MSc Project Specification and Proposed Design

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SUMMARY OF PROPOSAL

- This project seeks, through computational methods, to find a solution to a fundamental problem in macroeconomic policy: 'the Monetary Policy Trilemma' (known variously as the 'Impossible Trinity', the 'Trilemma' or 'the Mundell-Fleming trilemma').
- The Trilemma is a theoretical deduction with empirical basis which states that governments cannot simultaneously pursue these three desirable policy objectives because one needs to be sacrificed for the other two to be possible:
    - A fixed exchange rate.
    - Sovereign monetary policy (an independent/autonomous monetary policy).
    - Free capital flow.
- I seek to show, via computational simulation (Agent-Based Model), how having agents optimise their heterogeneous expectations-management preferences through using multiple monies freely (rather than being constrained to one currency by means of various institutions) could enable the Trilemma to be overcome.
- Since no constraints will be imposed upon capital flow (and, therefore, it can move freely), the project will involve testing the degree to which some exchange rates can be fixed and some monetary policies can be autonomous in various (pseudo-randomly generated) simulations. This will involve examining what happens when the money supply is drastically increased for some money or monies and observing whether there are at least some bilateral and/or multi-lateral exchange rates that remain 'fixed'. All the (implicit) parameters within this proposed method of hypothesis-testing can be varied accordingly to draw further insights regarding the extent to which multiple monies can 'solve' the Trilemma.
- The research on this topic seeks to formalise the research I have previously undertaken and articles I have previously written for think tanks and media outlets. More precisely, I have written on monetary reform for think tanks such as the Adam Smith Institute, the Cobden Centre and the Center for a Stateless Society (C4SS). For the Cobden Centre, I have produced a body of work on monetary reform and the benefits of multiple monies. However, owing to the nature of the Austrian School of Economics (which the Cobden Centre is based around), I believe that these theoretical arguments would be substantially strengthened if they were formalised mathematically and through computational simulation.
- Most recently, I have cited numerous instances of my research and articles published thus far (whether it be for the Cobden Centre, The Market Mogul or the Center for a Stateless Society (C4SS)) in written evidence submitted to the House of Commons' Treasury Committee (which is charged with holding the Bank of England, HM Treasury and the FCA to account) for their inquiry into the 'Effectiveness and impact of post-2008 UK monetary policy' and my written evidence was ordered to be published on the 18th April 2017 by the Treasury Committee.
- As such, this is a natural and much-needed evolution in my ongoing (policy-relevant and political) research agenda in monetary reform and policy – acting both as an alternative grounding and as an extension.

DESIGN

Model Parameters and Hypothesis Testing

After having discussed a range of options for this project with Rahul, the MESA framework sounded promising for this project (as opposed to coding an ABM from scratch in Python) and, upon reading the conference paper by David Masad and Jacqueline Kazil entitled "Mesa: An Agent-Based Modeling Framework" and published in the *Proceedings of the 14th Python in Science Conference (SCIPY 2015),* this introduction to MESA looks very promising and I believe that this will save a lot of time and enable maximum scientific progress. Rahul also discussed *pandas* in Python as being a useful tool for data analysis and modelling. Thus, the plan is to use this for the data analysis.

Parameters: Number of money-demanding agents, Number of money-supplying agents, number of monies (which is exactly equal to the number of money-supplying agents), amount of money injected in (as if it was 'helicopter money'), distribution of helicopter money, number of agents that receive helicopter money, Total amount of money initially in circulation within the system, distribution of initial monies across agents (equal or otherwise), the initial amount of each money in the system, expectations-formation mechanism for each agent.

