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Using the Solver add-in in MS Excel 2007

The Excel Solver add-in is a tool that allows you to perform simple optimizations and solve equations using Excel. Within the Kellogg School, it is used in multiple courses, including Operations Management, Finance I and II, Strategic Decision Making, and Pricing Strategies, among others. This handout explains the basics of using the Solver for three examples, an operations example (a network optimization), and two finance examples (a portfolio optimization and a calculation of the "plug" in pro forma financial statements.

The most recent version of this handout and the accompanying spreadsheet (solver-tutorial.xlsx) are linked from:

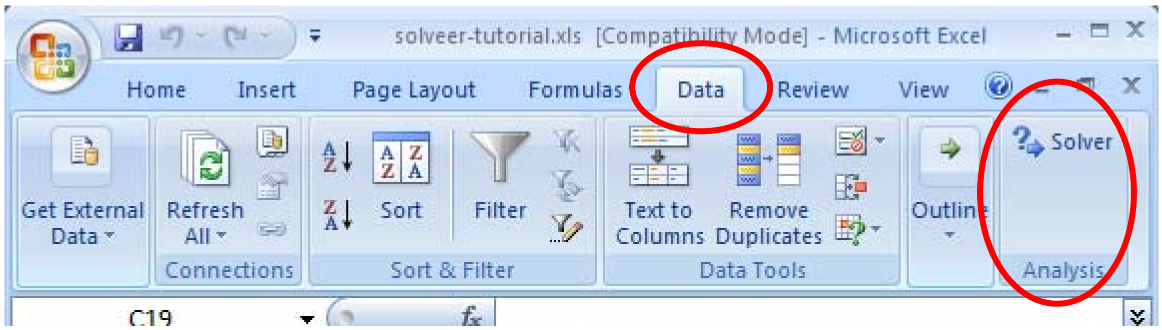
www.kellogg.northwestern.edu/researchcomputing/training.htm

Contents:

Installing the Solver add-in

To do exercises from this handout, you will need to use the "Solver" add-in for Microsoft Excel. When installed, it appears in the "Analysis" toolbar under the "Data" tab:

Figure 1. Solver Button



If the "Analysis" toolbar does not appear, or does not have the "Solver" button, the add-in must first be activated:

1. Click on the "Office" button in the top left corner: 
2. Choose "Excel Options" (Figure 2)
3. Choose "Add-Ins" in the vertical menu on the left (Figure 3)
4. Pick "Excel Add-Ins" from the "Manage" box and click "Go…" (Figure 3)
5. Check "Solver Add-In" and press "OK" (Figure 4)
6. The Solver add-in should now appear in the Analysis toolbar (Figure 1)

Figure 2. MS Office Menu

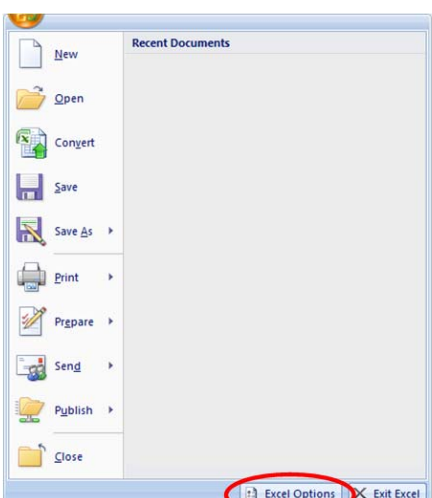


Figure 3. Excel Options Menu

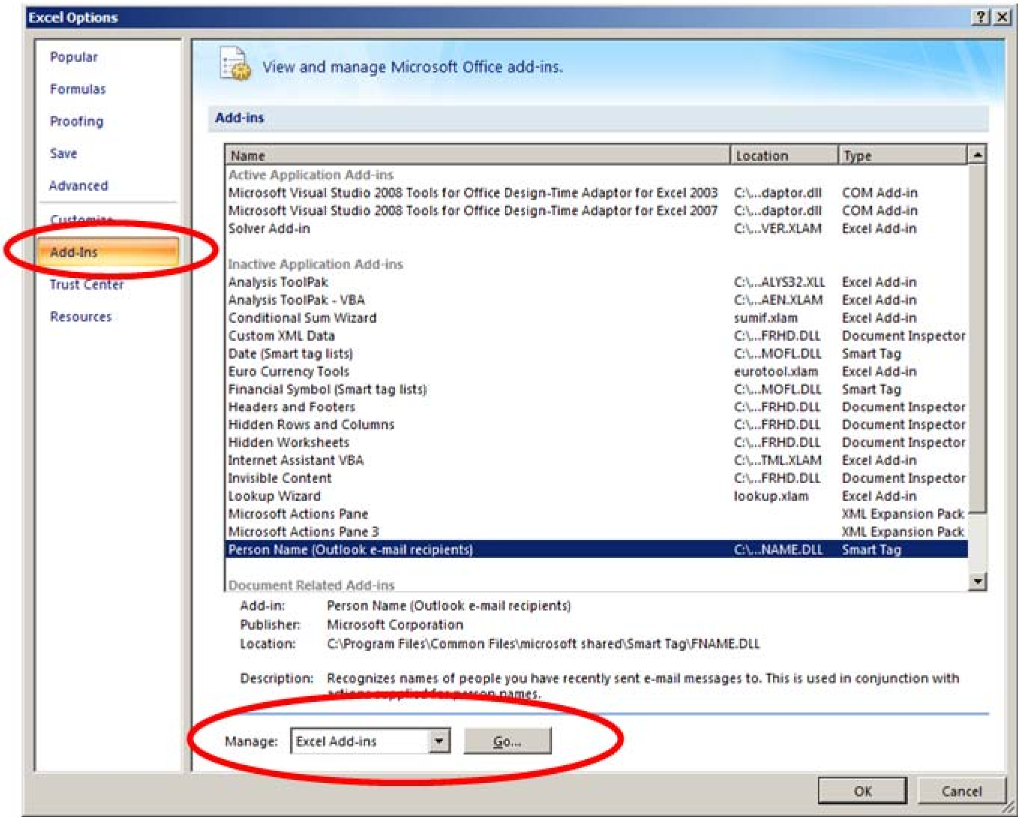
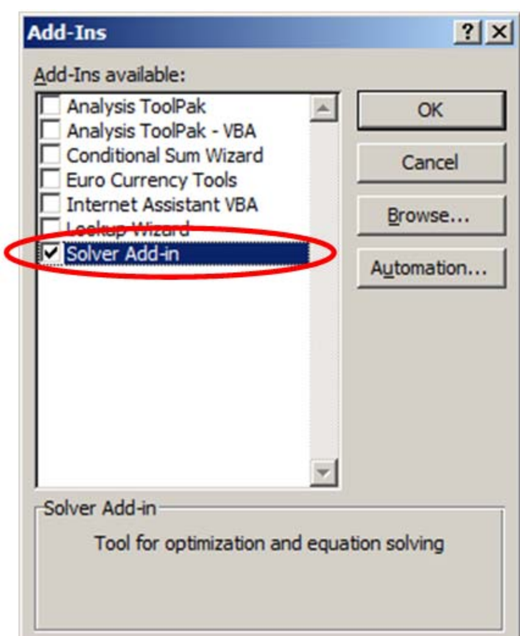


