Resurrecting a Forgotten Model: Updating Mashayekhi's Model of Iranian Economic Development

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Introduction

In 1978, *Ali Naghi Mashayekhi* developed a system dynamics model to investigate the dependency of the Iranian economy on oil revenue (Mashayekhi 1978). Although this study created a general awareness about Iranian oil-dependency among academics and politicians, the model itself has, by and large, been forgotten. The purpose of this chapter is to revisit and update Mashayekhi's model (the "M-model") and show that it deserves more attention. In particular, it will be demonstrated that the M-model has the potential to become a well-known starting point for future Iranian macroeconomic modeling efforts, especially in the area of energy–economy interactions.

The M-model was created as a part of Mashayekhi's Ph.D. dissertation at the Massachusetts Institute of Technology. Simulations of the M-model in the late-1970s revealed that Iran would face a severe depression during the 1980s if its government pursued a policy of importing intermediate goods purchased with revenue from oil exports.

Figure 1 is a simulation run from the original formulation of the M-model that illustrates this potential crisis. It presents the base run time paths for Iranian oil reserves (curve 1) in terms of billion barrels, oil production (curve 2) in terms of million barrels per year, oil revenues (curve 3) in terms of million rials[1] per year, gross national product (GNP) (curve 4) in terms of million rials per year, and non-oil outputs (curve 5) in terms of million rials per year.

[1] Rial is the Iranian currency unit.

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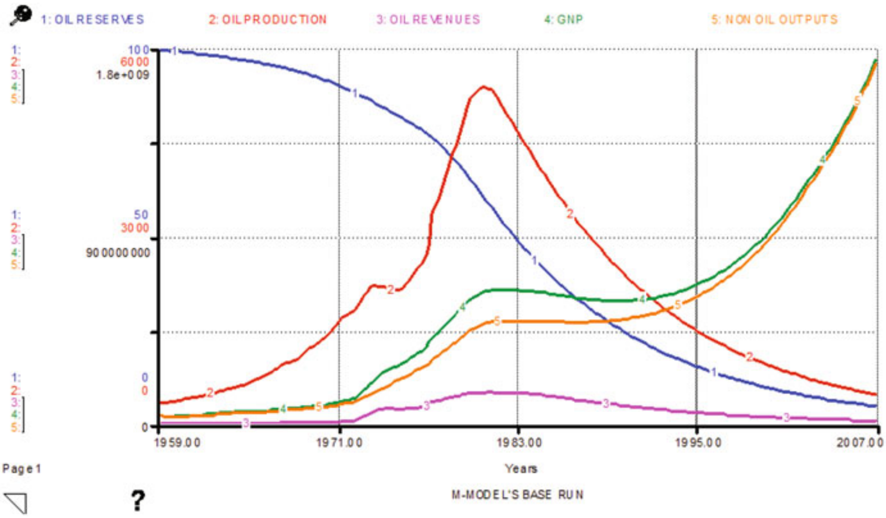


Fig. 1 Base simulation run of the M-model

The dynamics of this base simulation run are as follows. Iranian oil revenue grows from the late 1950s to the early 1980s. In the middle of the 1980s, however, they begin to decline due to the depletion of Iranian oil reserves. Consequently, Iran's stock of foreign exchange begins to shrink and it begins to limit the importation of intermediate goods. The shortage of intermediate goods causes the production capacity of the economy to fall and the growth rate of non-oil output to approach zero, and even briefly turn negative, during the 1980s. The stagnation of both oil and non-oil output leads to a severe depression that lasts until beginning of the 1990s.

In general, the M-model demonstrated that the high dependency of the Iranian economy on imports of intermediate goods, financed with oil revenue, would sooner or later cause Iran to run into serious economic difficulty. Although the specific scenario shown in Fig. 1 never occurred, the potential problems for the Iranian economy suggested by the M-model still exist. For example, Fig. 2 shows that during the period 1965–2008 the ratio of oil revenue to total revenue of the Iranian government ranged from 25 to 86 %, with an average value of 57 % (CBI 2012). This situation was mitigated somewhat by a downward trend in the ratio during the years 1999–2008, although its value is currently hovering around its historical average.

At the same time, Fig. 3 shows that Iranian imports of raw material and intermediate goods have increased dramatically in recent years. From these data it is clear that Iran continues to be dependent on oil revenue and must import raw material and intermediate goods as aggressively as ever. As a consequence, it makes sense to update the M-model and restate its message so that Iranian policy makers can be reminded of the strategic issues it raises.

Although Mashayekhi was a pioneer in identifying the problems associated with the dependency of the Iranian economy on oil revenue, his model and its conclusions have arguably never received the attention they deserve. There are several reasons for this including:

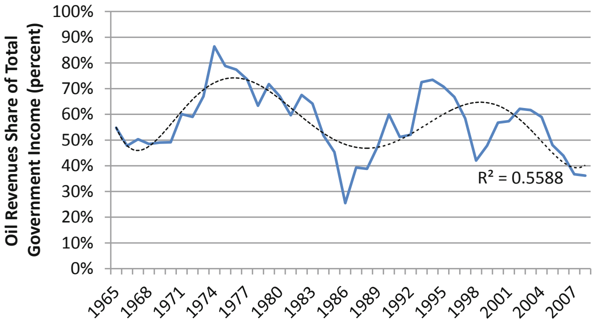


Fig. 2 Oil's share of total Iranian government revenue. (CBI 2012)

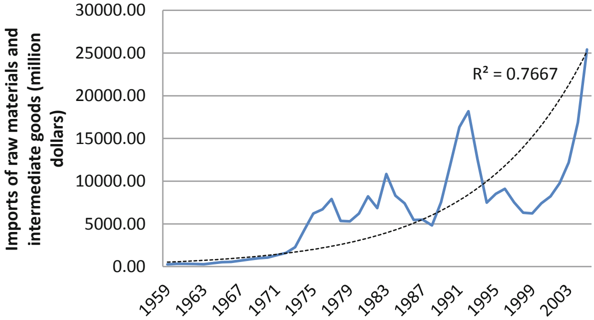


Fig. 3 Iranian imports of raw materials and intermediate goods. (CBI 2012)

- *The Islamic revolution*. The creation of the M-model coincided with the birth of the Islamic revolution. The revolution led to fundamentally different decision making processes within the highest levels of Iranian political and economic institutions. As a consequence, the usefulness of the M-model became ambiguous. Moreover, in 1980, 1 year after the revolution's success, an eight-year war began when Iraq invaded Iran. This national emergency changed the Iranian government's priorities from economic reform to financing the war and stabilizing the political economy of the country (Ahmadi Amouee 2006). Not surprisingly, few policy analysts paid attention to the oil-dependency issue during this period of time.
- *Unfamiliarity with system dynamics*. The intellectual origin of system dynamics is engineering and management, not economics. As a consequence, most of economists in Iran were—and still are—unfamiliar with the system dynamics methodology. In fact, during the late 1970s there was virtually no one in Iran who could fully understand and appreciate the M-model. Even now, there are few economists in Iran who know about system dynamics and it is thus not surprising that the first effort to apply system dynamics to the Iranian economy was largely ignored.
- *Competing obligations*. Mashayekhi himself believes[2] that the main reason his model has failed to make a significant impact on Iranian policy making is that his graduation from MIT and return to Iran coincided with the rise of the Islamic

[2] Telephone interview with Ali Mashayekhi on May 12, 2011.

regime and the new government asking him to help reconstruct the Iranian higher education system. As such, he was left with little time to publish, promote, and extend his model.