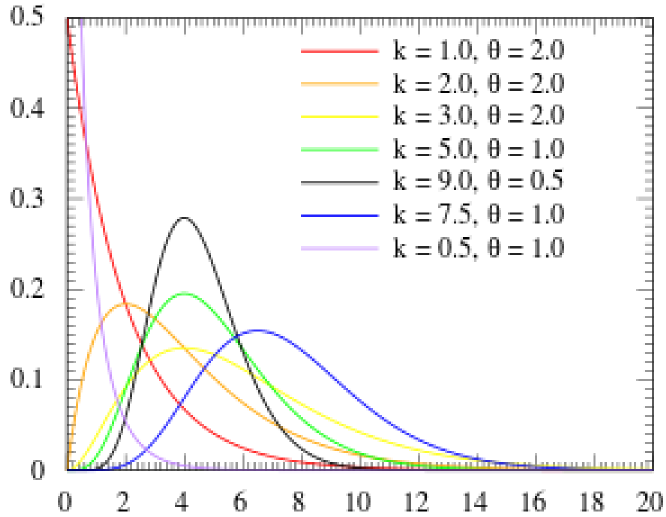
As Obstfeld, Shambaugh and Taylor (2004) note, "[In] practice, "fixed" exchange rates are fixed only up to a possibly narrow fluctuation band…" and they state that "their methodology for selecting *de facto* pegs has allowed for this". They go on to say that they "experimented with simulations of an extension of Krugman's (1991) target zone model, using Svensson's (1991) term-structure model to derive interest rates for non-infinitesimal maturities when the fluctuation band is quite narrow $(\pm 1\%)$". Thus, our benchmark for an exchange rate being effectively 'fixed' from one step to another will conform to this 1% interval either side of the exchange rate.

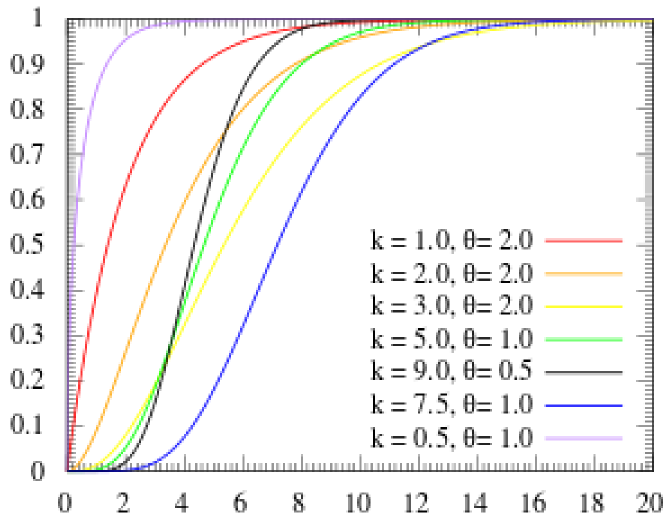
Hypothesis Testing – Compare the value of every bilateral and multi-lateral exchange rate within the model to its value in the previous period and, if it is within the $\pm 1\%$ fluctuation band, then we consider this a positive (successful) result (i.e it is a suitably 'fixed' exchange rate). We then measure the proportion of fixed exchange rates over all exchange rates. Thus, if an exchange rate at time t, ϵ_t is such that $0.99 \leq \frac{\epsilon_t}{\epsilon_{t-1}} \leq 1.01$ then this has tested positive for a fixed exchange rate within a narrow fluctuation band.

We now proceed to the outlines of key processes and/or, where appropriate, the pseudocode.

Distributions for Money-Demanding Agents' Heterogeneous Preferences over Interest Rates and Exchange Rates

As I discussed with my proposal with Rahul to have agents assign various weights that signify the value they place on each interest rate such that their sum is equal to one (and, similarly, to do this for exchange rates). One suggestion he made for this was to use gamma distributions and, upon reflection, I believe this would be ideal. The following charts are from Wikipedia and represent the probability density function and cumulative distribution function respectively. As such, each money-demanding agent would have preferences over exchange rates that would be represented by a Gamma distributions (where the k and θ values are generated randomly with, say for example, $k \in (0,10]$ and $\theta \in (0,2]$ as in the following charts).





A natural question here about the Gamma distribution over the exchange rates (specifically, which exchange rates should the Gamma distribution represent preferences over). In this case, there were two alternatives – to either have multiple Gamma distributions across all the possible bilateral and multilateral exchange rates or to simply have a Gamma distribution over a single, multilateral exchange rate. The former may have made sense for a model with fewer monies but, when the number of monies increases substantially (since this is a parameter) then it will rapidly grow in complexity. Instead, for the sake of simplicity, preserving computational capacity (at least initially) and reducing runtime, the exchange rate over which money-demanding agents have a randomly-generated Gamma distribution of preferences over will be a weighted, multilateral exchange rate with all other monies except that money which is held.