Figure 4. Add-Ins Menu



Once you have the Solver add-in working, you can proceed with the rest of this tutorial.

Example 1: SunOil – network optimization

This example is taken from Chopra & Meindl, *"Supply Chain Management"*, 3rd Ed., Pearson Prentice Hall, 2007.

STEP 0. DEFINING THE PROBLEM.

The Vice President of Supply Chain for SunOil is considering where to build new production facilities. There are five options: North and South America, Europe, Asia, and Africa. The *total* costs of production and transportation for each possible pair of "Supply" and "Demand" regions are given in the following table:

Figure 5. Cost and Demand Data for SunOil

	A	B	C	D	E	F	G	H	I	J
1	***Inputs - Costs, Capacities, Demands***									
2		*Demand Region* *Production and Transportation Cost per 1,000,000 Units*					**Fixed**	**Low**	**Fixed**	**High**
3	*Supply Region*	N. America	S. America	Europe	Asia	Africa	**Cost ($)**	**Capacity**	**Cost ($)**	**Capacity**
4	N. America	81	92	101	130	115	6,000	10	9,000	20
5	S. America	117	77	108	98	100	4,500	10	6,750	20
6	Europe	102	105	95	119	111	6,500	10	9,750	20
7	Asia	115	125	90	59	74	4,100	10	6,150	20
8	Africa	142	100	103	105	71	4,000	10	6,000	20
9	*Demand*	12	8	14	16	7				

For example, it costs $115,000 to produce 1 million units in Asia and transport them to North America. For simplicity, we assume that these costs are constant and each million units cost us the same to produce and transport.

In addition, there is a fixed cost to constructing a plant that does not depend on the production volume. There are two possible plant types: low capacity that can produce up to 10 million units a year at a fixed cost that depends on the region and is given in cells G4:G8 of Fig. 1, and high capacity that can produce up to 20 million units a year at a 50% higher fixed cost (thus exhibiting economies of scale). The associated cost and maximum capacity are given in cells I4:J8 of Figure 5.

Total demand in each region (in millions of units) is given in cells B9:F9.

We need to decide:

- How many, and what type of plants we should build in each region
- How to allocate production between them
- What markets should each plant supply

STEP 1. DESCRIBING THE SOLUTION.

Before we start the optimization, let us describe an arbitrary solution to the problem, and define the required constraints.

First, what plants to build and where?

The highlighted cells (G14:H18) in Figure 6 indicate how many plants of each type we build in each region. In this case, we suggest one small plant in North America and two large plants in South America.

Figure 6. Number and Location of Plants

	A	B	C	D	E	F	G	H
11	***Decision Variables***							
12	*Supply Region*	*Demand Region - Production Allocation (1000 Units)*					Small	Large
13		N. America	S. America	Europe	Asia	Africa	Plants	Plants
14	N. America	5	0	0	0	0	1	0
15	S. America	20	20	5	0	0	0	2
16	Europe	0	0	0	0	0	0	0
17	Asia	0	0	0	0	0	0	0
18	Africa	0	0	0	0	0	0	0

Now, *how much should we produce and where should we transport the goods?* Let us distribute the output from each location:

Figure 7. Capacity Allocation

	A	B	C	D	E	F	G	H
11	***Decision Variables***							
12	*Supply Region*	*Demand Region - Production Allocation (1000 Units)*					Small	Large
13		N. America	S. America	Europe	Asia	Africa	Plants	Plants
14	N. America	5	0	0	0	0	1	0
15	S. America	20	20	5	0	0	0	2
16	Europe	0	0	0	0	0	0	0
17	Asia	0	0	0	0	0	0	0
18	Africa	0	0	0	0	0	0	0

In cells (B14:F18) we specify that we would like to produce 5 units in North America and sell them locally. We would also like the Southern American facilities to supply 20 units locally, 20 more to North America and 5 to Asia. Unfortunately, such an arrangement is impossible as we shall see in a second.

Let us compute the *excess capacity* that we have in each region, in millions of units. It is equal to the amount produced:

[Number of Small Plants] x [Low Capacity] + [Number of Large Plants] x [High Capacity]

minus the amount transported from the region: e.g. excess capacity for North America (cell B22) is equal to [G14*H4+H14*J4-SUM(B14:F14)] (Figure 8).