Despite these setbacks, the M-Model has the potential to be updated and used for energy–economy analysis in Iran. By reintroducing the M-model, top-level Iranian political and economic decision makers can be reminded that oil dependency can be a potential danger to the long-term economic growth and stability of the country. Moreover the model can provide a foundation and road map for additional system dynamics modeling projects in the Iranian energy–economy space. Finally, this chapter will show how system dynamics models can be updated and expanded, which is a very important, yet often neglected, part of the system dynamics modeling process.

To achieve these goals, this chapter presents an updated and revalidated version of the M-model. The updating and revalidation process involves three main issues:

- *Improvements in software*. The M-model was developed in 1978. Since then there have been significant improvements in system dynamics validation methods and software tools. For example, the original M-model was written in DYNAMO which is an obsolete tool for applying modern methods of model validation. For this chapter, the M-model was reprogrammed in iThink,[3] which offers a wide range of validation and verification options.
- *Structural changes and historical data*. In 1978, Mashayekhi simulated the M-model forward in time to project the implications of various policy choices on the growth and stability of the Iranian economy. In the present day, of course, what was once the future is now the past. As such, it is possible to determine how accurately the M-model predicted the future. Not surprisingly, some inconsistencies between the projections of the M-model and the historical data have been identified. Although, system dynamicists believe that the point-by-point fit of a model to time series data is a weak proof of model validity (Forrester and Senge 1996; Sterman 1984; Saeed 1992; Radzicki 2004); modelers such as Sterman (1984) argue that it is an important consideration because it builds confidence in the eyes of model users. Hence, in order to increase the M-model's potential for acceptance by Iranian policy makers it will be shown that updating exogenous oil export and price data, along with some structural changes and parameter recalibrations, can significantly improve the model's ability to reproduce the historical behavior of the Iranian economy.
- *Model revalidation and publication*. Mashayekhi never published a comprehensive analysis of his model's ability to pass a traditional list of tests necessary to build confidence in a system dynamics model (Peterson 1980). This was probably due to software and/or time limitations, and/or to the level of knowledge of Iranian academics about the system dynamics methodology at that time. As a consequence, revalidating the model and publishing its results will potentially increase its creditability among those economists who insist that valid models require the application of statistical techniques to numerical data.

[3] iThink Analyst v9.1.4, 1985–2010.

In the next section a revalidation of the M-model according to criteria that are standard in the field of system dynamics (Sterman 2001) will be presented.

Revalidating the M-model

In the field of system dynamics, models are never considered to be purely "valid" or "invalid." Instead, they are evaluated according to their ability to generate confidence in their users. A model never can be validated absolutely because all models are wrong. All models are simplified and abstract versions of real systems. So they can never be regarded exactly as corresponding real systems. So, why do we look for validating a model? The answer is that you, as a leader, have to use a model to make your decisions. You may use only your mental models or a mathematical one, etc. Whatever you use, the question is which model you want to use; not whether you can use a model or not (Sterman 1991, 2001, 2002).

Indeed, putting a model through a validation process helps decision makers feel confident that the results they are seeing are legitimate and useful.

Over the years, system dynamicists have assembled a comprehensive list of tests to which a model can be subjected in an effort to build confidence among its users.[4] These tests include:

1. Boundary adequacy tests
2. Structure assessment tests
3. Dimensional consistency
4. Parameter assessment
5. Extreme condition tests
6. Integration error tests
7. Behavior reproduction tests
8. Behavior anomaly tests
9. Family member tests
10. Surprise behavior tests
11. Sensitivity analysis
12. System improvement tests

The application of these tests to the M-model will now be described.

Boundary Adequacy Tests

A model's boundary defines what is included in and excluded from its structure. Boundary adequacy tests evaluate the appropriateness of a model's boundary vis-a-vis the purpose for which it was created.

[4] See for example Forrester (1973); Peterson (1975, 1980); Mass and Senge (1978); Forrester and Senge (1996); Sterman (1984); Radzicki (2004); Barlas (1996); Sterman (2001); and Oliva (2003).

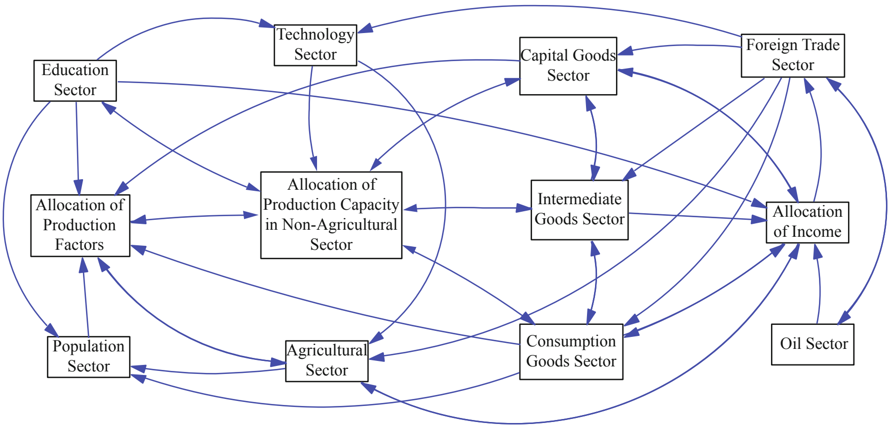


Fig. 4 Sector-level view of the structure of the M-model

Table 1 List of endogenous, exogenous, and excluded variables of M-model

Endogenous	Exogenous	Excluded
GNP	Labor market	Oil imports
Population	Oil exports	Financial market
Education	Oil prices	Exchange market
Capital accumulation		Alternative energies
Energy consumption		
Foreign trade		
Technology		

GNP gross national product

Figure 4 presents a sector-level view of the structure of the M-model. It consists of 325 variables and constants embodied in 12 interacting subsystems of the Iranian socioeconomic system. In addition, Table 1 lists some important macroeconomic variables that are endogenous, exogenous, and excluded from the M-model. The relevant question is whether or not this structure is still adequate for the M-model's purpose.

The endogenous variables can be examined first. Since the purpose of the M-model is to analyze the effect of oil revenue on the Iranian economy, it makes perfect sense to have it calculate a major economic summary index such as GNP. Furthermore, to replicate the dynamics of the aggregate production process in Iran, it is crucial to model population (as generator of the labor force), education (as an important input into the aggregate production function), capital accumulation (as the process that generates capital, which is another important production factor), and technology (again, an important input into the aggregate production function) as endogenous processes. Energy consumption is represented endogenously because it is a process that can limit oil exports and thus Iranian oil revenue. Finally, foreign trade is modeled as an endogenous process in order to capture the dynamics that drive the importation of intermediate goods and to show how foreign exchange is utilized.

