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A SIMULATION MODEL FOR CARBON RESOURCE PLANNING OF PRODUCTION SYSTEMS

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ABSTRACT

Under "Cap-and-Trade" conditions, a manufacturer is restricted in total carbon dioxide equivalent (CO2e) emission through an initial allocation of emission quotes (EQ), but allowed to purchase emission quotes (i.e. commercialized permits for emitting CO2e) to satisfy additional needs via a trading market. Alternatively it can reduce its emission through self-purification (SP) to decrease its need for EQ, and/or sell the surplus (in the form of certified-emission-quotes) to gain revenue. There are multiple risks associated with these carbon-resource planning decisions, e.g. fluctuation of EQ price and changing cost of performing SP. The dynamic interactions between decision variables and influencing factors, coupled with various uncertainties associated with risk profiles, make the planning process and the evaluation of solutions extremely difficult. This research proposed a discrete-event simulation based approach to characterize carbon-resource planning process and analyze production system's performance under the impact of multiple risks and mitigation strategies associated with a Cap-and-Trade setting.

1 INTRODUCTION

It has been recognized via scientific evidence that unrestricted carbon dioxide equivalent (CO2e) emission due to over-developed human activities is a primary cause for the global warming that caused significant environmental changes (Zhang, Min, and Chen 2011; IPCC 2007). To reduce CO2e emission, different mechanisms have been proposed and implemented. Among them Cap-and-Trade (C&T) is one of the widely implemented programs based on eco-economic theory (Dales 1968). Known as emission quotes (EQ) trading, C&T is a market-based program for controlling CO2e emission. Under such a program, emission generating companies (e.g. manufacturers) in a region are allocated emission allowances (EQ) to offset their operational emission needs. Initial allowance can be grandfathered or auctioned through a regulatory agency, and then be traded later among the generating companies through transactions at a regional emission trade market (EPA 2007). The total of emission allowances issued is restricted by a pre-determined cap, which is gradually tightened over time. There are successfully established regional emission trade markets (RETM) around the world, including European Union Emission Trade System (EU-ETS), CRC Energy Efficiency Scheme UK (CRC), Western Climate Initiative (WCI), Assembly Bill 32: Global Warming Solutions Act, California (AB32), and Tokyo Cap and Trade (TMG). In China, the government has committed to cut its CO2e emission per unit of gross domestic product (GDP) by 40% to 45% (of 2005 level) by 2020 (Yi et al. 2011), and is aggressively pushing for a compulsory carbon emission reduction program that combines administrative penalty and market trade of emission quotes (EN 2010). City of Shenzhen was chosen as one of the seven experimental regions in China where a RETM under C&T condition is being established (Shenzhen Emission Exchange 2012). This has inspired and provided a valuable opportunity for our research.