Figure 8. Excess Capacity Constraint

=G14*H4+H14*J4-SUM(B14:F14)

	A	B	C	D	E	F	G	H	I	J
1	***Inputs - Costs, Capacities, Demands***									
2	*Supply Region*	*Demand Region Production and Transportation Cost per 1,000,000 Units*					**Fixed**	**Low**	**Fixed**	**High**
3		N. America	S. America	Europe	Asia	Africa	**Cost ($)**	**Capacity**	**Cost ($)**	**Capacity**
4	N. America	81	92	101	130	115	6,000	10	9,000	20
5	S. America	117	77	108	98	100	4,500	10	6,750	20
6	Europe	102	105	95	119	111	6,500	10	9,750	20
7	Asia	115	125	90	59	74	4,100	10	6,150	20
8	Africa	142	100	103	105	71	4,000	10	6,000	20
9	*Demand*	12	8	14	16	7				
10										
11	***Decision Variables***									
12	*Supply Region*	*Demand Region - Production Allocation (1000 Units)*					Small	Large		
13		N. America	S. America	Europe	Asia	Africa	Plants	Plants		
14	N. America	5	0	0	0	0	1	0		
15	S. America	20	20	5	0	0	0	2		
16	Europe	0	0	0	0	0	0	0		
17	Asia	0	0	0	0	0	0	0		
18	Africa	0	0	0	0	0	0	0		
19										
20	***Constraints***									
21	*Supply Region*	*Excess Capacity*								
22	N. America	5								
23	S. America	-5								
24	Europe	0								
25	Asia	0								
26	Africa	0								

Here, the excess capacity is equal to 5, meaning that we produce 5 units fewer in North America than our capacity allows. Similarly we can compute the excess capacity for other regions and see that we allocated 45 units to be transported from South America whereas we can produce only 40 there, resulting in negative excess capacity. This discrepancy will be fixed when we have Excel solve the problem for us.

We can also compute the *unmet demand* in each region, equal to the initial demand minus the total amount of units transported there (Figure 9):

Figure 9. Unmet Demand

=B9-SUM(B14:B18)

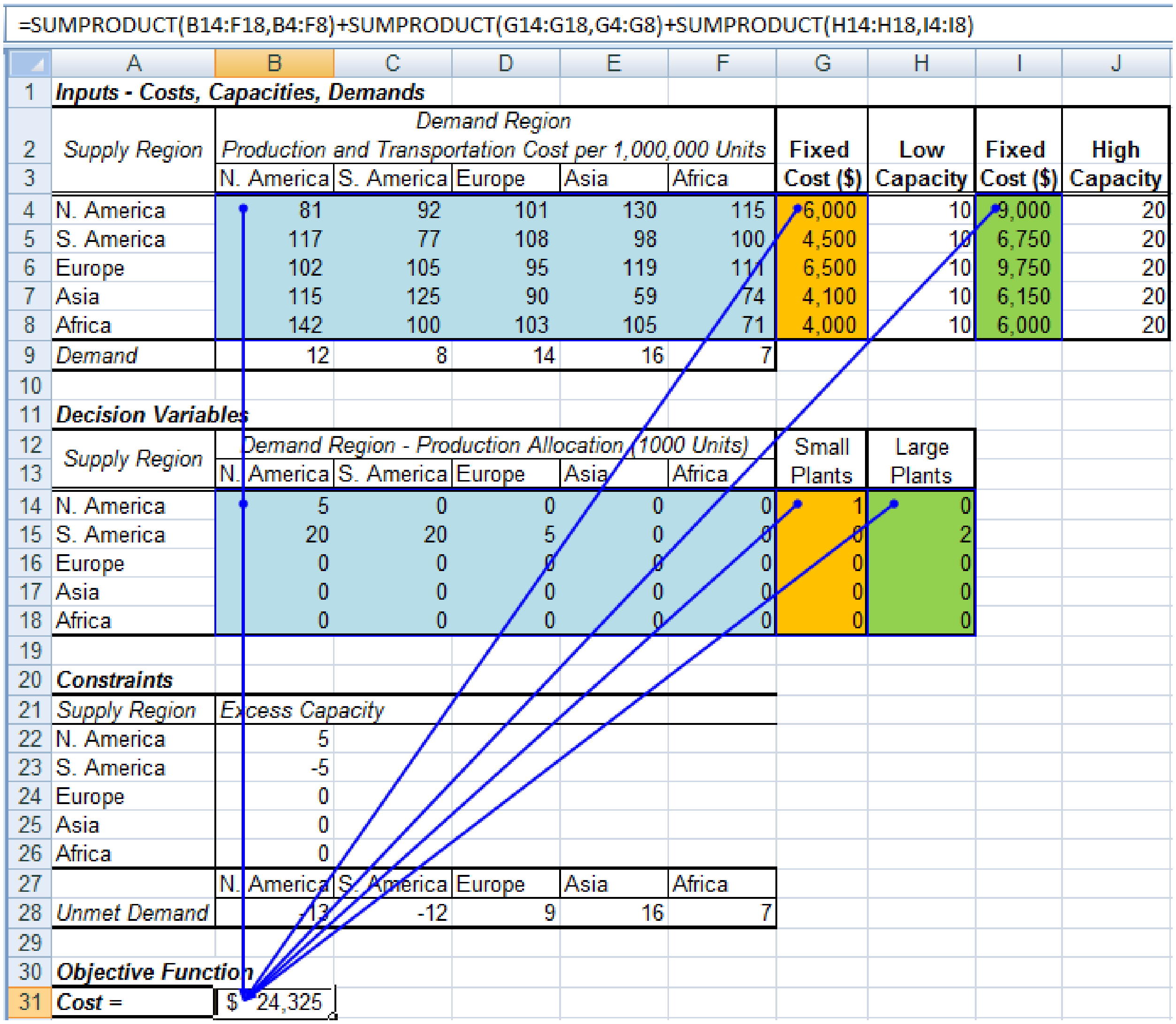
	A	B	C	D	E	F	G	H	I	J
1	***Inputs - Costs, Capacities, Demands***									
2	*Supply Region*	*Demand Region Production and Transportation Cost per 1,000,000 Units*					**Fixed**	**Low**	**Fixed**	**High**
3		N. America	S. America	Europe	Asia	Africa	**Cost ($)**	**Capacity**	**Cost ($)**	**Capacity**
4	N. America	81	92	101	130	115	6,000	10	9,000	20
5	S. America	117	77	108	98	100	4,500	10	6,750	20
6	Europe	102	105	95	119	111	6,500	10	9,750	20
7	Asia	115	125	90	59	74	4,100	10	6,150	20
8	Africa	142	100	103	105	71	4,000	10	6,000	20
9	*Demand*	12	8	14	16	7				
10										
11	***Decision Variables***									
12	*Supply Region*	*Demand Region - Production Allocation (1000 Units)*					Small	Large		
13		N. America	S. America	Europe	Asia	Africa	Plants	Plants		
14	N. America	5	0	0	0	0	1	0		
15	S. America	20	20	5	0	0	0	2		
16	Europe	0	0	0	0	0	0	0		
17	Asia	0	0	0	0	0	0	0		
18	Africa	0	0	0	0	0	0	0		
19										
20	***Constraints***									
21	*Supply Region*	*Excess Capacity*								
22	N. America	5								
23	S. America	-5								
24	Europe	0								
25	Asia	0								
26	Africa	0								
27		N. America	S. America	Europe	Asia	Africa				
28	*Unmet Demand*	-13	-12	9	16	7				

We can see that we have excess supply in some regions and unmet demand in others.

