^c = X_{i_{(j+1)}} + X_{i_{(j+2)}} + \cdots + X_{i_{Q_i}} \tag{2}$$

Further, the expected average waiting time that a specific individual order spends during the batch gathering stage for product i is given by:

$$E(W_{i_j}^c) = E(X_{i_{(j+1)}}) + E(X_{i_{(j+2)}}) + \cdots + E(X_{i_{Q_i}}) \tag{3}$$

Since the distributions of the inter-arrival times for all individual orders are identical, we can define the following:

$$E(X_{i_{(j+1)}}) = E(X_{i_{(j+2)}}) = \cdots = E(X_{i_{Q_i}}) \stackrel{def}{=} \frac{1}{\lambda_{ai}} \tag{4}$$

where λ_{ai} means the expected inter-arrival rate of an individual order for product *i*, that is, the expected average number of arriving orders per unit time period. Hence,

$$E(W_{i_j}^c) = (Q_i - j)/\lambda_{ai} \tag{5}$$

$E(W_i^c)$ may be perceived as a discrete random variable in terms of *j* with the following distribution law:

$$p_j = P\left[E(W_{i_j}^c) = (Q_i - j)/\lambda_{ai}\right] = 1/Q_i \tag{6}$$

Thus, we can conclude that

$$E\left(W_i^c\right) = \sum_{j=1}^{Q_i} p_j E\left(W_{i_j}^c\right) = (Q_i - 1)/(2\lambda_{ai}) \tag{7}$$

The setup and processing stages may be combined into the batch service stage to represent the total work-in-progress (WIP). So for product *i*, the expected mean time of WIP is the sum of those of the queuing for batch service and the batch service:

$$E\left(W_i^{WIP}\right) = E\left(W_{qs}\right) + E\left(W_i^s\right) \tag{8}$$

where $E\left(W_{qs}\right)$ can be estimated using an approximation relationship [18] which has been proved to work very well and popularly adopted [5, 19], as follows:

$$E(W_{qs}) = E\left(Y_{bs}\right)\frac{\left(c_{ba}^2 + c_{bs}^2\right)}{2}\frac{\rho}{1-\rho} \tag{9}$$

On the basis of Fig. 1 and the probability theory, we can derive the following equations:

$$E\left(Y_{bs}\right) = \sum_{i=1}^{N}\frac{\lambda_{ai}}{Q_i}\left(\tau_{si} + Q_i\tau_{pi}\right) \Big/ \sum_{i=1}^{N}\frac{\lambda_{ai}}{Q_i} \tag{10}$$

$$c_{ba}^2 = \left(\sum_{i=1}^{N}\lambda_{ai}/Q_i\right)^3 \Big/ \left(N^2\sum_{i=1}^{N}Q_i/\lambda_{ai}\right) - 1 \tag{11}$$

$$c_{bs}^2 = \frac{\sum_{i=1}^{N}\left(\frac{\lambda_{ai}}{Q_i}\times\left(\tau_{si} + Q_i\tau_{pi}\right)^2\right)\sum_{i=1}^{N}\frac{\lambda_{ai}}{Q_i}}{\left(\sum_{i=1}^{N}\frac{\lambda_{ai}}{Q_i}\left(\tau_{si} + Q_i\tau_{pi}\right)\right)^2} - 1 \tag{12}$$

$$\rho = \sum_{i=1}^{N}\frac{\lambda_{ai}}{Q_i}\left(\tau_{si} + Q_i\tau_{pi}\right) \tag{13}$$

where

- $E\left(W_{qs}\right)$ = expected waiting time for batch service for all types of products
- $E(Y_{bs})$ = weighted mean batch service time of all types of products
- c_{ba} = coefficient of variation of batch inter-arrivals for all types of products
- c_{bs} = coefficient of variation of batch service time for all types of products
- ρ = traffic intensity
- τ_{si} = expected batch setup time for product *i*
- τ_{pi} = expected processing time of each order for product *i*

