MTHM005 - Mathematical Sciences Project

# Pricing Asian Options

Candidate Number: 145670

Supervised by Prof. Byott

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**Abstract**

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All files available here:
https://github.com/leele2/Mathematics-in-Business-Project

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# Chapter 1: Introduction

This report studies a vital financial derivative in today's markets, namely options. The importance of the option market has been shown by empirical studies which suggest that option trading improves information efficiency in the broader stock market [PP06, Li21], and also that firms with listed options experience lower implied cost of equity capital [NNT13]; indicating that options trading reduces the cost of capital [Li21]. The popularity of the options market can easily be seen in Figure 1.1, which shows the exponential growth in trading volume since standardized, exchange-traded stock options were first listed in The Chicago Board Options Exchange in 1973 [Mar02]. In 2020 single stock option trading volume became higher than the underlying stock volume for the first time ever [Yah20].

It is this explosive popularity and significance which have motivated this report. We will begin by describing standard options and explore popular methods that are used to price them. We will then move onto Asian options and look at the literature surrounding how to price them before implementing several pricing methods with the use of MATLAB. Furthermore, we will then take an analytical approach to determine how Asian options can be priced accurately and efficiently.

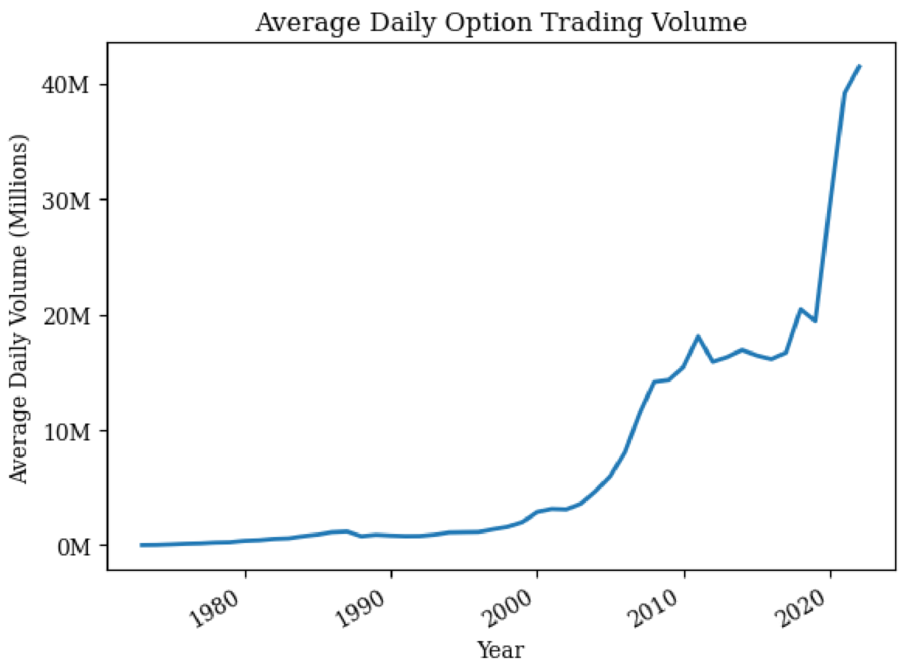


Figure 1.1: Time series plot of the average daily option trading volume per annum. Data provided by the Options Clearing Corporation (OCC) [Opt22]. Source code: Listing B.1

## 1.1 A brief overview of call and put options

Options are a particular type of financial derivative, a contract that details the conditions under which payments are made between two counterparties. They are purchased for a set fee, and in return the buyer is granted the right, but not the obligation to buy or sell an underlying asset - such as commodities, stocks or bonds - for a predetermined price (the strike price) on or before a determined date (the expiry date).

Call options allow the buyer to purchase an asset for the strike price at a future date. The buyer can make a return if the value of the asset is worth more than the strike price when exercised. Alternatively, put options allow the buyer to sell an asset for the strike price at a future date and the buyer can make a return if the value of the asset is less than the strike price when exercised.

The option market is widely considered a venue for informed trading [Li21, Hu14, CGM04], that is, investors trading with superior knowledge of the probability distribution of share prices, through either access to private information or skillful processing of public information [Gro75].

### 1.1.1 A short history of option trading

The history of financial options can be traced as far back as 6th century b.c. when ancient Greek mathematician and philosopher Thales of Miletus predicted through his astrological knowledge there was going to be a great olive harvest. As he did not have much money, he used what he had as a deposit on the rights to the local olive presses; due to no competition he secured this at a relatively low price. When the harvest proved to be bountiful leading to high demand, Thales charged a high price for use of the presses and reaped a considerable profit. His deposit gave him the right but not the obligation to hire the presses, thus his losses were limited to his initial deposit [Bus12, Ari77].