The *total cost of production* is equal to the sum of variable costs (equal to the sum of cell-by-cell product of unit costs and amounts produced) and fixed costs. In the screenshot below, note how the SUMPRODUCT function is used to compute the total variable cost:

:

Figure 10. Objective (Cost) Function



=SUMPRODUCT(B14:F18,B4:F8)+SUMPRODUCT(G14:G18,G4:G8)+SUMPRODUCT(H14:H18,I4:I8)

	A	B	C	D	E	F	G	H	I	J
1	*Inputs - Costs, Capacities, Demands*									
2	*Supply Region*	*Demand Region Production and Transportation Cost per 1,000,000 Units*					Fixed Cost ($)	Low Capacity	Fixed Cost ($)	High Capacity
3		N. America	S. America	Europe	Asia	Africa				
4	N. America	81	92	101	130	115	6,000	10	9,000	20
5	S. America	117	77	108	98	100	4,500	10	6,750	20
6	Europe	102	105	95	119	111	6,500	10	9,750	20
7	Asia	115	125	90	59	74	4,100	10	6,150	20
8	Africa	142	100	103	105	71	4,000	10	6,000	20
9	*Demand*	12	8	14	16	7				
10										
11	*Decision Variables*									
12	*Supply Region*	*Demand Region - Production Allocation (1000 Units)*					Small Plants	Large Plants		
13		N. America	S. America	Europe	Asia	Africa				
14	N. America	5	0	0	0	0	1	0		
15	S. America	20	20	5	0	0	0	2		
16	Europe	0	0	0	0	0	0	0		
17	Asia	0	0	0	0	0	0	0		
18	Africa	0	0	0	0	0	0	0		
19										
20	*Constraints*									
21	*Supply Region*	*Excess Capacity*								
22	N. America	5								
23	S. America	-5								
24	Europe	0								
25	Asia	0								
26	Africa	0								
27		N. America	S. America	Europe	Asia	Africa				
28	*Unmet Demand*	-13	-12	9	16	7				
29										
30	*Objective Function*									
31	*Cost =*	$ 24,325								

STEP 2. OPTIMIZATION

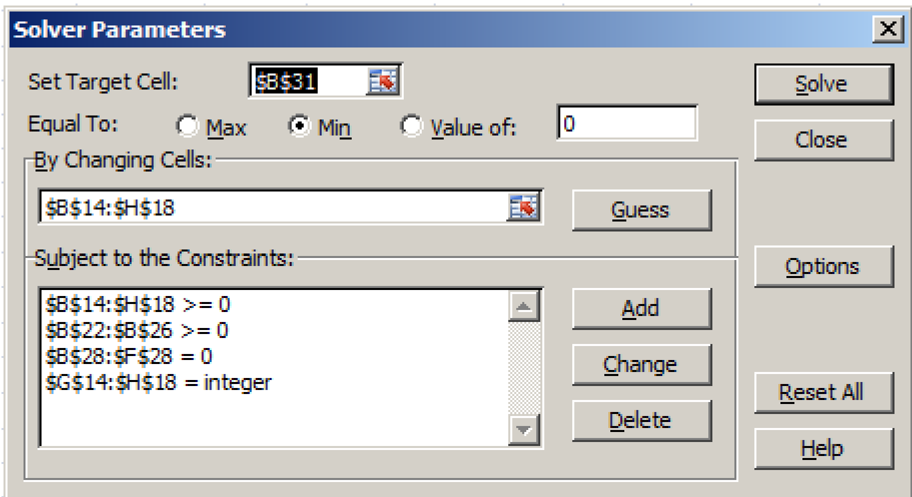
We will use the “solver” tool to find the optimal allocation. Our purpose is to find a cost-minimizing allocation by changing decision variables (B14:H18). Let us bring up the “Solver” window by clicking the “Solver” button (Figure 1) and enter the problem (just select cells in the spreadsheet to enter a reference to them):

- “Target Cell”: B31 (total cost)
- “Equal To”: Min (cost minimization)
- “By changing cells”: B14:H18

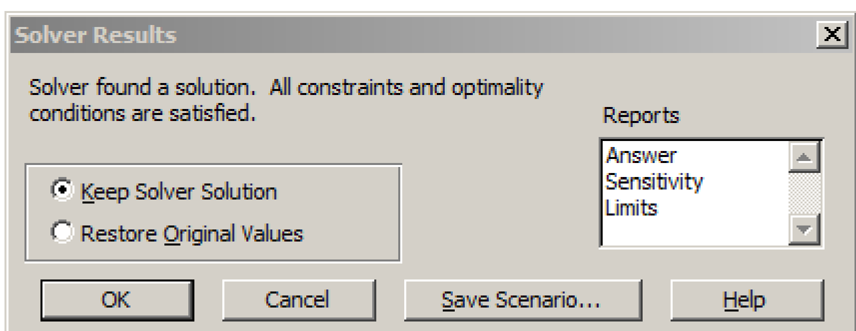
The allocation should also be feasible, meaning that we also enter some constraints (press “Add” to add a new constraint):

- The number of plants and the amount produced in each region are not negative: B14:H18 >= 0
- Excess capacity is not negative: B22:B26 >= 0
- All demand is satisfied: B28:F28 = 0
- We cannot build fractional plants: G14:H18 = integer

Figure 11. Solver Window



Press "Solve" to obtain a solution (choose "Keep Solver Solution" in the pop-up box):



The final result is shown in Figure 12:

Figure 12. Optimal Allocation

	A	B	C	D	E	F	G	H
11	***Decision Variables***							
12	*Supply Region*	*Demand Region - Production Allocation (1000 Units)*					Small Plants	Large Plants
13		N. America	S. America	Europe	Asia	Africa		
14	N. America	0	0	0	0	0	0	2.4E-14
15	S. America	0	0	0	0	0	0	0
16	Europe	0	0	0	0	0	0	0
17	Asia	12	0	12	16	0	0	2
18	Africa	0	8	2	0	7	0	1
19								
20	***Constraints***							
21	*Supply Region*	*Excess Capacity*						
22	N. America	0						
23	S. America	0						
24	Europe	0						
25	Asia	0						
26	Africa	3						
27		N. America	S. America	Europe	Asia	Africa		
28	*Unmet Demand*	0	0	0	0	0		
29								
30	***Objective Function***							
31	***Cost =***	**$ 23,207**						

The solution calls for two plants in Asia and one in Africa, all of high capacity type. The Asian plant will supply North America, Europe and Asia itself, and the African plant will supply South America, Europe and Africa.

Note that there is a small capacity underutilization at the African plant, but all demand is met, at a total cost of $23.2 million. This is due to our inability to build “fractional” plants, i.e. increase capacity in smaller units. If we were able to do so, we could disregard the integer constraint:

Figure 13. Removing the Integer Constraint

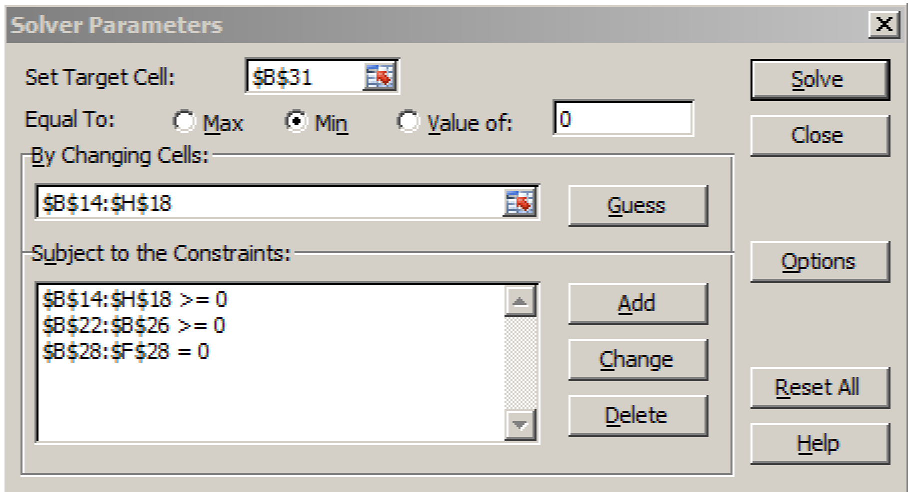


Figure 14. Optimal Fractional Solution

	A	B	C	D	E	F	G	H
11	***Decision Variables***							
12	*Supply Region*	*Demand Region - Production Allocation (1000 Units)*					Small Plants	Large Plants
13		N. America	S. America	Europe	Asia	Africa		
14	N. America	0	0	0	0	0	0	2.4E-14
15	S. America	0	0	0	0	0	0	0
16	Europe	0	0	0	0	0	0	0
17	Asia	12	0	14	16	0	0	2.1
18	Africa	0	8	0	0	7	0	0.75
19								
20	***Constraints***							
21	*Supply Region*	*Excess Capacity*						
22	N. America	0						
23	S. America	0						
24	Europe	0						
25	Asia	0						
26	Africa	0						
27		N. America	S. America	Europe	Asia	Africa		
28	*Unmet Demand*	0	0	0	0	0		
29								
30	***Objective Function***							
31	***Cost =***	**$ 22,296**						

As we see, had we been able to build fractional plants, we could have achieved full capacity utilization and lowered the cost. However when we are not, “integer” restriction on the number of plants is necessary to produce sensible results.

Example 2: Portfolio Optimization

Consider[1] a world where two stocks are traded: Amazon (AMZ) and McDonalds (MCD). What would be the optimal way to construct a portfolio of these stocks for an investor who cares about expected returns and their variance?

This problem is setup in the “Portfolio Optimization” tab of “solver-tutorial.xlsx”.

PROBLEM:

The expected return on Amazon (AMZ) equity is r_{AMZ} = 25 percent, with a standard deviation σ_{AMZ} = 75 percent; the expected return on McDonalds (MCD) equity is r_{MCD} = 10 percent, with a standard deviation σ_{MCD} = 25 percent. The correlation coefficient is ρ=.25 and the risk free rate is r_f = 3%. Find the mean-variance efficient portfolio.

SOLUTION:

The covariance between the two securities $Cov(r_{AMZ},r_{MCD}) = \rho\ \sigma_{AMZ}\,\sigma_{MCD} \approx 0.0469$ (cell G1).

If the weight of AMZ in the optimal portfolio is equal to a fraction x_{AMZ} (cell K2), then:

- The weight of MCD is the remainder of the portfolio, $x_{MCD} = 1\text{-}x_{AMZ}$ (cell L2)
- The portfolio variance $\sigma_P = (\sigma_{AMZ}\,x_{AMZ} + x_{MCD}\,\sigma_{MCD} + 2\ x_{AMZ}\ x_{MCD}\ Cov(r_{AMZ},r_{MCD}))^{1/2}$ (cell M2)
- The portfolio expected return: $E(r_P) = r_{AMZ}\,x_{AMZ} + r_{MCD}\,x_{MCD}$ (cell N2)
- Sharpe ratio $S = (E(r_P) - r_f) / \sigma_P$ (cell O2)

For example, an equal-weighted portfolio (i.e. $x_{MCD} = x_{AMZ} = .5$) has variance of about 42.4% (Figure 15).