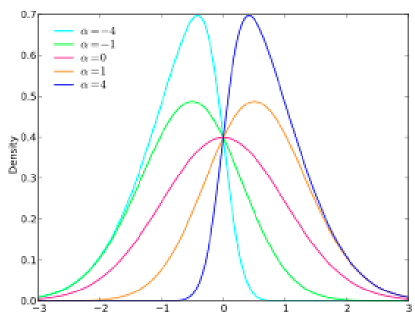
More formally, let M be the number of monies in the system. Then the multilateral weighted-average exchange rate of a money $m \in \{1, \dots, M\}$ is $\overline{\epsilon_m}$; this is the weighted average exchange rate of all the other monies (weighted according to the total amount of each money in the system). Let $\epsilon_m^1, \epsilon_m^2, \dots, \epsilon_m^{m-1}, \epsilon_m^{m+1}, \dots, \epsilon_m^M,$ be the exchange rates of that money m with respect to all monies except m (since the exchange rate with respect to itself would simply equal one). Let $M_1^S, M_2^S, \dots, M_{m-1}^S, M_{m+1}^S, \dots, M_M^S$ be the total amount of each of the monies respectively within the system (except money m) and across all agents. Then, the multilateral, weighted-average exchange rate that the Gamma distribution represents preferences over is given by:

$$\overline{\epsilon_m} = \frac{(M_1^S \times \epsilon_m^1) + \cdots + (M_{m-1}^S \times \epsilon_m^{m-1}) + (M_{m+1}^S \times \epsilon_m^{m+1}) + \cdots (M_M^S \times \epsilon_m^M)}{M-1}$$

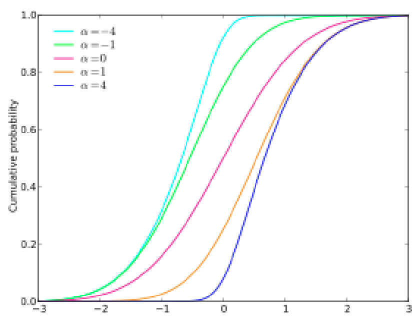
Nevertheless, based on the adapted interest-parity condition (mentioned later under the sub-heading entitled 'The Price-determination Mechanism for Interest Rates and Exchange Rates'), there is the possibility of negative interest rates. Therefore, there is a need for a probability distribution allows for a negative support (rather than a purely non-negative support like the Gamma distribution). After e-mail correspondence with Rahul regarding this difficulty, he said an alternative could be (Skew) Normal distributions. As such, the preferences for money-demanding agents over interest rates are represented by pseudo-randomly generated (Skew) Normal distributions to represent each money-demanding agent's preferences over interest rates. Examples of Skew Normal distributions are as follows:

Skew Normal

Probability density function



Cumulative distribution function



Another alternative to Gamma and Normal distributions discussed with Rahul was [to randomly sample from the unit simplex in a way that the random sampling is not skewed before normalising] (to determine the preferences for various interest rates and exchange rates) but, looking at the shapes of the Gamma distributions and Skew Normal distributions, they seem to be more fit for purpose here.

Distributions of Money-Supplying Agents' Heterogeneous Preferences over Interest Rates and Exchange Rates

We are left to represent the money-supplying agents' heterogeneous preferences over interest rates and exchange rates. More precisely, it should be that their preferences are concerning the interest rate and exchange rates of the monies which they supply (a sort of 'target' preference). Let us presume that the money-supplying agents also have these preferences over interest rates and exchange rates represented by Skewed Normal and Gamma distributions respectively. For the interest rate, it would just be their money's own interest rate and, for the exchange rate, it would be the multi-lateral weighted average exchange rate of the money that it issues compared to all the other monies as was previously described. Presuming the money-supplying agents place equal weight on their interest rate and exchange rate preferences, their maximisation problem would be as follows (where m denotes the money they issue and $SN(i_t^m)\ and\ \gamma(\epsilon_t^m)$ are the values corresponding to the Skewed Normal and Gamma distribution values for the interest rate and exchange rate at that time t respectively):

$$\max_{i_t^m, \epsilon_t^m} \ SN(i_t^m) + \gamma(\epsilon_t^m)$$

Of course, since money-supplying agents cannot directly change the interest rates and exchange rates (they are a function of the money-supply and money-demand of their own monies as well as the money-supply and money-demand of all other monies) and, thus, they can only maximise this with respect to the money-supply of their own money M_m^S, given the money-demand for their money M_m^D, the money-demands of all other monies M_{-m}^D and the money-supplies of all other monies M_{-m}^S:

$$\max_{M_m^S} \ SN(i_t^m(M_m^S, M_m^D, M_{-m}^S, M_{-m}^D)) + \gamma(\epsilon_t^m(M_m^S, M_m^D, M_{-m}^S, M_{-m}^D))$$

Clearly, this maximisation problem is contingent upon the way that prices are determined in these markets and this links directly to the adapted interest parity condition described under the sub-heading 'The Price-determination Mechanism for Interest Rates and Exchange Rates' in the sense that, when a money-supplying agent is asked to supply/issue more of their money to a money-demanding agent, it will be contingent upon what they expect to happen to their utility according to their knowledge of the interest parity condition.