Whilst this is quite a positive look on option trading, throughout history this has not always been the case. During the Dutch tulip bubble of the seventeenth century, tulips were seen as a status symbols which caused high demand and consequently drove their prices up, creating a bubble ()[Das11]. Tulip growers would buy puts to protect their profits in case the price of tulip bulbs went down and wholesalers would buy calls to protect against the risk of tulip bulbs going up. When the bubble eventually burst, there was no way to force investors to fulfil their obligations of the options contracts, due to the unregulated nature of the option market. This ultimately led to options gaining a dubious reputation and bans were later placed on them within Britain between 1733-1860 [Poi08].

During the late nineteenth century, brokers started to arrange deals between buyers and sellers of options for particular stocks at prices that were arranged between the two parties. Trades were arranged similarly until the 1960s when the options market started to become regulated by the Chicago Board of Trade. In 1973, the Chicago Board of Options Exchange (CBOE) began trading and for the first time options contracts were properly standardized. At the same time, the Options Clearing Corporation was established for centralized clearing and ensuring the proper fulfillment of contracts, ensuring that they were honored [Mar02].

### 1.1.2 Standard options

A standard option comes in two styles; European: which restricts the holder of the option to only exercise the option on the expiry date, and American: which allows the holder to exercise the option at anytime up till or on the expiry date. They will take the current value of the underlying asset as the spot price - that is the price that the asset can be purchased for on the open market. The payoff in this case then becomes the difference between the spot price and strike price.

### 1.1.3 Asian options

Whilst standard options involve using the spot price as the underlying value of the asset; this is not always the case with so-called exotic options. Exotic options differ in their payment structures, expiration dates, and/or strike prices. In the case of exotic fixed-strike price Asian options, the average price of the asset is used in place of the underlying asset value. This differs from fixed-price Asian options which instead use the average price of the asset to take place of the strike price. These are the two main variations of Asian style options but both of these can be varied further in how the averaging is calculated, for example: geometrically, arithmetically, average taken every day or average taken at the start of each month and so on. They can be varied further by having an expiry structure matching a European or American style option.

## 1.2 Pricing options

Since the holder of the contract is not obliged to exercise the contract at the expiry time, they do not hold any liability in the absence of a price to purchase the option. The problem then becomes, what is the correct price to charge the holder of the option to balance this inequality of liability.

### 1.2.1 Pricing standard options

#### Binomial method

#### Black-Scholes Formula

### 1.2.2 Pricing Asian options

#### Hull-White model

#### Costabile adjusted binomial method

#### Analytical solution for geometric average Asian options

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# Appendix A: Matlab Files

All files can be found: https://github.com/leele2/Mathematics-in-Business-Project/tree/master/MATLAB%20Files