In terms of exogenous variables, the dynamics of the labor market in the M-model are represented autonomously. More specifically, the model simply assumes that 56 % of the adult population is employed every year. This assumption is employed in order to avoid the complexity of the Iranian labor market. Since the main goal of the M-model is to reproduce the dynamics of Iranian oil dependency, it appears that this simplification is reasonable. Although including labor market dynamics can enhance the M-model's capacity to analyze a wider range of policies and scenarios, this capability is outside the focus of both the original, and present, studies. If the social consequences of oil dependency were the focus of the M-model, then a more sophisticated representation of the labor market would be required.

Oil exports are also largely determined exogenously. More precisely, they are set to their historical value for the years 1959–1978 and then determined endogenously thereafter. This is arguably a weakness in the original formulation of the M-model as oil exports are a key factor in generating the model's internal dynamics. The good news is that this problem can be eliminated by adding a comprehensive energy sector to the original M-model.[5]

Oil prices are also represented exogenously in the M-model. As with oil exports, the price of oil is set to its historical value for the years 1959–1978. However, unlike oil exports the price of oil is held constant from 1979 to the end of each simulation. Although different assumptions about the price of oil from 1979 forward can be tested, a superior formulation would generate oil prices endogenously because they are a major determinant of oil revenue.

The M-model's endogenous and exogenous variables represent factors that are part of its structure and are thus *inside* of its boundary. On the other hand, there are some important variables that are entirely excluded from the M-model's structure and hence lie *outside* of its boundary. For instance, the M-model assumes that the importation of oil to Iran is not possible. This assumption is both a boundary inadequacy and a structural deficiency. It implies that the Iranian economy has no source for oil other than its domestic supply. Of course, this is not true and when domestic oil resources decline significantly Iran will have to begin importing oil. Unfortunately, this scenario is impossible to be generated in the original formulation of the M-model.[6] Langarudi et al. (2011), however, present a remedy for this deficiency.

Financial and exchange markets are also excluded from the original version of the M-model. These exclusions have reduced the model's ability to fully analyze the impact of oil revenue on the Iranian economy. For example, the dynamics of the so-called "Dutch disease" cannot be explored. An economy afflicted with the Dutch disease experiences a rise in real exchange rates due to an unexpected increase in foreign exchange revenue generated by its natural resource exports. This in turn causes a fall in total output and employment in the nonnatural resource sectors (usually the manufacturing sector) as the stronger domestic currency makes nonnatural resource

[5] This has been done by Langarudi et al. (2011).

[6] Mashayekhi employed this assumption because the simulation period for the original M-model was 50 years and during this period domestic energy resources were sufficient for domestic energy consumption (see Footnote 10).

exports relatively more expensive (Van Wijnbergen 1984). Although this is clearly an issue with the boundary of the M-model, this chapter will demonstrate that it still provides an excellent foundation for a more complete model that can be used to analyze a wide range of Iranian macroeconomic issues.

Finally, another significant deficiency of the M-model's structure is its reliance on a single energy resource—oil. It can be argued, however, that this assumption poses no significant threat to the model's results because it was not designed to analyze the impact of competing energy resources. Nevertheless, adding alternative energy sources to the M-model, in particular natural gas, can certainly improve its usefulness for strategic planning in the energy sector.[7]

In sum, the M-model's boundary is somewhat inadequate for the purpose for which it was built. To better study the effects of oil revenue on the Iranian economy, the M-model's boundary must be expanded to include a financial market, an exchange market, an energy market, and the process of energy production. As these improvements are possible, the M-model is arguably still an appropriate base platform for undertaking Iranian socioeconomic analysis.

Structure Assessment Tests

Structure assessment tests check to see if a model is consistent with knowledge of the real system that is relevant to the purpose for which the model was created. These tests are concerned with the level of aggregation in a model, the fidelity of the model to basic physical facts, and the realism of the decision rules utilized by the agents in the model.

Structure assessment tests were performed in all steps of reviewing, recalibrating, and analyzing the M-model.[8] The result of this assessment is that, although the M-model has no egregious structural deficiencies, it contains two structural imperfections. These imperfections will be addressed after a detailed review of the M-model's general structure.

Resource Allocation Mechanism

The M-model's agricultural and nonagricultural production processes utilize three inputs: capital, labor, and education. Capital is calculated by accumulating investment in both machinery and construction, and then adding-in the flow of imported capital goods. Labor is supplied by the population sector while education is represented by the average number of years an Iranian citizen spends in school. These three production factors are allocated between the M-model's two production sectors: agricultural and nonagricultural (industrial) sectors.

[7] Langarudi et al. (2011) have also addressed this issue.

[8] For a comprehensive description of the model's structure see Mashayekhi (1978)

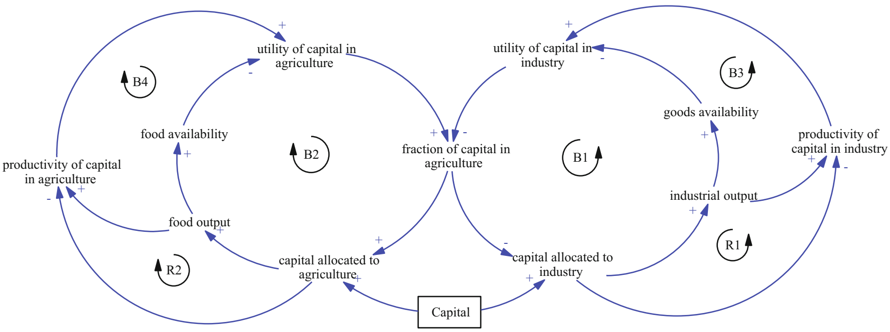


Fig. 5 Causal loop diagram of the resource allocation mechanism in the M-model

The resource allocation mechanism is based on the relative productivity of the three factors of production and the availability of each sector's output. The availability of a sector's output is a measure of demand relative to supply.

To illustrate how this mechanism works in the M-model, Fig. 5 presents a causal loop diagram of the process.[9] The allocation mechanisms for the other factors of production (labor and education) have the same structure.

Agricultural Sector

The model agricultural sector supplies the food demanded by the population. The production function in this sector utilizes the factors of production allocated to it, as well as available farmland and the sector's level of technology. The most important interactions between food production and the rest of the model are shown in Fig. 6.

Allocation of Production Capacity in the Nonagricultural Sector

Similar to the agricultural sector, a unique production function determines the total production capacity of the industrial (i.e., nonagricultural) sector. This production function utilizes the factors of production allocated to it, as well as the sector's level of technology. The total production capacity of the sector is allocated among four competing demands: capital goods production, intermediate goods production, consumption goods production, and educational capacity.

Figure 7 presents a causal loop diagram of the major processes that determine how the M-model allocates its nonagricultural (industrial) production capacity to consumption goods production. From an examination of the figure it is clear that the

[9] A causal loop diagram presents only the essential feedback structure of a system dynamics model so that the most important elements of cause and effect can be examined. The actual resource allocation mechanism in the M-model is substantially more sophisticated.