Constrained Optimisation of Money-Demanding Agents' Portfolio to Maximise Utility

For each agent, we multiply the values of the probability density functions corresponding to the interest rates and exchange rates of the monies they hold currently from the Skew Normal and Gamma Distribution for the interest rates and exchange rates respectively with the amounts of each money held to obtain the current utility derived from the portfolio of monies.

Pseudocode for calculating Money-Demanding Agents' Current Utility

To calculate the utility of each agent which corresponds to their current portfolio:

```
For each agent:
    Utility ← 0
    InterestWeight ← 0
    ExchangeWeight ← 0
    ExchangeUtility ← 0
    InterestUtility ← 0
    For each money held by agent:
    Let x(money) be the quantity of that money held by the agent
    Let interest(money) be the interest rate of that money
    Let exchange(money) be the exchange rate of that money
    Let pdf[…] be value of the Skew Normal or Gamma Distribution corresponding to
    a specific interest rate or exchange rate for this agent.
        InterestWeight ← pdf[interest(money)]
        ExchangeWeight ← pdf[exchange(money)]
        ExchangeUtility ← x(money) x (ExchangeWeight x exchange(money))
        InterestUtility ← x(money) x (InterestWeight x interest(money))
        Utility ← Utility + ExchangeUtility + InterestUtility
    End for-loop.
    Return Utility
```

Optimisation problem for determining Agent's desired (optimal) portfolio of Monies

Assume that money-demanding agents' expectations are simplistically adaptive such that $\epsilon_{t+1}^{e} = \epsilon_t$ and $i_{t+1}^{e} = i_t$ ∀ money – this is equivalent to saying that the expected value of an exchange/interest rate in the next period is equal to the current value of the exchange/interest rate. Recall that the exchange rate referred to here is the previously described weighted, multilateral exchange rate that heterogeneous agents have preferences represented by Gamma distributions over and, furthermore, money-demanding agents have preferences over interest rates represented by Skew Normal distributions.

This assumption will strike a macroeconomist as being a simplistic form of 'adaptive expectations' and this is done to simplify analysis to a reasonable degree (since 'rational' expectations would be more difficult to model and 'naïve'/'static' expectations are too unrealistic/unrepresentative for the purposes of this exercise).

To run the simplex algorithm, we must formulate the optimisation problem as a Linear Program (LP) and then we can use a standard LP solver to solve it. Assume there are M monies. Then it follows that there are expected weighted multilateral exchange rates $\epsilon_{t+1}^{e,m} = \epsilon_t^m$ and expected interest rates $i_{t+1}^{e,m} = i_t^m$ such that $m \in \{1, \ldots, M\}$. Denote the amount of each money held in an agent's portfolio of monies by $x_m : m \in \{1, \ldots, M\}$.

Further denote the values of the Skew Normal and Gamma distributions over interest rates and exchange rates respectively corresponding to a money m as $SN(i_t^m)$ and $\gamma(\epsilon_t^m)$ respectively. From this notation, the maximisation problem for each agent is:

$$\max_{x'_1, x'_2 \ldots, x'_{M-1}, x'_M} \sum_{i=1}^{M} [SN(i_t^m) + \gamma(\epsilon_t^m)]x'_m$$

$$Budget\ Constraints\text{:} \sum \epsilon^{n,m} x_n + x_m \leq x'_m : \ m \in \{1, \ldots, M\}\ and\ n \in \{1, \ldots, M\} \backslash \{m\}$$

$$x_1, x_2, \ldots, x_{M-1}, x_M, x'_1, x'_2, \ldots, x'_{M-1}, x'_M \geq 0$$

The constraints preceding the non-negativity constraints are, collectively, the budget constraints represented such that $\epsilon^{n,m}$ is the exchange rate of money n with respect to money m.