Under C&T conditions, resource planning decisions become much more complicated for a production or service provider who participates in a regional emission trading market. First the enterprise faces more constraints and must fulfill new obligations that are dictated by exogenous factors, i.e. following rules and regulations set by government agencies (for the purpose of control and operation of a RETM), such as estimating carbon-footprint and accepting emission allowance, obeying transaction regulation, and participating in monitor-report-verification (MRV) compliance. These functions are usually designed and controlled by policy makers (governmental agencies) and involved with complicated logic and accompanied by many uncertainties. Together they form a “macro-system structure” imposed on the enterprise and significantly influences the decision behavior of a company (e.g. as it plays the role of potential buyer or seller of EQ through interactions with a RETM). Consequently participating enterprises operate significantly different under the conditions of a C&T program (Du et al. 2009). In addition to traditional production resources (e.g. labor, equipment and raw materials), they now have to consider the acquisition and disposition of environmental resource (i.e. carbon-resource or emission quote), and balance between production economy and CO2e reduction. Operation managers have to plan and acquire enough EQ to meet their production/service need, which unavoidably generates CO2e emission. Given the production requirements over the periods of a planning horizon, the emission needs corresponding to each period can be estimated. Decision makers need to choose from purchasing EQ (by trading at a RETM), or reducing emission level via self-purification (SP), or carrying over surplus emission quote to meet the required emission for the planning period. In this paper, self-purification is defined as a process conducted autonomously by a generating company to reduce its total emission of CO2e due to production/service activities through the improvement of product design, processing methods or technology, or production/service operations, e.g. adopting a green production method or replacing equipment for lower energy consumption. Previous studies have revealed some important characteristics of this decision-making process: (1) market price of EQ follows a random fluctuation (Wei et al. 2010); (2) the abatement cost of performing SP to reduce emission level increases as accumulated emission reduction increases, i.e. the more reduced, the more difficult to reduce (Zhou et al. 2013; Zhang and Li 2007); and (3) there exist trade-offs between decision alternatives that may lead to significant cost-saving. For instance, purchasing more emission quotes via market trade might be a better solution than reducing emission level by SP when the market price of EQ is low. Consequently it is important for managers to decide how to satisfy the emission needs of planning periods through different options available under a C&T mechanism. Unfortunately there are multiple risks associated with the decisions when an enterprise participates in a regional emission trade market under C&T conditions. For example, when a generating company is a potential buyer (having positive needs for additional EQ), it has to face at least three new type of risk: random fluctuation of EQ price at market, risk of performing SP to reduce its emission level, and the risk of paying penalty if it cannot fulfill the emission reduction target. When it is a potential seller (having surplus EQ), the risks include the fluctuation of EQ price and unpredictable change of product demand that often drives the adjustment of production capacity.

Apparently these risks influence enterprise decisions significantly and are driven by complicated internal and external factors that change dynamically and stochastically. This has raised important questions regarding the evaluation and implementation of such complex decision-making processes. For instance, how to build a model that can adequately represent and effectively simulates the characteristics and dynamics of a carbon-resource planning and disposition process, and design and implement appropriate experiments using the model to analyze the decision outputs (or system’s performance) under various combinations of system conditions (e.g. C&T policies and risk profiles)? Such a model and related analyzes also help to compare different mitigation strategies.

There has been a rich body of literature related to the study of Cap-and-Trade application or emission trade system. Many are qualitative studies that used a descriptive approach to discuss the risks and allocating initial emission allowance to generating companies, for instance the development of various assessment index systems and evaluation schemes using the variants of AHP method (Yi et al. 2011; Cong and Wei 2012; Wei, Ni and Du 2012; James and Chen 2012; Wang et al. 2013) and the design of mechanism for carbon-credit trade (Zhang and Wei 2010; He, Wang, and Wang 2012; Robert, Flachsland, and Jakob 2012; Robert et al. 2012; Christos and Woodland 2013). Some papers focused on optimization issues related to the carbon-resource planning from a production system perspective (Chen, Benjaafar, and Elomri 2013; Rong and Lahdelma 2007; Catalao et al. 2008; Absi et al. 2010). Mathematical programming models (e.g. LP, NLP, MIP) in particular have been developed to optimize resource decisions for single manufacturer (Kockar, Conejo, and McDonald 2009; Wang, Wang, and Wang 2012; Chang et al. 2012). These studies demonstrated that C&T conditions generate significant impact on resource selection and allocation, and analytical models can be effective in identifying decision trade-offs that lead to "optimal" solutions. However the dynamic nature of the decision process, contextual logic peculiar to carbon resource planning, and uncertain mechanism (and impact) of multiple risks associated with the decision-making process were typically ignored in these studies or replaced by naive assumptions.