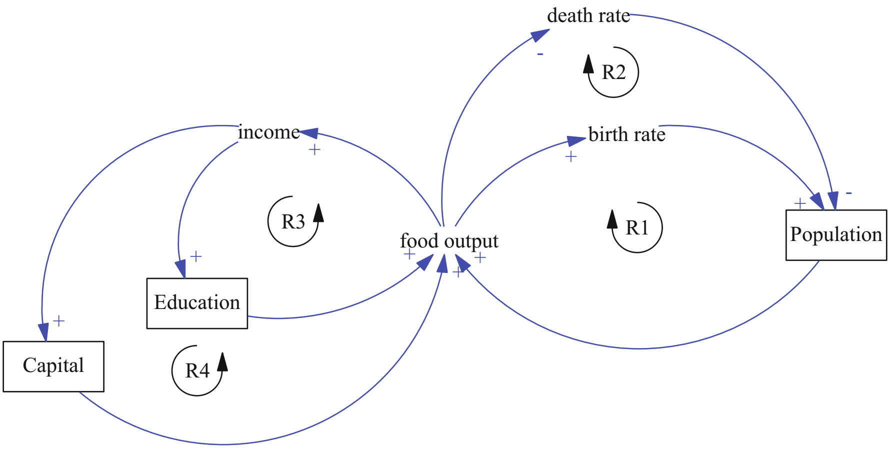


Fig. 6 Causal loop diagram of food production interactions in the M-model

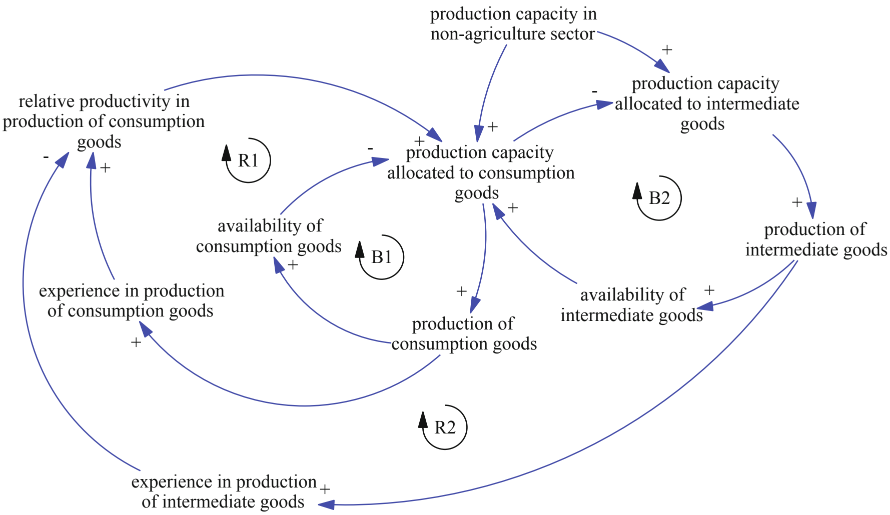


Fig. 7 Causal loop diagram of the resource allocation mechanism for consumption goods in the M-model

production capacity allocated to consumption goods depends on the total production capacity in the nonagricultural sector, the relative productivity of the production factors in consumption goods, the availability of consumption goods, and the availability of intermediate goods. Similar interactions are used to allocate production capacity to the production of capital goods, the production of intermediate goods, and educational capacity.

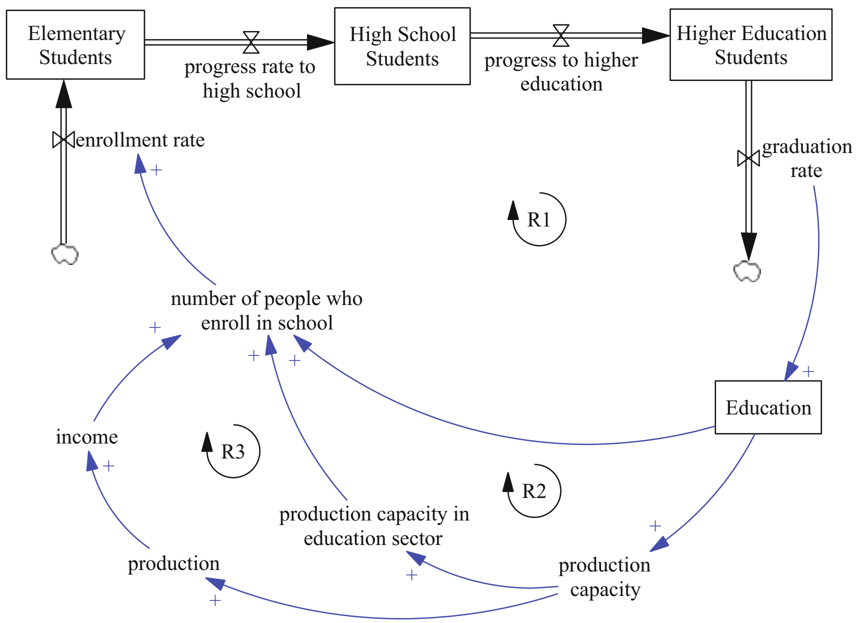


Fig. 8 Aggregate causal relationships in the education sector of the M-model

Education Sector

The output of the education sector is people possessing person-years of schooling. Educational output increases when the M-model's education production capacity and the demand for utilizing this capacity, increase. Educational production capacity depends on the demand for education and government policies. The demand for education is a direct function of both personal income and the educational level of Iranian adults. Figure 8 shows the aggregate causal relationships in this sector.

Technology Sector

The technology sector determines how technical progress diffuses into the Iranian economy. The M-model assumes that technical progress depends on technology transfer from developed countries. The transfer rate is determined by two factors: (1) the availability of required technologies that have not yet been transferred to Iran (i.e., the difference between the technology level in advanced countries and the corresponding technology level in Iran) and (2) Iran's ability to transfer technologies. Iran's ability to transfer technology depends on the education level of its work force and its level of foreign trade with developed countries. Figure 9 illustrates this mechanism for the industrial sector. Technical progress in the agricultural sector has a similar structure.

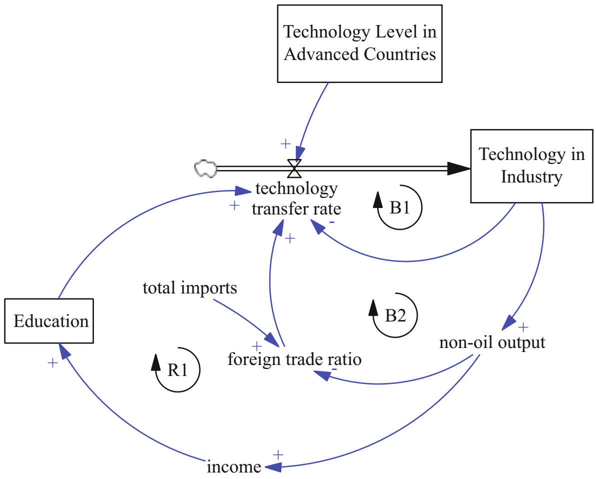


Fig. 9 Technology transfer in the industrial sector of the M-model

Allocation of Income

The allocation of income sector determines the allocation of Iranian national income among five competing demands: expenditures on (1) consumption goods, (2) services, (3) food, (4) saving, and (5) investment. The structure of this sector is based on standard microeconomic theory which specifies that the income elasticity of the demand for food and consumption goods is lower than the income elasticity of investment and saving.