Thus, $E(W_i^{WIP})$ may be formulated as

$$E(W_i^{WIP}) = E(Y_{bs})\frac{c_{ba}^2 + c_{bs}^2}{2}\frac{\rho}{1-\rho} + \tau_{si} + Q_i\tau_{pi} \tag{14}$$

In a similar fashion, we get

$$E\left(W_i^{FG}\right) = (Q_i - 1)\tau_{ri}/2 \tag{15}$$

$$E\left(W_i^d\right) = \tau_{di} \tag{16}$$

$$E\left(W_i^t\right) = \tau_{ti} \tag{17}$$

The total lead time for product i is then computed as follows:

$$\begin{aligned} E\left(W_i\right) = {} & \frac{Q_i - 1}{2\lambda_{ai}} + \tau_{di} + E(Y_{bs})\frac{c_{ba}^2 + c_{bs}^2}{2}\frac{\rho}{1-\rho} + \tau_{si} + Q_i\tau_{pi} \\ & + \frac{(Q_i - 1)\tau_{ri}}{2} + \tau_{ti} \end{aligned} \tag{18}$$

where

- τ_{ri} = expected value of the inter-delivery time for the finished products of type *i*
- τ_{di} = expected value of the random variable W_i^d
- τ_{ti} = expected value of the random variable W_i^t

C. Sales Price

Intuitively, a firm can ask higher prices for products with relatively shorter lead times; conversely, it may have to reduce the prices for products with longer lead times, or customers may simply go for substitutes. This close relationship between sales price and lead time has also been demonstrated by a majority of literatures [20-22].

Based on the intuitive experience and relevant literatures, we assume an inverse linear relationship between the selling price p_i and the lead time for product i, as in

$$p_i = -\kappa_i\left(E(W_i) - E(W_i)_{AVG}\right) + p_i^{AVG} \tag{19}$$

where κ_i indicates the level of customer sensitivity to the lead time of product *i*. A large κ_i means that customers have a strong desire to acquire the product soon. Since it is difficult to determine κ_i theoretically, we set it heuristically between the range of 0 and 100. $E(W_i)_{AVG}$ and p_i^{AVG} respectively represent the industrial average lead time and the industrial average sales price for product *i*.

D. Shareholder Wealth

As mentioned in the previous section, we adopt CFROI to represent the shareholder interests, for it is considered a better financial metric of sustainable long-term profitability. The first key input to CFROI is the real periodic cash flow, composed of operational, financing, and investing cash flows. According to [8], the operational cash flow OCF_t is estimated as the net income NI_t plus noncash expenses NC_t. NI_t equals the sales revenue minus the variable and fixed costs, denoted by VC_t and TC_t respectively, that is,

$$OCF_t = NI_t + NC_t = \lambda_i p_i - VC_t - FC_t + NC_t \tag{20}$$

ISBN: 978-988-19251-0-7
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

where VC_t can be estimated as

$$VC_t = \sum_{i=1}^{N}\left(\omega_{i,t} + \frac{s_{i,t}}{Q_i} + E(W_i^{WIP})h_{i,t}^{WIP} + E(W_i^{FG})h_{i,t}^{FG} + v_{i,t} + \xi_{i,t}\right)\lambda_i \quad (21)$$

The terms $\omega_{i,t}$, $s_{i,t}$, $\upsilon_{i,t}$ and $\xi_{i,t}$ represents respectively the unit raw material cost, unit setup cost, unit sales price, and unit tax cost for product *i* at period *t*. $h_{i,t}^{WIP}$ and $h_{i,t}^{FG}$ are the unit inventory cost corresponding to the WIPs and finished products.

In addition to operational cash flow, financing and investing cash flows are equally important to equity holders. In our model, the manufacturer is allowed to adopt a policy of rolling over the excessive cash through short-term financial tools, which results in the following investing cash return ICF_t :

$$ICF_t = IR_t \sum_{k=1}^{t} \max\left(OCF_t\ ,0\right)\ \left(t = 1,2,\cdots,T\right) \quad (22)$$

where $\max\left(OCF_t\ ,0\right)$ denotes the excessive cash at period t . IR_t stands for the investment rate of return.