While the literature seems abundant, there is clearly a lack of research to address the risk analysis of carbon-resource planning decisions from a production enterprise perspective when the enterprise is confined under the C&T conditions as a participant in a regional emission trade market. It becomes a significant challenge and contribution to build a robust model that can adequately represent the structure and effectively simulates the dynamics of carbon-resource planning and implementation problem to allow managers to assess the impact of multiple risks on the system performance and evaluate the effectiveness and efficiency of different mitigation strategies (in terms of both production economy and environmental sustainability). The purpose of this study is to develop a discrete-event simulation model (Law and Kelton 2001) to conduct experimental studies on manufacturing enterprise's decisions in planning and disposing carbon-resources (EQ) via interactions with a regional emission-quotes trade market under multiple risks and conditions associated with a Cap-and-Trade program, particularly to evaluate system performance under various decisions and the impact of related risks. The rest of the paper is organized as follows. Section 2 introduces conceptual modeling of the planning problem. Section 3 presents and discusses the limited experimental results designed for verifying the functions of proposed model. Finally Section 4 summarizes the study and identifies the directions for the on-going research.

2 SIMULATION MODELING OF ENVIRONMENTAL RESOURCE PLANNING AND DISPOSITION PROCESS

In this paper we focus on the development of a conceptual model to capture the decision-making logic by a production company in carbon-resource planning under the conditions of C&T, and to represent essential mechanisms or functions that fulfill the decision-making process (e.g. estimating the needs for additional emission quotes). In addition, the model also need to represent multiple risk factors associated with the decision types and system structure to allow the assessment of the risk impact on system performance or the comparison of different mitigation strategies. This paper presents the work for developing a basic model (called "*baseline model*" hereafter) that represents the general structure and logic flow of the planning-under-risk problem, and creates a conceptual framework that defines the functions and elements to compose the system (including decisions, risk factors and their distributions) and define its behavior.

The proposed overall flow logic of the carbon-resource planning and implementation process (embedded with risk evaluation functions) is depicted in Figure 1. At the most abstract level, when a decision agent enters a new decision cycle (a new planning period, e.g. a month or week), it first estimates how much additional emission quotes are needed for the production period (i.e. determining net-emission need $\Delta e(t)$) based on production demand and emission allowance allocated for the period. If the need is positive then the agent has to either purchase additional EQ from market or perform SP to compensate its emission need, which leads to module "*potential buyer logic*". On the other hand, when the net-emission need is negative (meaning that the agent has a surplus EQ for the period), the agent must decide whether to sell the surplus EQ on the marker or hold it for the next period, which is described via module "*potential seller logic*". In these subsequent modules, the relevant risks (and their impact) corresponding to the decision type are identified and evaluated. After the role of buyer or seller is played, the experimental conditions are set according to the decisions made at higher level. Then the lower level simulation of a production process is activated and run in accordance with the conditions set to collect data on related variables, including the actual impact of the risks identified. Then the simulation is either stopped or forwarded to next decision cycle (t+1).

The procedure "*Estimate net-emission need*" takes the following steps: (1) estimate market demand for products $d(t)$~UNIF(d_l, d_u); (2) determine a production quantity $q(t)$ that satisfies the demand and planned expansion; (3) estimate total product $TP(t) = q(t) \times p_d$, where p_d = unit product price; (4) convert $TP(t)$ into standard-coal-equivalent (NBSC 2011, Jiang 2009): $TP(t) \rightarrow STC(t) = TP(t) \times \alpha_1$, where α_1 is a transformation coefficient between total product and standard coal equivalent; (5) convert $STC(t)$ into expected CO2e emission $e(t)$: $e(t) = STC(t) \times \alpha_2$, where α_2 is a transformation coefficient between STC and CO2e emission (NBSC 2011, Jiang 2009); (6) calculate actual over-emission $\Delta e(t) = e(t) - EQ(t)$, where $EQ(t)$ is the emission quote allocated to period t and determined by weighting annual allocation EQ_A with $e(t)$, i.e. $EQ(t) = (e(t)/E_a) \times EQ_A$, where E_a = estimated annual emission.