Foreign Trade Sector

Any discrepancy between supply and demand in different sectors of the M-model is addressed through foreign trade. A demand surplus would be imported and a supply surplus would be exported. Imports and exports are also restricted by the availability of foreign exchange and government policies. Figure 10 depicts the feedback structure that determines Iranian foreign trade in consumption goods. The M-model utilizes the same structure to generate the dynamics of Iranian foreign trade in food, capital goods, and intermediate goods.

Oil Sector

In the oil sector, oil is produced and exported to provide Iran with the foreign exchange it needs for its imports. This sector also computes Iran's domestic energy consumption. The feedback structure of the oil sector is shown in Fig. 11.

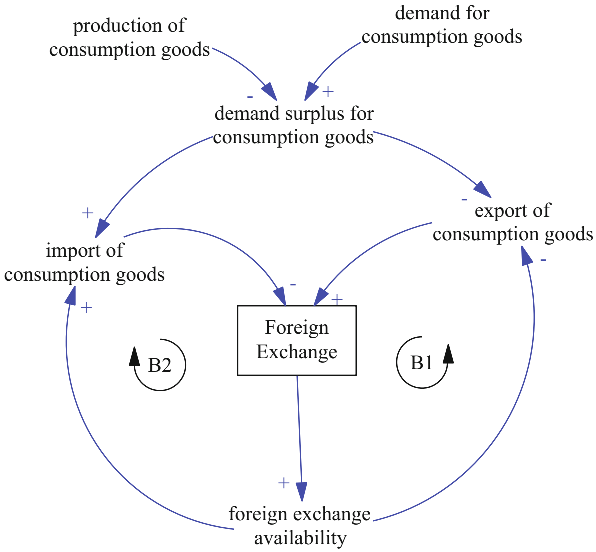


Fig. 10 Feedback structure determining Iranian foreign trade in consumption goods

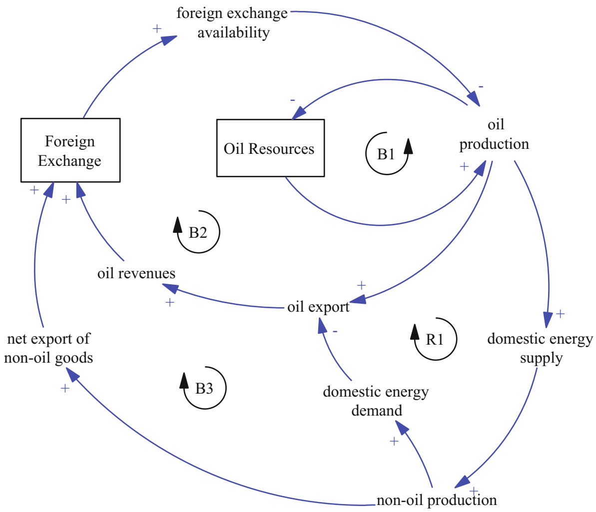


Fig. 11 Feedback structure of the oil sector of the M-model

Population Sector

The population sector of the M-model supplies both the workforce for the economy's production sectors and the consumers of the output from the production sectors. The Iranian birth rate depends on the adult population, available food per capita, the level of Iranian industrialization, and the level of Iranian education. Similarly, the Iranian death rate depends on available food per capita and the level of industrialization. Figures 12 and 13 show the feedback structure of this sector.

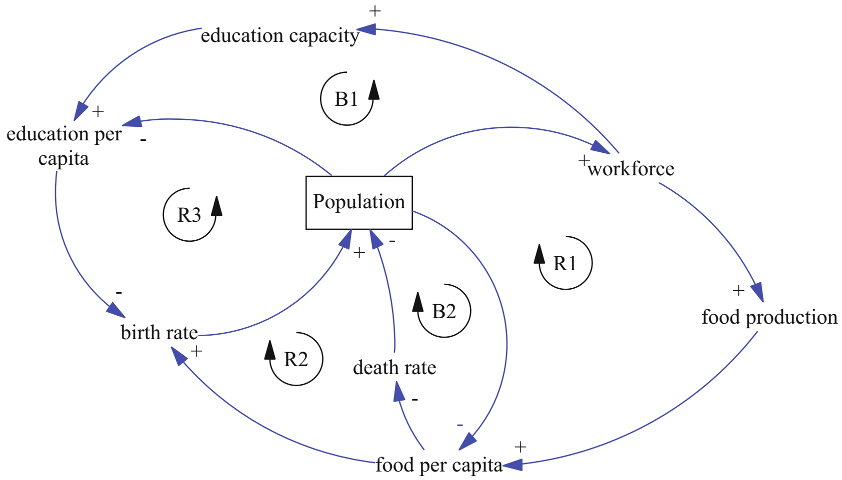


Fig. 12 Feedback structure of the population sector of the M-model (Part 1)

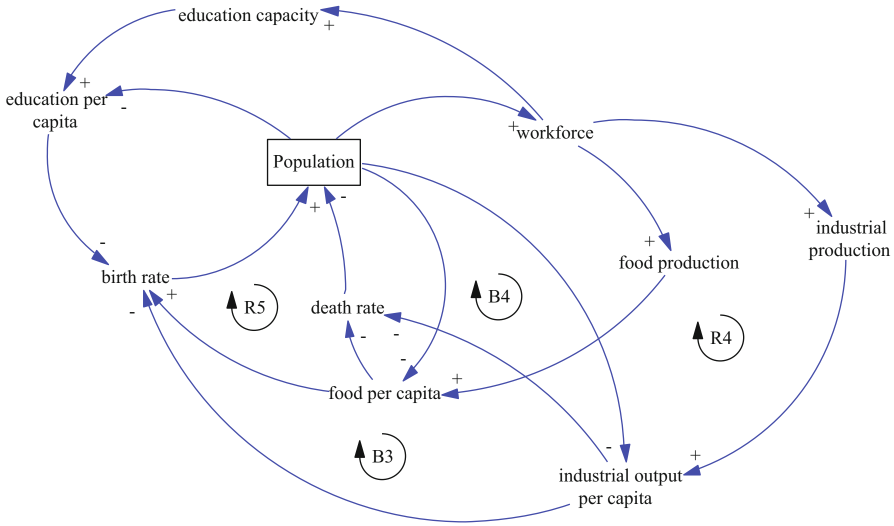


Fig. 13 Feedback structure of the population sector of the M-model (Part 2)

Minor Structural Imperfections in the M-Model

Although the overall structure of the M-model is excellent, there are two areas in which it is deficient. The first involves oil production; more specifically, oil production in the original version of the M-model can be doubled in just 1 year. Although this assumption might have been reasonable for the period before the Islamic revolution of 1979, when the Iranian state was able to attract as much foreign investment as it needed due to its good relationship with the developed world, it is not a valid assumption for the postrevolution era. Indeed, after the 1979 revolution the Iranian government could not persuade major oil companies to invest in its oil and gas industry (Katouzian 2009).

The second area in which the structure of the original M-model is deficient involves energy supply. The original model assumes that there is only one source of Iranian energy—domestic oil production. This assumption implies that the importation of energy is impossible. Even if the domestic supply of energy is sufficient for domestic energy demand, this assumption weakens the robustness of the M-model vis-a-vis extreme conditions. In other words, good system dynamics modeling practice requires that a model behaves correctly under extreme conditions, even if those conditions have never occurred in the actual system and/or will only occur in the model under extreme circumstances.