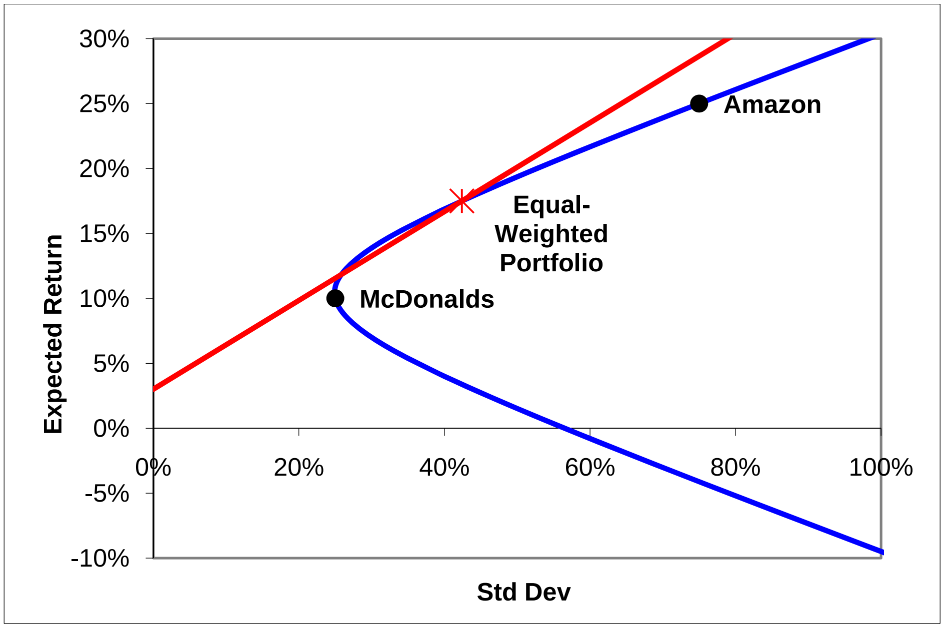
Figure 15. Equal-Weighted Portfolio

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1		sig	E(r)		rhoAMZ,McD	Rf	covAMZ,McD		*MVE Port:*		xAMZ	xMcD	sigP	E(rP)	SR
2	Amazon	75%	25%		0.25	3%	0.046875		(use Solver)		0.5	0.5	0.4239	0.1750	0.342065
3	McDonalds	25%	10%												

The blue line in Figure 16 shows all possible return/standard deviation combinations that one can obtain by combining the two stocks with different weights, and the red line shows the possible combinations of the equal-weighted portfolio with the risk-free asset. Obviously, the equally-weighted portfolio is not mean-variance efficient: part of the blue line lies above the red one and thus some portfolios have a higher Sharpe ratio.

[1] Example derived from Professor Andrew Hertzberg’s lecture notes for Finance I.

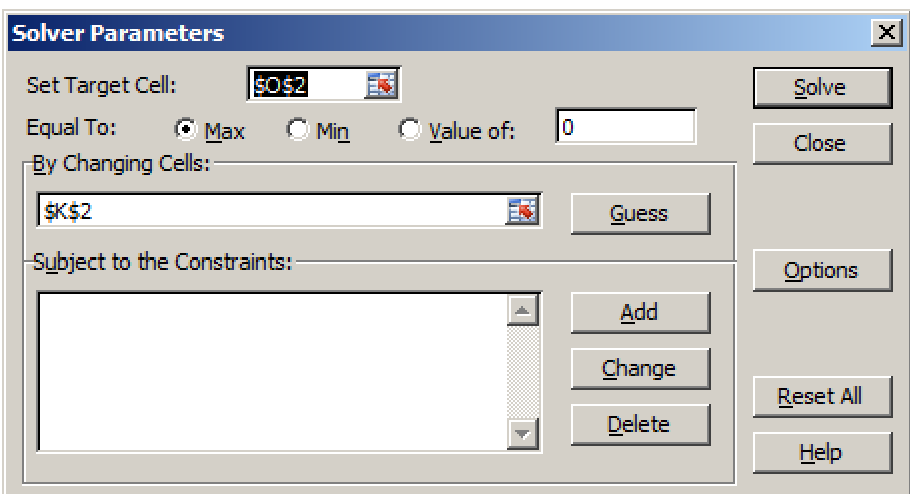
Figure 16. Suboptimality of an Equal-Weighted Portfolio.



Let us solve for the optimal asset allocation. We will again use the Solver tool:

- "Target Cell": O2 (Sharpe ratio)
- Set it "Equal To": Max
- By Changing Cells: K2 (AMZ weight)

Figure 17. Solver Parameters for Portfolio Optimization

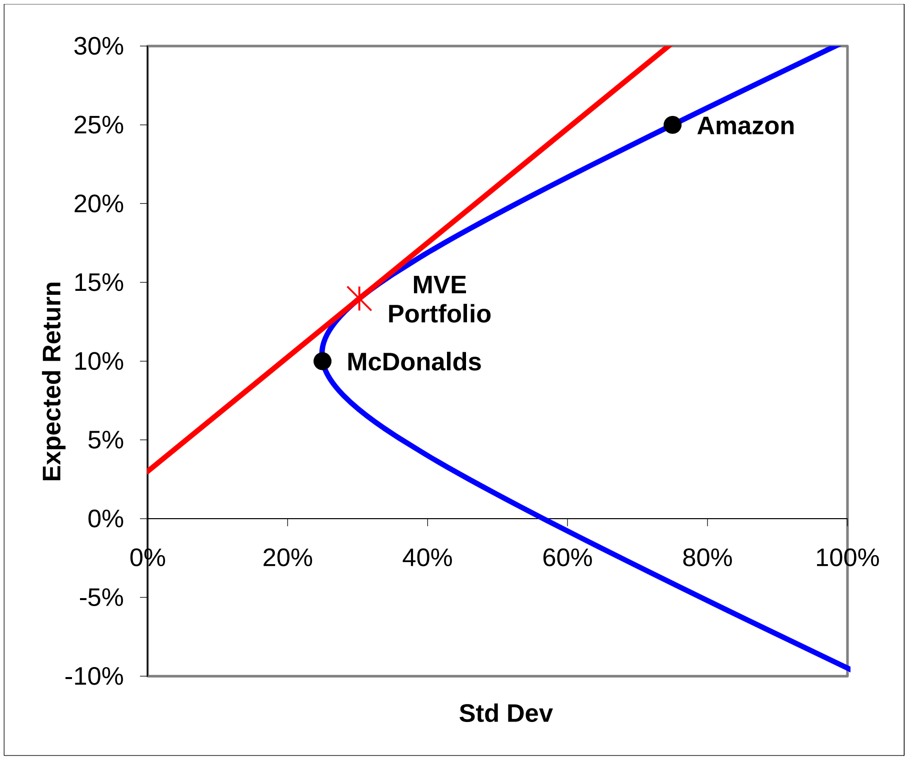


Click on the "Solve" button to obtain:

	I	J	K	L	M	N	O
1	*MVE Port:*		xAMZ	xMcD	sigP	E(rP)	SR
2	(use Solver)		0.26482	0.735178	0.3025	0.1397	0.362771

Thus, the mean-variance efficient (MVE) portfolio has about 26.5% of Amazon stock. This portfolio clearly maximizes the Sharpe ratio:

Figure 18. Mean-Variance Efficient Portfolio



Example 3: Calculating the "plug" in pro forma statements

Pro formas are predictions of the firm's future financial statements (balance sheet and income and cash flow statements). It is important for them to be consistent with accounting rules.

Typically some fields are forecasted independently (*e.g.* from assumptions on growth rates or financial ratios), while others are calculated from them. A "Debt (Bank) Plug" field serves to "close the model", *i.e.* to ensure that the forecasted assets are equal to the sum of liabilities and equity.

Let us consider a concrete example[2].

[2] Derived from Profesor Andrea Eisfeldt's lecture notes for Finance II

COMPUTING DEBT PLUG: METHOD 1 (USING SOLVER)

Figure 19 shows the actual balance sheet of Au Bon Pain (ABP) for 1997, and forecasted values of sales, expenses, total assets, other liabilities, and planned dividends for 1998. The corporate tax rate is 34% and the cost of debt is 10%:

Figure 19. Au Bon Pain: 1997 Results and 1998 Forecast

Income Statement	**1997**	**1998 Pro-Forma**
Sales		10,000.00
COGS+operating expense		8,000.00
Interest expense		
Net income before tax		
Tax		
Net income after tax		
Dividends		50.00
ΔRetained earnings		
Balance Sheets		
Assets		
Total Assets	1,800.00	3,000.00
Liabilities		
Bank loan	300.00	
Other liabilities	1,000.00	1,500.00
Total liabilities	1,300.00	
Retained earnings	500.00	
Total liabilities and equity	1,800.00	

Let us suppose that the value of the bank loan by the end of 1998 is zero. We can then fill in the rest of the balance sheet and the income statement (the calculated values are in italic).

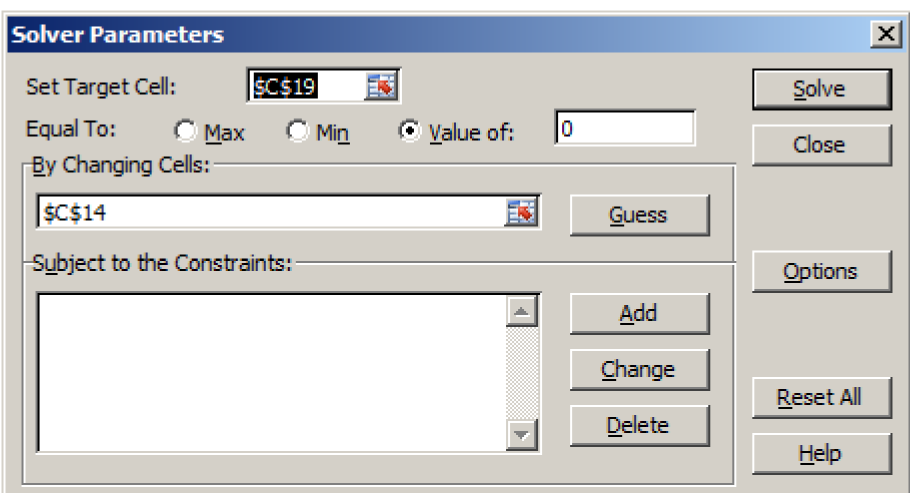
We compute the interest expense as the average value of the bank loan in 1998, equal to (300+0)/2, multiplied by the cost of debt of 10% (Figure 20):

Figure 20. ABP: 1998 Pro-Forma with zero PLUG

	A	B	C	D
1	**Income Statement**	**1997**	**1998 Pro-Forma**	**Notes**
2	Sales		10,000.00	
3	COGS+operating expense		8,000.00	
4	Interest expense		*15.00*	Interest expense at 10% of avg. balance
5	Net income before tax		*1,985.00*	
6	Tax		*674.90*	Assuming a 34% tax rate
7	Net income after tax		*1,310.10*	
8	Dividends		50.00	Given
9	ΔRetained earnings		*1,260.10*	
10	**Balance Sheets**			
11	*Assets*			
12	Total Assets	1,800.00	3,000.00	
13	*Liabilities*			
14	Bank loan	300.00	-	
15	Other liabilities	1,000.00	1,500.00	
16	Total liabilities	1,300.00	*1,500.00*	
17	Retained earnings	500.00	*1,760.10*	
18	Total liabilities and equity	1,800.00	*3,260.10*	
19	**Discrepancy [A-(L+E)]**	-	***(260.10)***	

Note that the books do not add up and there is a discrepancy between assets and liabilities. To close the model, we need to compute the amount of additional financing the company will need in 1998 to support the forecasted growth. In other words, we need to find such a value for the bank loan (B14) that would result in zero discrepancy (C19):

Figure 21. Solver options to find the PLUG



Press "Solve" to obtain the solution:

Figure 22. Solution: 1998 Pro-Forma and PLUG

Income Statement	1997	1998 Pro-Forma
Sales		10,000.00
COGS+operating expense		8,000.00
Interest expense		*15.00*
Net income before tax		*1,985.00*
Tax		*674.90*
Net income after tax		*1,310.10*
Dividends		50.00
ΔRetained earnings		*1,260.10*
Balance Sheets		
Assets		
Total Assets	1,800.00	3,000.00
Liabilities		
Bank loan	300.00	-
Other liabilities	1,000.00	1,500.00
Total liabilities	1,300.00	*1,500.00*
Retained earnings	500.00	*1,760.10*
Total liabilities and equity	1,800.00	*3,260.10*
Discrepancy [A-(L+E)]	**-**	***(260.10)***

So, the forecasted growth will not require any additional bank financing (PLUG = -269).