The detailed logic when decision-maker plays the role of a *potential buyer* is presented in Figure 2. The agent observes EQ trade market and develops an expected price $P_c(t)$ for the carbon credits it needs to pay. If this price is less than the cost of performing SP, $P_{sp}(t)$, the agent assess the risk of purchasing EQ (and therefore not performing SP). If the chance of risk is low ($p_{re} < p_{r0}$) or cost at the risk is low ($C_{re} < Y_{re}$), the agent enters the market to make the purchase for the EQ needed; else it decides better to perform SP to reduce emission (therefore the need for additional EQ). If the cost of SP is less than the cost of expected purchasing price, i.e. $P_{sp}(t) \leq P_c(t)$, the agent assess the risk of performing SP; if the chance of the risk is low ($P_{sp} < p_{s0}$) or the cost at risk is low ($C_{sp} < Y_{sp}$), it will perform SP; Otherwise it evaluates the cost at risk for purchasing EQ (C_{re}), and compares this cost with the cost of performing SP (C_{sp}). The final decision goes with the one of lower cost. Note that both p_{s0} and p_{r0} are threshold values that can be empirically determined and were initially set at a moderate level (e.g. 10%) in the baseline model. The entire logic is depicted in Figure 2.

The module "*Purchase EQ*" fulfills the required actions for agent to obtain needed EQ via market transaction, and invokes a function that generates a risk event associated with purchasing decision, and calculates the cost at the risk for the event. In the baseline model, only one risk type was considered and defined as the event that the actual market price of EQ, $p'(t)$, is higher than the expected price $p(t)$ (estimated earlier by the potential buyer). Based on our analysis of the market price fluctuation of EU-ETS during 2012, we assume that the value of $p'(t)$ follows a regressed distribution $F(\mu_p(t), \sigma_p(t))$. Since the expected $p(t)$ is estimated using a moving average of last week's EQ price, we assume that the actual price distribution at a time t can be approximated by a normal distribution, i.e. $p'(t) \approx N(p(t), \sigma_p)$. Therefore probability $P(p'(t) > p(t) + k\sigma_p)$ can be used as a measure for the likelihood that the actual price of EQ is higher than the expected price when a potential buyer decides to purchase. During the risk analysis step (Figure 2), a moderate threshold value p_{r0} (e.g. 10%) was used: when $P(p'(t) > p(t) + k\sigma_p) = p_{re} \leq p_{r0}$, the agent believes that the risk would not occur, therefore proceeds with the decision to purchase; Otherwise ($p_{re} > p_{r0}$)it will evaluate the cost at the risk and act accordingly.

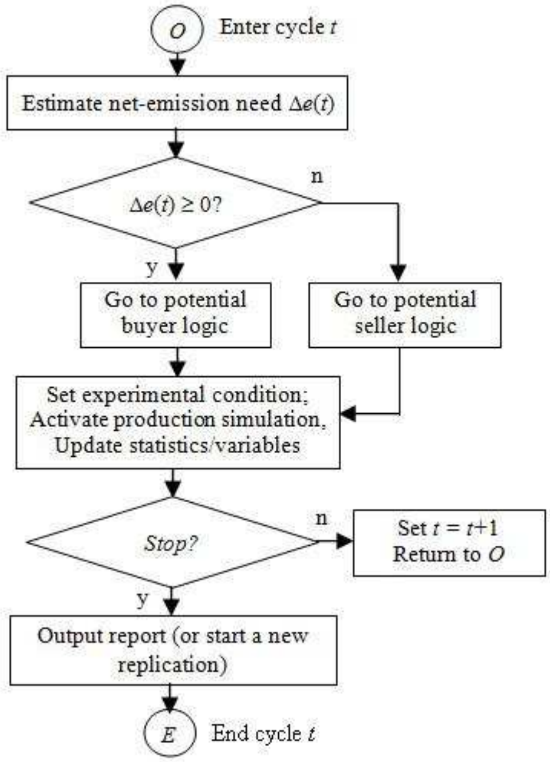

Figure 1: Top logic flow of proposed simulation.