Similarly, the financing cash flow FCF_t is

$$FCF_t = FR_t \sum_{k=1}^{t} \min\left(OCF_t\ ,0\right)\ \left(t = 1,2,\cdots,T\right) \quad (23)$$

where $\min\left(OCF_t\ ,0\right)$ represents the short capital quantity at period t . FR_t is the financing cost of capital.

Then, we can get the total nominal cash flow NCF_t by summing up (20), (22), and(23), as in

$$NCF_t = OCF_t + ICF_t + FCF_t \quad (24)$$

Afterwards, we adjust NCF_t for the inflation rate r to obtain the periodic real cash flow RCF_t :

$$RCF_t = NCF_t \big/ (1+r)^t \quad (25)$$

Finally, the conception of IRR and DCF can be adopted to calculate CFROI [8], as follows:

$$TA = \sum_{t=1}^{L} \frac{RCF_t}{(1+CFROI)^t} + \frac{NA}{(1+CFROI)^t} \quad (26)$$

where TA and NA respectively denotes the total asset amount and the amount of non-depreciating assets.

E. *Constraints*

We take both the operational and the financial constraints into consideration in our approach. Operation constraints involve the lot size and the traffic intensity. In any cases, the lot size should be larger than or equal to one, and traffic intensity less than 100% is assumed for realistic queuing. Additionally, a firm's manufacturing capacity and production factors impose restrictions on the changing range of its sales price. Consequently, the relevant constraints on (26) can be summarized as follows:

$$Q \ge 1;\quad \rho < 100\%;\quad F_i \le p_i \le C_i \quad (27)$$

III. Numerical Demonstration

Our research aims to optimise multi-item lot sizing for manufacturing under uncertainty, taking financing and investing activities into consideration, for maximisation of the shareholder wealth. The proposed model incorporates some real industrial practices. In manufacturing of specialised bicycles, for example, orders for bicycles arrive on an individual basis and are gathered by the sales department, and then some operations, such as electroplating, are conducted on a batch basis. Subsequently, a setup procedure is triggered contingent on the type of bicycles to be produced. Finally, components are assembled into finished bicycles one by one for delivery to customers. Another typical example is in the metal industry, where metal workpieces arrive individually at furnaces for heat treatment. As soon as a given number of metal workpieces are batched, they are loaded as a whole for heat treatment. Subsequently, they are sandblasted on an individual basis before delivery.

To test the proposed model, three independent numerical experiments are performed. The first one compares the proposed shareholder wealth maximisation model to the traditional operation optimisation. The second one explores the impacts of financing and investing activities on corporate wealth. In the last one, we examine the effects of various risks on the proposed approach by risk analysis to provide insights into how possible and at what level these risks affect the interests of investors, especially equity holders. For simplicity, we assume that there are only two types of products for all numerical experiments, although our model can deal with any number of types of products.

A. *Shareholder Wealth vs. Operational Optimisation*

To optimise the shareholder wealth, which is represented by equation (26) subject to constraints (27), we firstly need to determine the optimal combination of lot sizes that can maximize CFROI. The trend of CFROI in relation to the combination of lot sizes is graphically illustrated in Fig. 2. It can be seen that an optimal combination of lot sizes of Q_1 =334.0470 and Q_2 =397.1531 corresponds to a maximum CFROI of 82.44%.

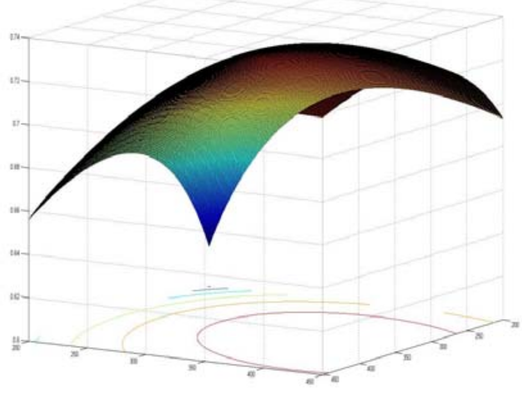

Fig. 2 Shareholder value as a function of lot sizes

To compare the result with its traditional operational optimisation, we find out the optimal combination of lot sizes based on (18). Obviously, the optimal combination is supposed to minimise the total lead time, which can be achieved in the case of Q_1 =202.3934 and Q_2 =306.7601 with a shareholder wealth of 78.26%. The comparative information, listed in Table I, illustrates that the lead time minimisation does not align with the shareholder wealth

ISBN: 978-988-19251-0-7
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

maximisation since it omits shareholder interest by approximately 4.18%.