Nevertheless, although the current plan is to use adaptive expectations, the ideal situation would be for agents to use rational expectations (or possibly even a mixture of rational, adaptive and/or naïve expectations for agents' expectations) but this makes the system more complex to program and will be done if and only if there is sufficient time after programming the basic requirements of the system to function.

Maximising Utility through Identifying and Exploiting Arbitrage Opportunities

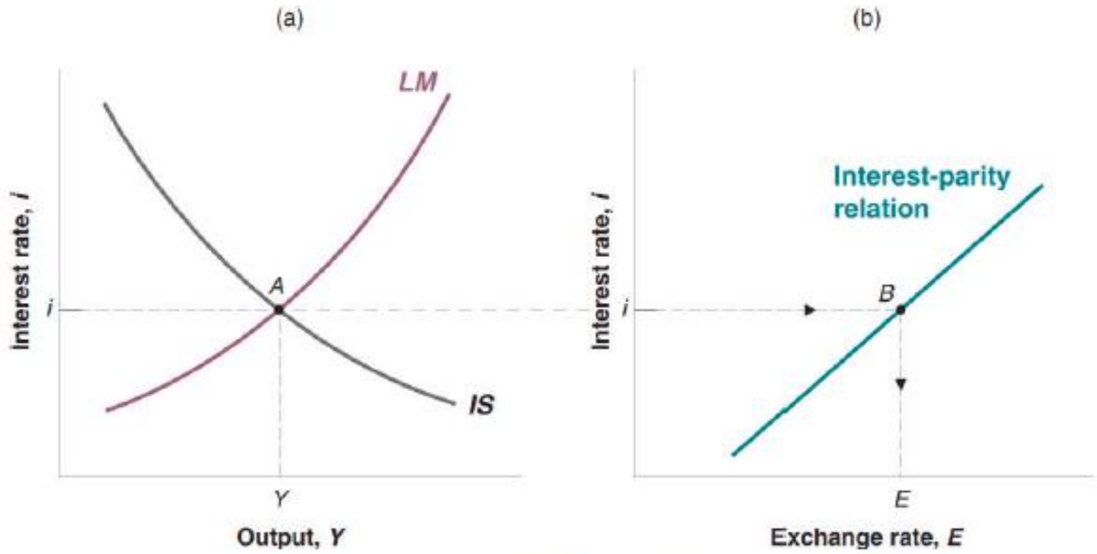
An economist would be forgiven for wondering whether monotonicity (a standard assumption held in microeconomics) holds here. It still does for money-demanders because, based on their preferences, it is clear to see why more of a money (regardless of the weight an agent assigns to it or whether it is optimal), ceteris paribus (holding all other things equal), would result in higher utility (from the utility functions) even if the agent still does not have its optimal portfolio, given their budget constraints. As such, if arbitrage opportunities arise in the model, it would make sense for agents to want to exploit this (until they disappear) before working to optimise their portfolio. E-mail correspondence with Rahul revealed that this is well-studied and would likely be implementable with pre-existing code. After every transaction, however, the limit order book would have to be updated.

Proposed Scheduling Regime

Either 'synchronous or simultaneous' (where all agents act simultaneously) activation or 'random' activation (where each agent is activated in each step of the model, but the order in which they are activated is randomised for each step of the model) and it may be worth trying both to see if this alters pricing dynamics – the latter seems preferable when considering the potential for implementing a 'limit order book' where exchange rates are updated after every transaction. Of course, this will increase runtime significantly.

The Price-determination Mechanism for Interest Rates and Exchange Rates: The Interest Parity Condition

The most fundamental aspect of this model is the underlying mechanism for determining exchange rates and interest rates since, in this case, the prices of monies are interest rates (relative to the bond market, which is exogenous to this model) and exchange rates (in the ForEx markets). This will determine the results and, therefore, for the results to be thought of as even remotely valid or useful by mainstream economists, there is a need to either use a pre-existing model or a logical extension of a pre-existing model. As such, the price-determination mechanism should ideally be extended from the widely used Mundell-Fleming (1962, 1963) model (which, incidentally, in this context, would be worth a paper in itself). The following is taken from Blanchard's (2011) standard macroeconomics textbook:



Source: Blanchard (2011)