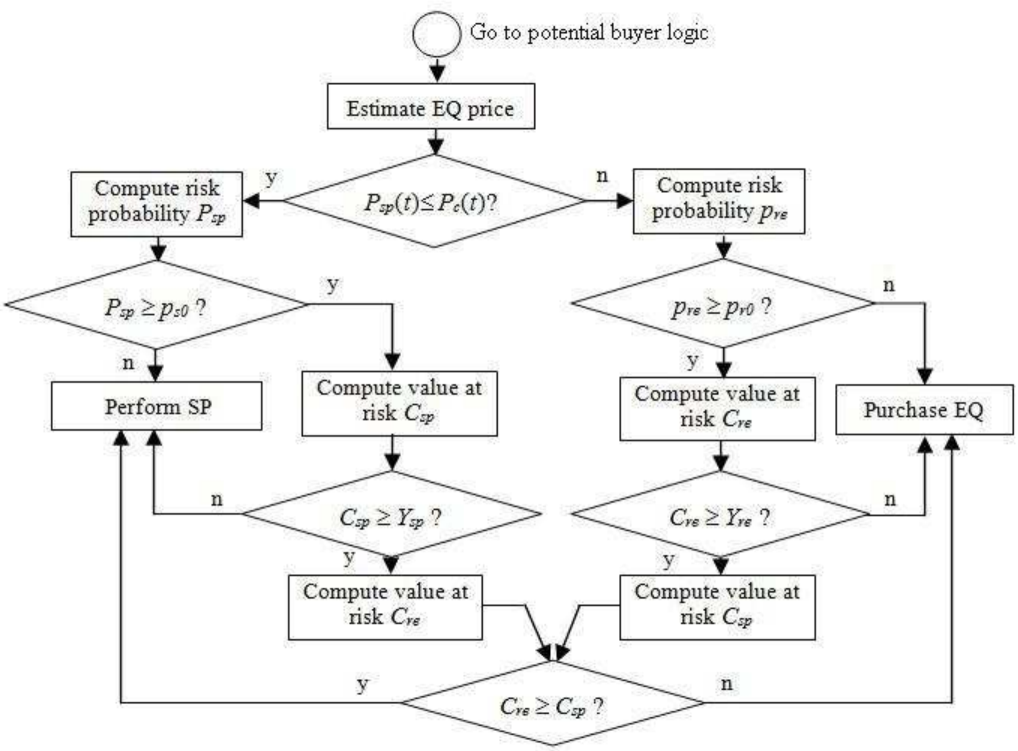

Figure 2: Logic flow for decision-making as a potential buyer.

For the role of *potential seller*, its decision logic is described through Figure 3. The agent first estimates the market trend of EQ price and develops an expected market selling price $P_{es}(t)$. If the estimated price is higher than the observed price $P_a(t)$, it goes on to evaluate the risk of selling the EQ. If the chance of the risk (or the cost at the risk) of selling surplus EQ is low ($C_{se} < Y_{se}$), it decides to sell surplus EQ. Otherwise it evaluates the risk (and the cost at the risk) of holding the EQ; if the risk (or the cost at the risk) of holding the surplus EQ is low ($C_{he} < Y_{he}$), it will hold the EQ; else sell the EQ. The detailed logic of the relevant modules is omitted here due to the limit of space.