If a simulation run of the M-model depletes all Iranian energy resources, the economy still survives. Of course, this is extremely unrealistic. Mashayekhi (1978) argues that people will use wood when oil resources are scarce and the M-model implicitly assumes that burning wood is costless—which is simply not true. Despite these criticisms, available energy data shows that the net export of energy for Iran will be positive for at least next eight decades.[10] As a consequence, the structure of the M-model can be said to be adequate in simulation runs shorter than fifty years in duration.

Dimensional Consistency

Good system dynamics modeling practice requires that all of a model's equations be dimensionally consistent. This means that all of a model's equations must produce stocks that are measured in "units" and flows that are measured in "units/time." All of the equations in the M-model were checked and no dimensional inconsistencies were found.

Parameter Assessment

The parameter assessment test determines whether a model's parameter values are consistent with relevant descriptive and numerical knowledge of the actual system, and whether all the model's parameters have real world counterparts.

To answer these questions, all parameters of the model were checked and no inconsistencies were found among them and their real world counterparts. Mashayekhi's dissertation presents a comprehensive documentation of the M-model's parameters and how they were obtained.

[10] Simulations by Langarudi et al. (2011) show that Iran's net export of energy won't become negative until 2094. This result is yielded under this assumption that world demand for Iran's oil is infinitive so Iran can export that portion of its produced oil remaining after domestic consumption.

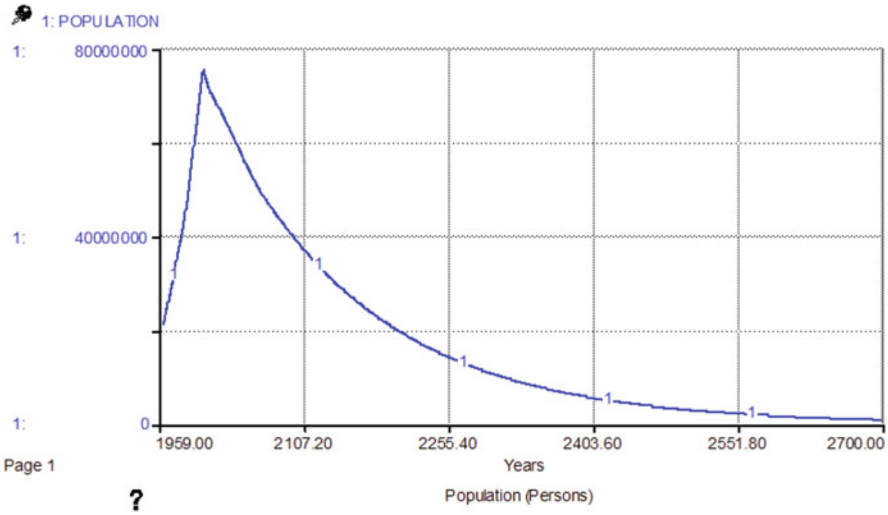


Fig. 14 Iranian population when the birth rate is set to zero after the year 2000

Extreme Condition Tests

Tests of extreme conditions are designed to evaluate whether or not each equation in a model makes sense when its inputs take on extreme values. In other words, they test whether or not a model's equations respond reasonably when subjected to extreme policies, shocks, and parameters.

To test the M-model for extreme conditions, each equation was evaluated, in isolation, for its response to extreme values for each of its inputs, alone and in combination. In addition, the overall M-model was subjected to large shocks and extreme conditions and then inspected for conformance to basic physical laws (e.g., an absence of inventory should mean there will be no shipments; zero labor should mean zero production).

All these tests revealed no serious problems with the M-model. However, some minor defects were detected. For example, the birth rate in the population sector was set to zero for all years after 2000. The result is shown in Fig. 14.

The Iranian population should have reached zero in approximately 150 years. However, Fig. 14 show that the Iranian population is still positive at year 2700. This implies that there are some individuals who can live for more than 700 years! The good news is that this deficiency does not significantly influence the primary results of the M-model and it can be corrected in a future version of the model.

Integration Error Tests

System dynamics models are continuous time models run on discrete machines (digital computers) and are thus solved via numerical integration. As a result, modelers must choose both a numerical integration method, and a time step, to approximate the continuous dynamics of the underlying system. Too large a time step utilized in concert with a particular numerical integration technique may yield too much integration error and thus simulated time paths that are too inaccurate for the problem at hand. Too small a time step utilized in concert with a particular numerical integration technique may yield simulated time paths that are unnecessarily precise for the problem at hand and thus simulation runs that are needlessly computationally intensive (i.e., slow).[11] Good system dynamics modeling practice, therefore, requires picking a time step/numerical integration combination that is no more accurate than is necessary for the problem at hand. This is typically accomplished by selecting an initial time step/numerical integration technique combination, running the model, cutting the time step in half, rerunning the model, and inspecting the pre- and postcut synthetic time paths for significant differences. When no significant differences in dynamic behavior can be detected, the model is deemed to be accurate enough for the problem at hand.[12]

The M-model was systematically tested with different numerical integration methods and time steps.[13] Euler's method (the default simulation method in most system dynamics modeling packages due to its simplicity and computational ease) proved to be fine and a time step reduction to 0.1 year yielded no significant change in model behavior.

Behavior Reproduction Tests

Many system dynamicists believe that historical fit is a weak test for model validity (Forrester 1973; Forrester and Senge 1996; Sterman 1984; Radzicki 2004). As Forrester (2003, p. 5) has written:

> There is no reason that a generic model should reproduce any specific historical time series. Instead, it should generate the kind of dynamic behavior that is observed in the systems that are being represented. If one runs the model with different noise sequences one will get simulations that have the same character, but not the same values at different points in time. Likewise, the time series from an actual economy represent only one of a multitude

[11] In the extreme, the smallness of a model's time step is limited by the precision of the digital computer being used.

[12] Mathematical rules of thumb relating a model's time step to its smallest time constant also exist in system dynamics modeling.

[13] Various numerical integration techniques have well-known strengths and weaknesses that come into play under different circumstances.

of detailed behaviors that might have occurred if the random effects in the real system had been different. In other words, historical data from a real economy should be interpreted as only one of a multitude of possible data histories.

The consensus view in the field of system dynamics is that, although reproducing historical behavior is only one of many tests required to build confidence in a system dynamics model, it can often be essential. Failure to convince a reviewer that a model's historical fit is satisfactory, for example, is often sufficient grounds for him/her to dismiss the model and its conclusions (Sterman 1984).

Sterman (1984) lays out a detailed example of how Theil's inequality statistics (Theil 1966) can be used to analyze the fit of a system dynamics model to historical data. These statistics are used in this chapter to examine the fit of the modified M-model to historical data from Iran. Before applying these statistics, however, the structural deficiencies of the M-model must be addressed and its behavior updated.

The first step in this process is to update the M-model's exogenous variables with the latest available data. Recall that the major exogenous variables in the M-model are oil exports and oil prices.