TABLE I COMPARABLE INFORMATION BETWEEN LEAD TIME MINIMISATION AND SHAREHOLDER VALUE MAXIMISATION

Optimisation objective	Optimal lot sizes Q_1	Q_2	CFROI
Lead time	202.3934	306.7601	78.26%
Corporate wealth	334.0470	397.1531	82.44%.
Difference	131.6536	90.3930	4.18%

B. *Impacts of Financing and Investing Activities*

From the first numerical experiment, we find that the maximum shareholder wealth of 82.44% can be reached at Q_1 =334.0470, Q_2 =397.1531 when both financing and investing activities are considered. To further illustrate their implications on shareholder wealth, we set IR_t and FR_t to zero, which means that both financing and investing activities will be neglected in the solution. We rerun our algorithm and get the new optimal combination of Q_1 =334.0470 and Q_2 =397.1531, yielding a maximum shareholder wealth of 73.31%. As shown in Table II, this indicates that the shareholder wealth drops by 9.13% without financing and investing activities, even though the optimal combination of lot sizes remains unchanged. To further demonstrate the relevance of these two activities to a firm, we provide a graphical illustration on how the shareholder wealth changes with the lot size of each product type in Fig. 3 and Fig. 4. Both figures clearly reveal their importance in manufacturing optimisation.

TABLE II COMPARISON IN SHAREHOLDER WEALTH MAXIMISATION BETWEEN WITH AND WITHOUT FINANCING AND INVESTING ACTIVITIES

Shareholder wealth optimisation	Optimal lot sizes Q_1	Q_2	CFROI
With financing and investing activities	334.0470	397.1531	82.44%.
Without financing and investing activities	334.0470	397.1531	73.31%
Difference	0	0	-9.13%

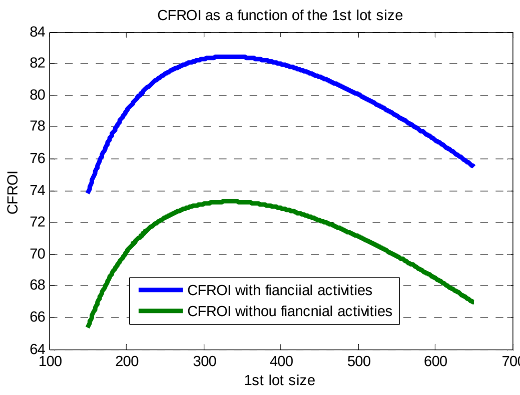

Fig. 3 Shareholder wealth as a function of Q_1

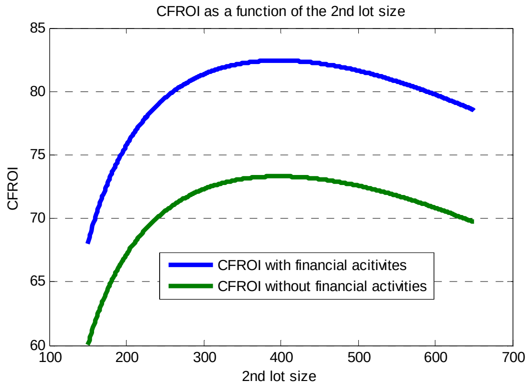

Fig. 4 Shareholder wealth as a function of Q_2

C. *Risk Analysis*

In addition to the absolute return of CFROI, its dispersion from the optimal expected value, well known as risk in finance, is another concern, especially in times of dramatic market swings. Here, the riskiness facing the manufacturer is measured by the dispersion of CFROI. The popular risk analysis method, i.e., sensitivity analysis, is used to provide guidance on how to respond to a risky environment. We therefore use sensitivity analysis to determine the effect on the shareholder wealth by changing one single input variable at a time.