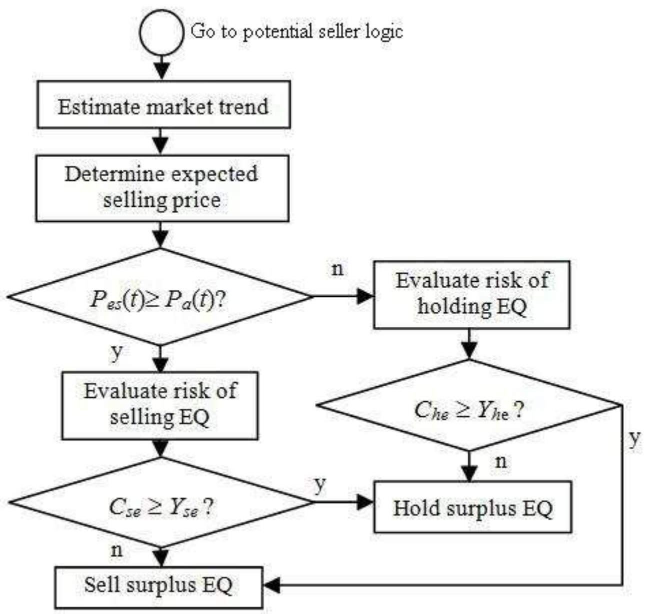

Figure 3: Logic flow for decision-making as a potential seller.

3 IMPLEMENTATION AND EXPERIMENTAL RESULTS OF THE BASELINE MODEL

The conceptual baseline model described in the previous section was realized or implemented with ARENA©. The experimental system mimics the behavior of a production enterprise in carbon-resource planning and disposition. We ran the simulation model for 36 months (i.e. three years of phase-I implementation in Shenzhen) and repeated the simulation for 30 times. The statistics were collected to compare the key performance measures over the three years. Part of the experimental results is presented in this paper. The purpose of the experiment with the baseline model was to verify the structure and functions proposed. For instance, Figure 4 (left) compared the decisions with and without risk evaluation. It showed that the decisions with risk evaluation significantly outperformed those without risk evaluation in terms of total risk cost. Figure 4 (right) compared the total cost of EQ purchase between the baseline allocation (higher) and reduced allocation. It showed that the total cost of EQ purchase increased as the allocation reduced. In Figure 5, we compared the changes on total emission reduction and total EQ purchase between the baseline value (higher) and reduced value of the marginal cost of performing SP. It showed that the total emission reduction increased and total EQ purchase decreased as the marginal cost reduced. Figure 6 compared total emission reduction and total EQ purchased with changing EQ price. All the results conformed to the observations on matured RETM systems such as EU-ETS (Zhang and Wei 2010) and verified the design intent of (baseline) model functions. Paired-t tests were also conducted to analyze the differences of the performance measures between the years, but omitted here due to the limits on the numbers of pages. It will be discussed and presented in a full paper under development.

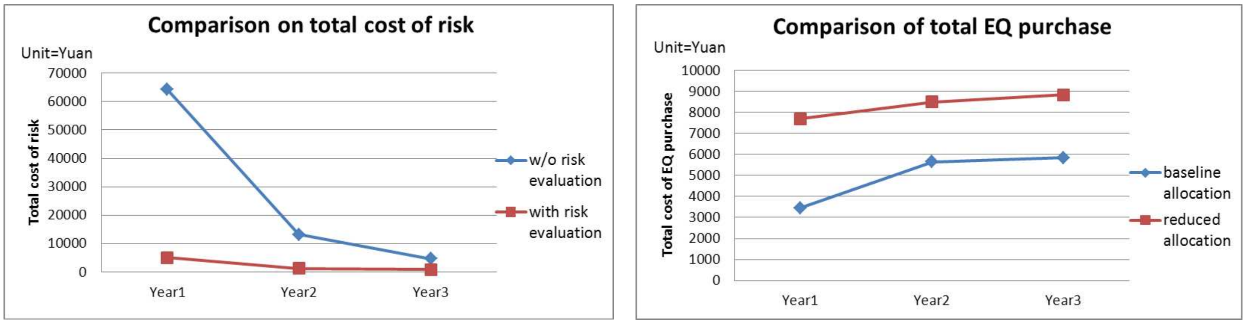

Figure 4: Comparison of total cost of risk and total EQ purchase.