However, this deals only with a domestic currency in relation to a single foreign currency which is not adequate for the context envisioned here. On a preliminary examination, it is evident that we would need the interest rates and exchange rates on the axes of an extended/adapted model for our context to conform to the values of the x-axes of the Skew Normal and Gamma distributions corresponding to agents' preferences. We need, in particular, to adapt the interest parity condition (see Feenstra and Taylor (2008)) for our purposes. The original interest parity condition for determining domestic interest rates is as follows (it implies a positive relation between the exchange rate and the domestic interest rate) where E^e is the expected exchange rate and i_t^* is the foreign interest rate:

$$E_t = \frac{1 + i_t}{1 + i_t^*} E^e$$

However, in our model, the (expected) exchange rate in question is the multilateral weighted average (expected) exchange rate. Thus, the interest rate will also be the multilateral weighted average interest rate of all other monies. The resulting identities are:

$$\overline{i_t^*} = \frac{M_1^S i^1 + M_2^S i^2 + \cdots + M_{m-1}^S i^{m-1} + M_{m+1}^S i^{m+1} + \cdots + M_{M-1}^S i^{M-1} + M_M^S i^M}{M-1}$$

$$E_t = \frac{M_1^S E^{m,1} + M_2^S E^{m,2} + \cdots + M_{m-1}^S E^{m,m-1} + M_{m+1}^S E^{m,m+1} + \cdots + M_{M-1}^S E^{m,M-1} + M_M^S E^{m,M}}{M-1}$$

It is clear from the interest-parity condition that if $E_t = E^e$ (as would be the case with simplistic adaptive expectations) then $\overline{i_t^*} = i_t$ but this will not hold more broadly where the expected multilateral weighted average exchange rate diverges from the current multilateral weighted average exchange rate. However, even under other forms of expectations (such as rational expectations) that money's nominal interest rate would still be proportional to the (expected) multilateral weighted average exchange rate.

A Limit Order Book

After speaking to Rahul about how a Limit Order Book is used in ForEx markets, it may be the best way to determine the exchange rates which will, in turn, feedback into the previously mentioned interest parity condition. The idea is that, based on the interest parity condition, the money-supplier agents will decide whether to supply their money to money-demander agents or not (otherwise, money-demander agents will simply ask other agents who will then trade monies if and only if they gain utility by doing so).

Nevertheless, there is still considerable uncertainty regarding how I might model this and how the initial exchange rates will be determined (which will obviously be determined by the initial quantities of each money in the system). An initial thought is that the default exchange rate proposed in the order book for each money would be the desired exchange rate for the money-supplier (within reason based on the interest-parity condition) but then this would adjust based on the actual supply and demand that is derived from agents' preferences. The limit order book would, therefore, be updated after every transaction and exchange rates and interest rates would adjust after every transaction according to the previously introduced, extended interest-parity condition.

Monetary Autonomy via 'Helicopter Money'

The key means by which the hypothesis is tested is by a significant expansion of the money-supply after a few steps (say, 3-5) of the model running without this 'intervention'; through this 'helicopter money', the potential for 'monetary autonomy' is tested. This entails an expansion of money (the parameter could be adjusted so that the quantity of the money-supply increase could be all the way from 10% of the total amount of that money in the system to 100%) which could then be allocated (pseudo-randomly) to (a subset of) money-demanding agents. Then, the model would be allowed to run for a few more steps so the agents can adjust their portfolios and one can examine examine there are at least some ‘fixed’ exchange rates (defined previously under the ‘Model Parameters and Hypothesis Testing’ subheading).

Another variation of this hypothesis test could be the number of money-supplying agents that engage in these money-supply expansions (of varied volumes). I suspect that there will be a higher probability that some fixed exchange rates will exist in this model when there are more money-supplying agents in the system (i.e more monies in the system) since each additional money would have diminished relative influence upon exchange rates throughout the system (and would, simultaneously, diminish the influence each of the monies would have had in a system with fewer monies). Conversely, the probability of successful tests would also diminish as more money-supplying agents engaged in the ‘helicopter money’ intervention.

Another factor that will influence the possibility for fixed exchange rates is how the ‘helicopter money’ is distributed/allocated amongst the (subset of) money-demanding agents. If it is distributed such that it is amongst a smaller subset of money-demanding agents, then I suspect it would be more likely for some ‘fixed’ exchange rates to exist after money-demanding agents adjust their portfolios. If all agents were allocated equal amounts of the helicopter money, then this would likely make the existence of relatively fixed exchange rates less likely as agents work to re-adjust their portfolios.