Listing A.1: ../../MATLAB Files/BinoAsian.m

```matlab
%function BinoAsian(S0,E,T,r,sigma,N,F)
%% Test
clear; tic; S0=50;  E=50; T=1.0; r=0.1; sigma=0.3; N=50; F=@(S,A)max(A-E,0);
%% Function to evaluate European Call option by Binomial Method
%   Parameters:
%   S0 = initial share price
%   E = exercise price`
%   T = time to expiry
%   r = riskfree interest rate
%   sigma = volatility
%   N = Number of steps
%   F = Option Payoff (European Call in given)
%% Calculated parameters
dt   = T/N;                    %Timestep
u    = exp(sigma*sqrt(dt));    %Up price movement
d    = 1/u;                    %Down price movement
disf = exp(-r*dt);             %Discount factor over each timestep
p    = (1/disf - d)/(u-d);     %Risk-neutral probability
%% Initalizing Arrays and Functions
S      = zeros(N+1,N+1);   %Underlying Asset Price
S_k    = cell(N+1,N+1);    %S_max %% Cells are used so different sized vectors can be stored at each element in cell array
A      = zeros(N+1,N+1);   %Average of Underlying Asset Price
A_k    = cell(N+1,N+1);    %Representitive averages
C      = zeros(N+1,N+1);   %Price of Option
C_k    = cell(N+1,N+1);    %Option price for given representitive avg
%F      = @(S,A)max(A-E,0); %Option Payoff (European Call)
%% Functions to Calculate Maximum and Minimum Representative Averages
A_min = @(i,j) (1/(i+1)) * (sum(S0*d.^(0:i-j)) + sum(S0*d.^(0:(j-1)+i-(2*j))));
A_max = @(i,j) (1/(i+1)) * (sum(S0*u.^(0:j)) + sum(S0*u.^((0:(i-j-1))+(2*j)-i)));
%% Calculate Underlying asset price
for i = 0:N
    for j = 0:i
        S(i+1,j+1) = S0*u^(j)*d^(i-j);
    end
end
%% Calculating All S_max and Representitive Averages
for i = 0:N
    for j = 0:i %j indexes at j+1 due to matlab not allowing C_k{:,0)
        A_k{i+1,j+1} = zeros(j*(i-j)+1,1); %Create Vector to hold rep avgs
        S_k{i+1,j+1} = NaN(j*(i-j),1);     %Create Vector to hold S_max
        A_k{i+1,j+1}(1) = A_max(i,j);      %Assign A_max to first element in vector
        % Paths with only up (i = j) or down movements (j = 0) or i = 1 will only have one representative average
        if i < 1 || i == j || j == 0
            S_k{i+1,j+1}(1) = S0*(u^j)*d^(i-j);
            continue
        end
        %% Filling S_max Vector
        % Setting Paramaters
        n = j*(i-j);         %Size of vector
        rep = min([j;i-j]); %Maximum element repetition in vector
        % Calculating unique elements in vector
        unique = 2*numel(1:rep-1) + (n - (2*sum(1:rep-1)))/rep;
        % First and last values
        S_k{i+1,j+1}(1)   = S0 * (u ^ j);
        S_k{i+1,j+1}(end) = S0 * (u ^ (j - unique + 1));
        %%The following if statement changes the final output%%
        if n ~= 2
            % Ascending/Descending repeated values
            k     = 2; %iterator
            count = 2; %Number of elements filled
            while k < rep
                % Filling from top
                S_k{i+1,j+1}(sum(1:k-1)+1:sum(1:k-1)+k) = repmat(S0*(u^(j-k+1)), k, 1);
                % Filling from bottom
                S_k{i+1,j+1}(n-sum(1:k-1)+1-k:n-sum(1:k-1)) = repmat(S0*(u^(j-unique+k)), k, 1);
                count = count + 2*k;
                k = k + 1;
            end
            % "Middle" repeated values
            for l = 0 : (n-count)/rep - 1
                S_k{i+1,j+1}(count/2+1+l*rep:end) = [repmat(S0*u^(j-k+1), rep, 1);
                    S_k{i+1,j+1}(count/2+1+l*rep+rep:end)];
                k = k + 1;
            end
        end
        %% Calculating Representitive Averages Using S_max
```

```matlab
        A_k{i+1,j+1}(j*(i-j) + 1) = A_min(i,j); %Assign A_min to last element in vector
        for k = 2:j*(i-j)
            A_k{i+1,j+1}(k) = A_k{i+1,j+1}(k-1) - (1/(i+1))* ...
                (S_k{i+1,j+1}(k-1) - S_k{i+1,j+1}(k-1)*(d^2));
        end
    end
end
%% Pricing Option Value at Final Time (N)
for j = 0:N
    C_k{N+1,j+1} = F(S(N+1,j+1),A_k{N+1,j+1});
end
%% Pricing Option
err = 1e-3;
for i = N-1:-1:0
    for j = 0:i
        C_k{i+1,j+1} = zeros(j*(i-j)+1,1);
        for k = 1:j*(i-j)+1
            %% Find K_u
            Ku  = ( (i+1)*A_k{i+1,j+1}(k) + u*S(i+1,j+1) )/(i+2);
            [loc, ubound, lbound] = findInSorted(Ku,A_k{i+2,j+2},err);
            % If found set accordingly
            if loc > 0
                Cu = C_k{i+2,j+2}(loc);
            else
                % If not found, interpolate between closest values
                Cu = C_k{i+2,j+2}(lbound)+(Ku-A_k{i+2,j+2}(lbound))*(...
                    (C_k{i+2,j+2}(ubound)-C_k{i+2,j+2}(lbound))/...
                    (A_k{i+2,j+2}(ubound)-A_k{i+2,j+2}(lbound)));
            end
            %% Find K_d
            Kd = ( (i+1)*A_k{i+1,j+1}(k) + d*S(i+1,j+1) )/(i+2);
            [loc, ubound, lbound] = findInSorted(Kd,A_k{i+2,j+1},err);
            %If found set accordingly
            if loc > 0
                Cd = C_k{i+2,j+1}(loc);
            else
                %If not, interpolate between closest values
                Cd = C_k{i+2,j+1}(lbound)+(Kd-A_k{i+2,j+1}(lbound))*(...
                    (C_k{i+2,j+1}(ubound)-C_k{i+2,j+1}(lbound))/...
                    (A_k{i+2,j+1}(ubound)-A_k{i+2,j+1}(lbound)));
            end
            %% Calculate option value at previous node (i,j decreasing)
            C_k{i+1,j+1}(k) = disf*(p*Cu + (1-p)*Cd);
        end
    end
end
disp(C_k{1,1})
toc;
```