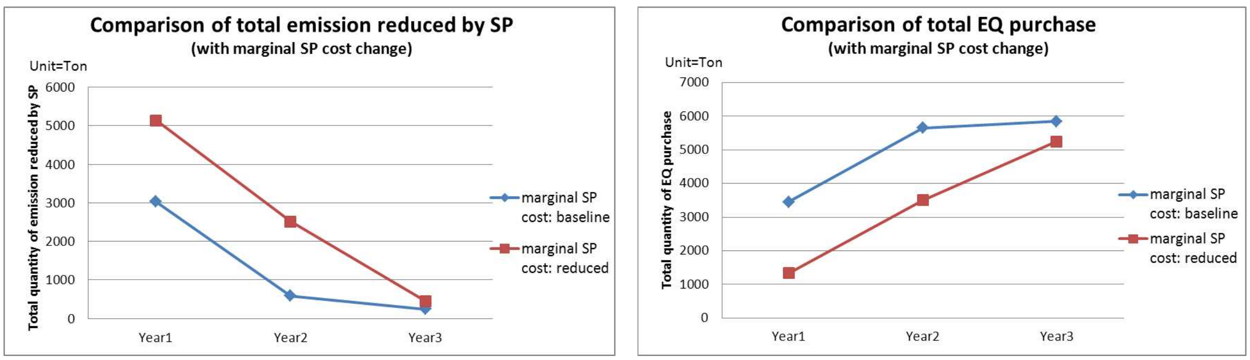

Figure 5: Comparison of total emission reduction and total EQ purchased with marginal SP cost change.

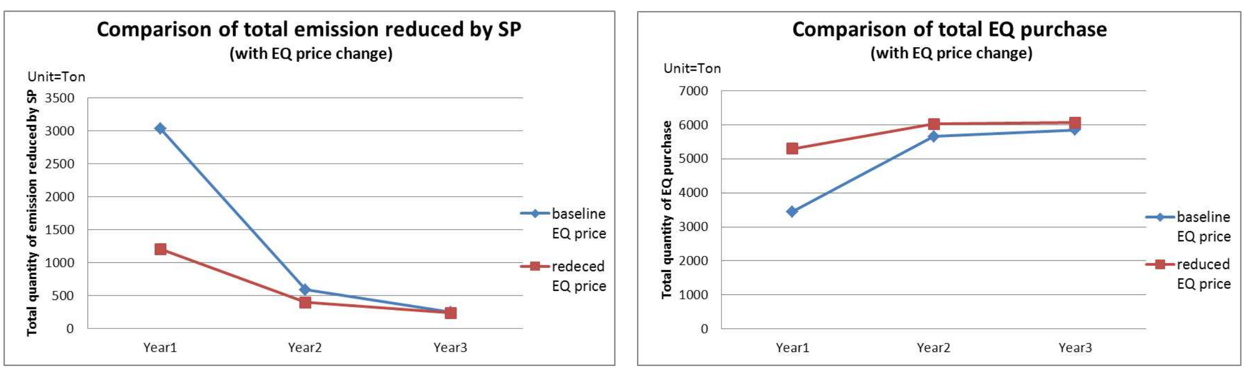

Figure 6: Comparison of total emission reduction and total EQ purchased with EQ price change.

4 CONCLUSION

This research built a discrete-event simulation model to analyze the multiple risks and their impact on the environmental resource (emission quotes) planning and disposition process of manufacturing enterprise under the conditions of a C&T program. A basic model (*baseline model*) was implemented with ARENA© and limited experiments were conducted to verify the functions of the model. The results conformed to the observed system behavior, verified the intended model functions and validated the original idea that the dynamics and composition of an environmental resource planning process can be sufficiently represented through a simulated platform so that various risk profiles and mitigation strategies can be analyzed to improve the decision-making and enhance system performance. Currently on-going research has significantly extended the scope and functions of the baseline model. The development and experimental results will be reported through a full paper under the on-going research.

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