We first determine which variables to change and by how much. Since we are more concerned about k_i, $E(W_i)_{AVG}$, p_i^{AVG}, FR_t, IR_t, and NA due to their large influences on the shareholder wealth and their susceptibility to market changes. Table III lists the base values for these key parameters on which the sensitivity analysis will be performed. The CFROI is recalculated by changing one variable from its base value either to a higher value (10% higher than base case) or a lower case value (10% less than base case).

The results of the sensitivity analysis are listed in Table IV. It can be seen that the firm's shareholder wealth is most sensitive to changes in the industrial average price. Changes in the investing rate of return have also a substantial effect, but not as much as the changes in the industrial average price.

TABLE III CHANGES IN KEY PARAMETERS FOR SENSITIVITY ANALYSIS

Inputs	Base value	Low value	High value
k_i	1	0.90	1.10
$E(W_i)_{AVG}$	0.9	0.81	0.99
p_i^{AVG}	100	90	110
FR_t	10%	9%	11%
IR_t	10%	9%	11%
NA	3000	2700	3300

The shareholder wealth is less susceptible to the changes in the delivery sensitivity, the industrial average lead time and the portion of non-depreciation assets in total assets. In the risk analysis, the financing rate has no effect on the

ISBN: 978-988-19251-0-7
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

shareholder value since the optimisation nature of our model excludes the possibility of financing using external capital.

TABLE IV SENSITIVITY OF CFROI TO CHANGES IN KEY FACTORS

Inputs	Base value	Low value	High value	Changing Range
k_i	82.44%	82.47%	82.42%	0.05%
$E(W_i)_{AVG}$	82.44%	82.38%	82.50%	0.12%
p_i^{AVG}	82.44%	75.68%	89.14%	13.46%
FR_t	82.44%	82.44%	82.44%	0
IR_t	82.44%	81.54%	83.35%	1.81%
NA	82.44%	82.37%	82.52%	0.15%

IV. CONCLUSION AND DISCUSSIONS

In this paper, we propose a multi-item stochastic lot sizing optimisation model for enhancing the sustainable long-term performance of a manufacturing firm under uncertainties.

The proposed model is characterised by taking operational activities as well as financing and investing activities into consideration. It adopts general distributions for stochastic variables, instead of the traditional theoretical distributions such as Poison process, to improve its generality and extensibility for dealing with multi-item lot sizing in more realistic manufacturing scenarios. Most importantly, the model optimises the sustainable long-term profitability of a firm in terms of CFROI, which is considered a relevant financial metric that can better reflect the firm's overall business goal and hence the full interest of equity holders. Moreover, the proposed model eliminates distorting impacts of inflation, such that the optimisation results are projected in real purchasing power, rather than in nominal terms.

Numerical experiments reveal that there is considerable spread of optimisation between the traditional operational approach and the proposed model. This highlights the importance of taking financial and economic factors into account for manufacturing optimisation. It is found that financing and investing activities are as important as operational activities in promoting the shareholder wealth. Hence, in addition to the traditional short-term operational objectives, a firm should also put attention on the interest of its equity holders—the global long-term business goal. This provides a practical guidance on the use of cash flow from operations, and highlights the importance of cash reinvestment in advancing the firm's performances.

Risk analyses are performed to test the susceptibility of a firm's shareholder wealth to microeconomic and macroeconomic market swings. This numerical experiment is designed to address a real management concern that a firm should care not only about how to maximise its prospective shareholder value, but also about its capability to hedge various risks to keep a stable performance improvement. The result shows that the shareholder wealth is most sensitive to the industrial average price of a product, followed by investing rate of return, while the impacts of other key factors seem negligible.

Currently, the proposed model has some limitations which may be addressed in future work. For example, the lot sizing model may be extended to cope with a multi-item, multi-machine stochastic manufacturing environment; the specific linkage between the lead time and sales prices should be investigated in depth; furthermore, a multi-stage stochastic programming may be adopted as a more practical tool in line with periodic accounting purposes.