COMPUTING DEBT PLUG: METHOD 2 (CIRCULAR REFERENCE RESOLUTION)

An alternative way to do the same thing, which does not rely upon using the Solver add-in, is to allow circular references and have Excel iteratively find the solution. That option has to be enabled first:

1. As with Solver, click the Microsoft Office button and chose "Excel Options" (Figure 2)

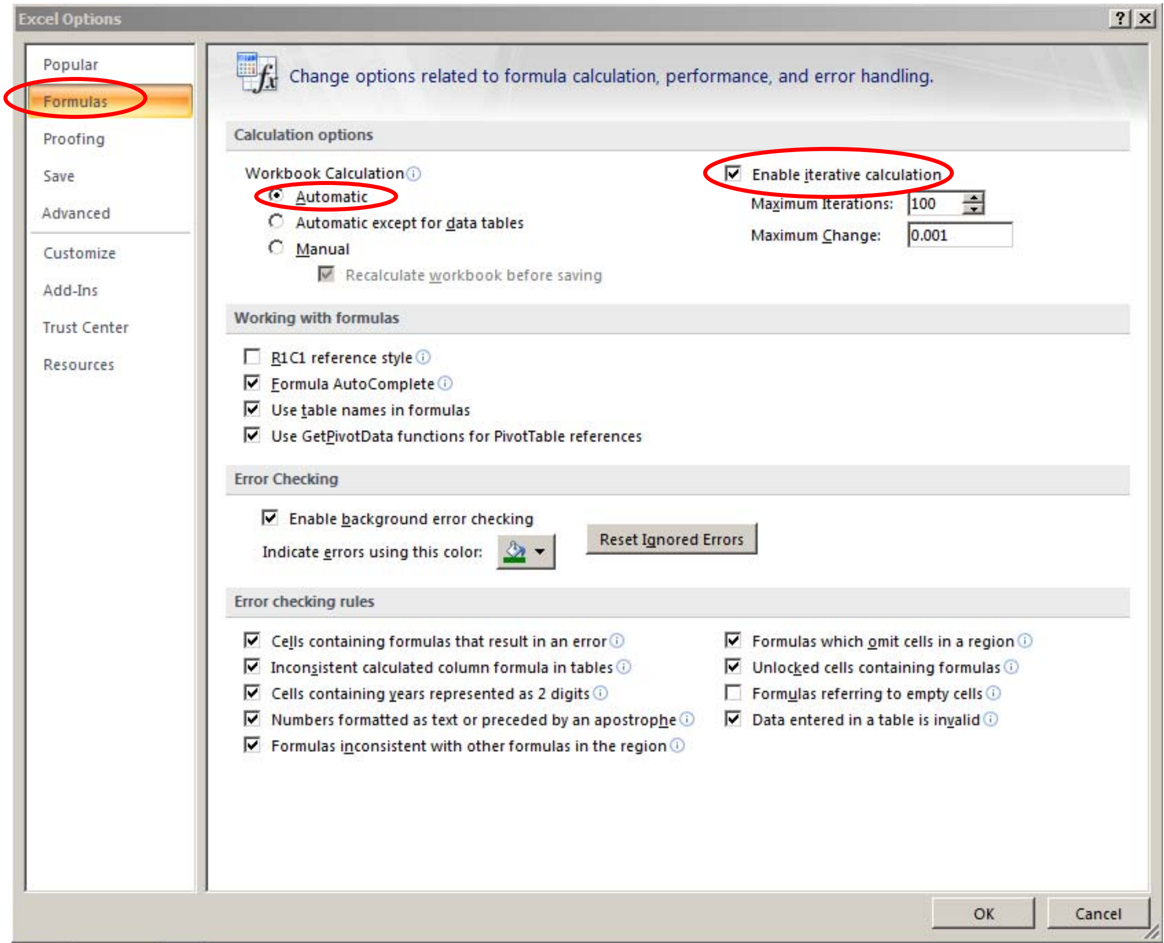
2. Check "Enable iterative calculations" under "Formulas" tab[3] (Figure 23)

3. Set "Workbook Calculation" to "Automatic"

4. Press OK

[3] The lower is the "Min. Change", the more precise is the solution, and the longer it takes to find it. Increasing "Max. Iterations" allows Excel to take longer to find the solution.

Figure 23. Enabling iterative calculations



Once the iterative calculations are enabled, we can enter circular cross-references and Excel will resolve them. In this case, we can compute PLUG knowing Total Assets, Other Liabilities and Retained Earnings for 1998:

(PLUG) = (Assets) – (Liabilities) – (Retained Earnings)

which will force the discrepancy to 0 (Figure 24).

If we have set the “Workbook Calculations” option in Excel to “Automatic”, it will automatically find the solution for PLUG.

Otherwise (or if you just opened a new spreadsheet and didn’t choose to resolve circular references) you can press F9 to compute the solution[4]. Generally you might want automatic resolution for simplicity, but if your spreadsheet is overly complicated and takes a lot of time to process, you may want to switch to manual updates, in which case you would have to press F9

[4] You may have to repeat this a few times.

every time you make a circular reference. This may also be necessary if you have just opened an existing spreadsheet.

Figure 24. Entering a circular reference

C14 | f_x =C12-C15-C17

	A	B	C
1	**Income Statement**	**1997**	**1998 Pro-Forma**
2	Sales		10,000.00
3	COGS+operating expense		8,000.00
4	Interest expense		*1.55*
5	Net income before tax		*1,998.45*
6	Tax		*679.47*
7	Net income after tax		*1,318.98*
8	Dividends		50.00
9	ΔRetained earnings		*1,268.98*
10	**Balance Sheets**		
11	*Assets*		
12	Total Assets	1,800.00	3,000.00
13	*Liabilities*		
14	Bank loan	300.00	*(268.98)*
15	Other liabilities	1,000.00	1,500.00
16	Total liabilities	1,300.00	*1,231.02*
17	Retained earnings	500.00	*1,768.98*
18	Total liabilities and equity	1,800.00	*3,000.00*
19	**Discrepancy [A-(L+E)]**	-	-

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