Listing A.2: ../../MATLAB Files/Functions/findInSorted.m

```matlab
function [loc, A, B] = findinSorted(x,range,err)
%%%%%%%%%%%%%%% inputs %%%%%%%%%%%%%%%
% x = value to find                 %
% range = (sorted) vector to search %
% err = tolerence on search         %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Outputs
A   = 1;             %left boundary
B   = numel(range); %right boundary
loc = 0;            %initially set to 0 implying not found
%% Binary Search Algorithm
while B-A > 1
    mid = floor((A+B)/2);
    if x > range(mid)
        B = mid;
    else
        A = mid;
    end
end
%% Returning returned value if found (within tolerance)
if abs(range(A) - x) < err
    loc = A;
    return
elseif abs(range(B) - x) < err
    loc = B;
    return
end
```

# Appendix B: Python Files

All files can be found: https://github.com/leele2/Mathematics-in-Business-Project/tree/master/Python%20Files

Listing B.1: ../../Python Files/OptionVolume.py

```python
# -*- coding: utf-8 -*-
"""
Created on Wed Jun  8 18:05:55 2022
Scraping and plotting data from theocc.com
@author: leele2
"""
import pandas as pd
import matplotlib as mpl
import matplotlib.pyplot as plt
import matplotlib.dates as mdates
from datetime import datetime
from bs4 import BeautifulSoup
from os import listdir
from pathlib import Path

def string_to_int(string):
    if not string:
        return 0
    if string[0] == "$":
        string = string[1:]
    return int(string.replace(',', ''))

# Ensuring html file is on path
"""
html file taken from:
https://www.theocc.com/Market-Data/Market-Data-Reports/Volume-and-Open-Interest/Historical-Volume-Statistics
"""
html_file = [f for f in listdir('.') if f.endswith('.html')]
if len(html_file) != 1:
    raise ValueError('should be exactly one html file in the current directory')
# Importing html file
with open(html_file[0], 'r', encoding='utf-8') as file:
    soup = BeautifulSoup(file, 'lxml')
# Finding Table
table = soup.find_all("table")
# Selecting Data
table_data = table[0].find_all("tr")
# Finding Table Names
table_names = []
for names in table_data[0]:
    table_names.append(str(names.find("span").string))
del table_names[0]
del table_names[-1]
# Finding Headers
headers = []
for header in table_data[1]:
    headers.append(str(header.find("span").string))
# Populating Data
Data = {}
for rows in table_data[2:]:
    temp = {}
    for i, data in enumerate(rows):
        if i > 6 and i < 10 or i == 0:
            temp[headers[i]] = data.get_text()
    Date = datetime.strptime(temp["Date"], "%Y")
    del temp["Date"]
    Data[Date] = {k: string_to_int(v) for k, v in temp.items()}
# Converting data into pandas dataframes
Data = pd.DataFrame.from_dict(Data, orient="index")
# Plotting time-series
plt.rc('font', family='serif')
fig, ax1 = plt.subplots()
plt.gcf().set_size_inches(6, 4.5)
ax1.plot(Data['Options']/1e6, linewidth=2, zorder=1, label="Options")
# ax1.plot(Data[Data['Futures'] != 0]['Futures']/1e6, linewidth=2, zorder=1, label="Futures")
# ax1.legend()
ax1.set_title('Average Daily OptionS Trading Volume')
ax1.set_xlabel('Year')
ax1.xaxis.set_minor_formatter(mdates.DateFormatter("%Y"))
ax1.set_ylabel('Average Daily Volume (Millions)')
ax1.yaxis.set_major_formatter(mpl.ticker.StrMethodFormatter('{x:,.0f}M'))
fig.autofmt_xdate()
plt.tight_layout()
plt.show()
# Saving plot
cwd = str(Path(__file__).parent.parent.absolute())
fig.savefig(cwd + "\Latex_Files\Main\Chapters\C1\plots\OptionVolume.png", bbox_inches='tight')
```