In each case, these parameters would be tested after having ‘frozen’ and ‘saved’ the data from the model after it ran without intervention and then restoring that latest step each time a change in parameter is sought to be tested. Of course, this could also be tried with several different initial runs before the model is eventually ‘frozen’ and that point continuously restored for hypothesis testing.

Key limitations of this model

- The bond market is exogenous and, therefore, interest payments for bond-holders and bond-issuers are not modelled. This also means that the interest parity condition still holds within this model in the way that is proposed.
- The goods and services markets are not modelled.
- More sophisticated expectations-formation and expectations-management preferences are not modelled.
- Agents’ preferences remain static across time periods.
- The weighting between preferences for interest rates and exchange rates are equal rather than varying between agents (and these weightings remain equal across time periods).
- Only a Limit Order Book is used for determining exchange rates and for transactions rather than other price-determination and transaction mechanisms (and agents can only use that, rather than having a choice between other mechanisms).
- Inflation is not included (assumed to be zero) and, therefore, real and nominal interest rates are assumed to be equal.

Deliverables

- Software for running the ABM simulation and yielding results.
- Dissertation to summarise and analyse results, provide rationale for aspects of the ABM and explain practical significance for pre-existing literature(s) and ongoing debates.
- If the software works, the results will almost certainly be new (or at least interesting) and, even if they are not what is hoped for, if the software works adequately and interesting insights are found, then a write-up would be worth submitting to an academic journal.

Risk Assessment

Risk Likelihood (RL)	Score
Low	1
Medium	2
High	3

Risk Consequence (RC)	Score
Very Low	1
Low	2
Medium	3
High	4
Very High	5

Risk Impact (RI) = (Risk Likelihood x Risk Consequence)

Risk	Risk Consequence	Risk Likelihood	Risk Impact	Symptoms	Risk-management approach
Inability to model Limit Order Book adequately for this context.	4	2	8	If prices behave very strangely from after each transaction or step and the Limit Order Book seems to allow for several, unrealistic or bizarre situations.	Possibly implement pre-existing Python code for Limit Order Books if I am unable to model and code it adequately for this context.
Hardware failure.	4	1	4	If the computer continuously crashes or even ceases	Backup code and software regularly so that the project can continue with

				to work whilst programming and/or running the software.	different machines, if necessary.
Very slow runtime followed by error messages.	2	3	6	Simulation is taking a long time to run on the laptop and/or desktop. Error messages appear on screen.	Debug continuously at each stage of software development before running the code and try to make operations more efficient where possible.
Inability to finish coding the software.	5	2	10	Software is not complete when project is meant to be handed in so there are no results available.	Use Google, StackOverflow, consult with supervisor(s), look at others' Mesa-based ABM code etc. to ensure this does not happen.
Trilemma is not solved via the proposed solution within this environment.	4	3	12	From the hypothesis testing, it turns out that there are no instances where the Trilemma can be solved in this ABM.	Report the results even if they are negative because there may still be other useful insights from the model.

DATA REQUIRED

- Since there are relatively few instances in the world where multiple monies are currently used (investigations limited mostly to some tax havens, border towns and historical case studies and, furthermore, not to the scale envisioned within this simulation), the available real-world data is sparse, unreliable and unsuitable for testing the hypotheses of this project.
- Thus, the data that is analysed will be generated from the simulation (an Agent-Based Model) within this project.
- Human participants are not involved nor are they necessary for this project.

PLAN

This provisional timetable/plan is taken from the COMP702 webpage (since I see no obvious reason to significantly deviate from this timetable):

Important Date	**Activity**
5 June 2017	MSc projects officially begin **(Week 1).**
Weeks 1 and 2	Background reading and literature review.
Weeks 3 and 4	Development of project design.
30 June 2017 (5:00pm) (to turn in Specification and Design report)	Specification and Proposed Design report (end of **Week 4**). Oral presentation (by end of **Week 5 (July 3-7)**).
Weeks 5, 6, 7, 8, 9, 10, and 11	Software implementation and testing.
28 August 2017 (5:00pm) (13 November 2017 (5:00pm))	Final presentation + software demo when appropriate (by end of **Week 13 (28 Aug – 1 Sept)**).
Weeks 11, 12, 13, and 14	Software experimentation and analysis of results.
Weeks 13, 14, and 15	Write-up of dissertation.
22 September 2017 (5:00pm) (noon) (Monday, 11 December 2017 (5:00pm))	Dissertation hand in **(Friday in Week 16, Firm deadline).**

References

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