Utilizing modern data, the initial value of Iranian oil reserves was updated from 100 to 221 billion barrels. Iran's remaining proven reserves at the end of 2011 were estimated to be 154.6 billion barrels (OPEC 2012). The cumulative production of oil in Iran since 1959—which is the starting date for M-model simulations—until the end of 2011 was about 66.5 billion barrels (OPEC 2010). This means that Iran should have had 221.1 billion barrels of total proven reserves in 1959 ($154.6 + 66.5 = 221.1$ billion barrels). Of course, alternative values for initial oil reserves also can easily be tested in the model.

Figure 15 presents a comparison of actual and simulated Iranian non-oil output, from 1959 to 2007, after updating the initial value of Iranian oil reserves in the M-model as described earlier.[14] Other key variables from the M-model were monitored during this recalibration process but are not presented here due to space limitations.[15]

Non-oil output was chosen as a more plausible index of general economic output than GNP because GNP includes oil revenue. Since oil revenue is exogenously determined by a historical time series from 1959 to 2007, a large portion of the M-model's ability to reproduce Iranian GNP would be attributable to an exogenous input. Focusing on non-oil output, on the other hand, can better illustrate the M-model's ability to *endogenously* replicate the real system's behavior.

Figure 15 shows that the updated M-model's *qualitative* behavior, i.e., exponential growth followed by a peak, a decline, and the resumption of exponential growth, is very close to the real system's behavior. The point-by-point fitness of the M-model, however, is clearly not acceptable. Therefore, it is necessary to review the original assumptions of the M-model and if possible, modify them in order to improve the model's ability to replicate Iranian economic history.

[14] All real world data presented in this chapter comes from three main sources: (1) the electronic database of the Central Bank of Iran (CBI 2012), (2) OPEC Annual Statistical Bulletin (OPEC 2010, 2012), and (3) the BP Statistical Review of World Energy (BP 2012)

[15] A summary of the M-model's ability to replicate the dynamics of the key variables in the Iranian economy is presented at the end of this section in Table 2.

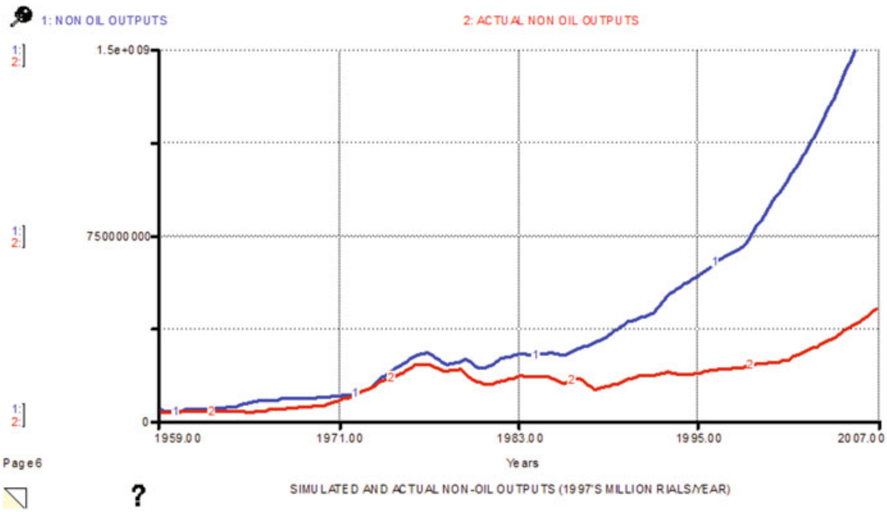


Fig. 15 Actual and simulated Iranian non-oil output from 1959 to 2007 after updating the initial value of Iranian oil reserves

As Fig. 15 demonstrates, the discrepancy between the behavior of the updated M-model and Iranian historical data starts and expands after 1979 when the Islamic revolution took place. As was previously mentioned, this revolution was followed by an eight-year war with Iraq. The most likely cause of the divergence between the actual and synthetic data presented in Fig. 15, therefore, is these events and the changes they caused in Iranian political economy. To test this hypothesis, structural changes representing the revolution and war must be introduced into the M-model. Katouzian (2003) argues that Iranian society had to endure the following impacts from the revolution and the war beginning in 1979:

1. A reduction in oil exports.
2. A reduction in the utilization of production capacity in the economy.
3. A high rate of capital flight.
4. A high rate of brain drain.
5. A reduction in the rate of investment.
6. A deep enmity between Iran and Western countries.

Here is an explanation of how these impacts are introduced into the M-model:

1. *Reduction in oil exports*. Since oil exports are treated as an exogenous input into the M-model until 2007 no further action is required.
2. *Reduction in the utilization of production capacity in the economy*. To introduce this effect a new variable called the "economic security indicator" (ESI) is introduced into the M-model. This variable is positively influenced by the growth rate of Iranian GNP, but only after a significant asymmetrical delay. More precisely, when the Iranian GNP growth rate increases the ESI increases, and when it decreases the ESI decreases. However, the delay between a change in Iranian GNP

and a change in the ESI is *longer* when GNP is rising compared to when GNP is declining. Changes in the ESI then influence the utilization of production capacity in the economic sectors of the M-model. The rationality behind this assumption is that after the 1979 revolution many business owners left or had to leave the country because they were suspected to be in contact with the dethroned Shah or his family (Katouzian 2009). In addition, many factories were underutilized due to an economic recession which was the natural result of the 1979 political turmoil and the war with Iraq (Pesaran 2000).

3. *High rate of capital flight*. To introduce this effect into the M-model, the ESI is also modeled to affect foreign exchange reserves.
4. *High rate of brain drain*. The M-model assumes that a fixed percent of highly educated people emigrate every year from Iran after the 1979 revolution. The percent rate of emigration can be changed by the model user.
5. *Reduction in the rate of investment*. Since investment rates in the M-model are determined by desired investment rates, and desired investment rates are based on the current utilization of a sector's production capacity, the effect of the ESI on the utilization of production capacity automatically adjusts the M-model's investment rates in response to the overall condition of the Iranian economy.
6. *The enmity between Iran and Western countries*. After the 1979 revolution some actions by radical Iranian revolutionists turned the governments of many western nations against the new Iranian state. The response of these governments was to implement political and economic sanctions against Iran. This forced Iran to pay higher prices for imported goods. Another result of this hostility was an increase in the difficulty Iran faced in transferring-in technology from developed countries. These facts are introduced into the M-model by defining a "hostility effect multiplier." This multiplier is an autonomous number between zero to four. When it is zero, it means that there is no hostility effect while "four" represents the highest tension in Iranian foreign relationships. Then, this multiplier affects two variables in the model: it has a negative impact on "technology transfer rate" and a positive impact on the value of "imports" (it increases the import expenses). Users of the M-model can manually change this multiplier to see how it influences the system's dynamics.

Figure 16 presents a comparison of actual and simulated Iranian non-oil output, from 1959 to 2007, after the next set of modifications (described earlier) are introduced into the M-model. A quick visual inspection of the figure reveals that the changes have significantly improved the ability of the M-model to reproduce Iranian historical data.