REFERENCES

[1] Lazonick, W. and O'Sullivan, M., *Maximizing shareholder value: a new ideology for corporate governance.* Economy and Society, 2000. **29**(1): pp. 13-35.

[2] Martin, J.D. and Petty, J.W., *Value based management: the corporate response to the shareholder revolution.* 2000, New York: Oxford University Press.

[3] Lambrecht, M.R., Ivens, P.L. and Vandaele, N.J., *ACLIPS: A capacity and lead time integrated procedure for scheduling.* Management Science, 1998. **44**(11): pp. 1548-1561.

[4] Missbauer, H., *Lot sizing in workload control systems.* Production Planning & Control, 2002. **13**(7): pp. 649-664.

[5] Hopp, W.J., Spearman, M.L., Chayet, S. and Donohue, K.L., *Using an optimized queueing network model to support wafer fab design.* IIE Transactions, 2002. **34**(2): pp. 119-130.

[6] Erasmus, P.D. and Lambrechts, I.J., *EVA and CFROI: A comparative analysis.* Management Dynamics, 2006. **15**(1): pp. 14-26.

[7] Young, S.D. and O'Byrne, S.F., *EVA and Value-Based Managment: A Practical Guide to Implementation.* 2001, USA: McGraw-Hill.

[8] Bodie, Z., Merton, R.C. and Cleeton, D.L., *Financial Economics.* 2 ed2008, USA: Pearson Prentice Hall.

[9] Yi, G. and Reklaitis, G.V., *Optimal design of batch-storage network with financial transactions and cash flows.* AIChE Journal, 2004. **50**(11): pp. 2849-2865.

[10] Guillén, G., Badell, M. and Puigjaner, L., *A holistic framework for short-term supply chain management integrating production and corporate financial planning.* International Journal of Production Economics, 2007. **106**(1): pp. 288-306.

[11] Reiner, G., *Rapid Modelling and Quick Response Intersection of Theory and Practice.* 2010, London: Springer.

[12] Obrycki, D.J. and Resendes, R., *Economic Margin: The Link Between EVA and CFROI.* 2000, New York: John Wiley and Sons.

[13] Madden, B.J., *CFROI Valuation: A Total System Approach to Valuing the Firm.* 2002, Oxford: Butterworth Heinemann.

[14] Gunasekaran, A., Patel, C. and Tirtiroglu, E., *Performance measures and metrics in a supply chain environment.* International Journal of Operations & Production Management 2001. **21**(1/2): pp. 71-78.

[15] Absi, N. and Kedad-Sidhoum, S., *The multi-item capacited lot-sizing problem with safety stocks and demand shortage costs.* Computers & Operations Research, 2009. **38**(11): pp. 2926-2936.

[16] Lu, L. and Qi, X., *Dynamic lot sizing for multiple products with a new joint replenishment model.* European Journal of Operational Research, 2011. **212**(1): pp. 74-80.

[17] Govil, M.K. and Fu, M.C., *Queueing theory in manufacturing: A survey* Journal of Manufacturing Systems, 1999. **18**(3): pp. 214-240.

[18] Whitt, W., *The Queueing Network Analyzer.* The Bell System Technical Journal, 1983. **62**(9): pp. 2779-2815.

[19] Choi, S. and Enns, S.T., *Multi-product capacity-constrained lot sizing with economic objectives.* International Journal of Production Economics, 2004. **91**(1): pp. 47-62.

[20] George, K., Canel, C. and Neureuther, B.D., *The impact of lot-sizing on net profits and cycle times in the n-job, m-machine job shop with both discrete and batch processing.* International Journal of Computer Integrated Manufacturing, 2005. **97**(3): pp. 263-278.

[21] Kenyon, G.N., *A profit-based lot-sizing model for the n-job,m-machine job shop Incorporating quality, capacity, and cycle time*, 1997, Texas Tech University: Texas.

[22] So, K.C. and Song, J.S., *Price, delivery time guarantees and capacity selection.* European Journal of Operational Research, 1998. **111**(1): pp. 28-49.