A more rigorous analysis of the ability of the M-model to reproduce historical data from the Iranian economy involves Theil's Inequality Statistics. Table 2 presents the Theil Statistics for four key variables from the M-model. In this table, r represents the correlation coefficient between simulated and actual data; U represents the inequality coefficient and U^M, U^S, and U^C reflect the fraction of the mean square error (MSE) attributable to bias, unequal variance and unequal covariance, respectively.

Fig. 16 Actual and simulated Iranian non-oil output from 1959 to 2007 after introducing the second set of changes

Table 2 Theil statistics for four variables from the M-model after introducing the second set of changes

Variables	r	U	U^M	U^S	U^C
GNP	0.984697	0.057733	0.192186	0.100753	0.707062
Non-oil outputs	0.978745	0.062130	0.208761	0.161118	0.630121
Oil production	0.929713	0.090369	0.174969	0.012924	0.812107
Population	0.996077	0.017460	0.045054	0.019337	0.935609

GNP gross national product

Inspection of Table 2 reveals that the correlation coefficient for all four variables is quite high and the inequality coefficient is reasonably low. Moreover, the majority of the MSE for all four variables is concentrated in unequal covariation (U^C). *Sterman* (1984, p. 220) interprets this situation as follows:

> If the majority of the error is concentrated in unequal co-variation U^C, while U^M and U^S are small, it indicates that the point-by-point values of the simulated and actual series do not match even though the model captures the average value and dominant trends in the actual data well. Such a case might indicate a fairly constant phase shift or translation in time of a cyclical mode otherwise reproduced well. More likely, a large U^C indicates one the variables has a large random component or contains cyclical modes not present in the other series. In particular, a large U^C may be due to noise or cyclical modes in the historical data not captured by the model. A large U^C indicates the majority of the error is unsystematic with respect to the purpose of the model, and the model should not be faulted for failing to match the random component of the data.

Therefore, it is reasonable to conclude that the second set of revisions to the M-model enable it to reproduce the actual system's behavior reasonably well. Not only are all the inequality coefficients from the Theil statistics small but most of the errors are unrelated to bias or unequal variance between the simulated and actual data.

Behavior Anomaly Tests

Data limitations often lead to difficulty in establishing the statistical significance of many relationships in a model. The importance of these relationships can, nevertheless, be examined by "behavior anomaly tests." These tests involve determining whether or not anomalous model behavior arises when a relationship is deleted or modified. Anomalous behavior generated due to the elimination of a relationship would be a sign of the importance of the relationship. Most of the relationships in the M-model were tested and no unnecessary or useless structure was found.

Family Member Tests

The family member test examines a model's ability to generate the behavior of other cases within the same class as the system being modeled. The greater the number of cases a model can mimic, the more general the theory the model represents.

The M-model was developed to address Iranian macroeconomic issues. Iran is an oil-exporting country and is highly dependent on its oil revenue. It also has a relatively large population and a notable agricultural sector with about 16 % average share of total GNP value (during 1959–2007) (CBI 2012).

In the real world it is possible to identify clusters of nations that are somewhat similar to Iran. Karl (1997, 1999), for example, argues that Iraq, Nigeria, Algeria, Indonesia, Venezuela, Ecuador, and Mexico possess many common characteristics and refers to them as "capital-deficient" countries. To pass a family member test, the M-model must be able to generate the macroeconomic behavior of at least some of these countries after a reasonable amount of modification to reflect each nation's unique features. Although this sort of effort is beyond the scope of this chapter, it can be argued that the M-model possesses a generic structure that can be applied to all "capital-deficient" countries.

Surprise Behavior Tests

Inconsistency between a model's behavior and its expected behavior reveals that there are some deficiencies in the formal model, the modeler's "mental model," or both. According to Sterman (2001, p. 882):

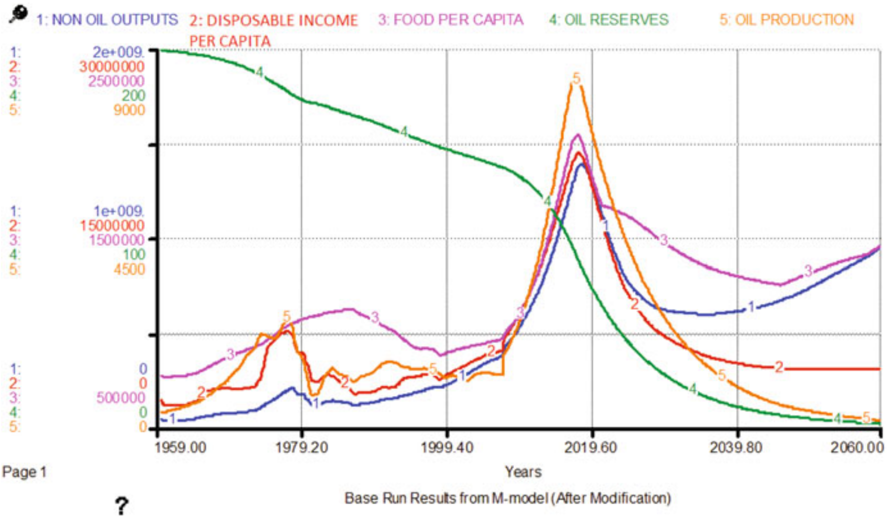


Fig. 17 Base run of the M-model from 1959 to 2060 after the second set of modifications have been introduced

> Often, of course, discrepancies between model output and our understanding of the system's dynamics indicate flaws in the formal model. Occasionally, however, it is our mental model and our understanding of the data that require revision.

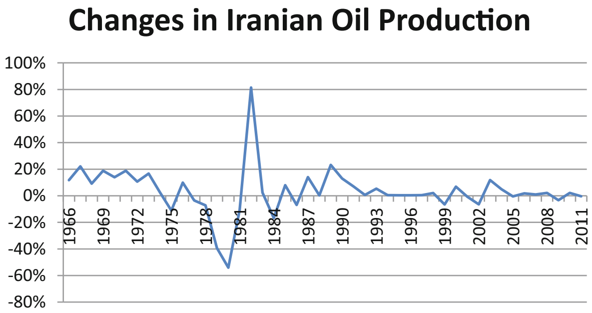
The surprise behavior test is passed when a model generates a certain behavior, previously unrecognized, and it does indeed occur in the real system.

To test the M-model for surprise behavior it must be run under a variety of scenarios and its results carefully examined. Figure 17 presents a base run for the M-model from 1959 to 2060 after the second set of modifications has been introduced. The synthetic variables presented include: non-oil outputs (million rials per year), disposable income per capita (rials per person per year), food output per capita (rials per person per year), oil reserves (billion barrels), and oil production (million barrels per year).

After the second set of modifications the M-model produces the following behavior from the year 2007 forward. Oil production and oil exports grow exponentially causing Iranian oil reserves to deplete rapidly. The increase in oil exports provides the Iranian government with an influx of foreign exchange. This huge windfall of oil revenue makes it possible for Iran to import the goods it needs. It also improves the people's purchasing power, so the demand for consumption goods rises. The urgent need for an increased supply of consumption goods shifts the economy's production factors from its other sectors to the consumption goods sector. As a result, the intermediate goods sector weakens.

Of course, the economy needs intermediate goods to keep the production capacity of the consumption goods sector fully utilized. A quick response to this pressure is to import intermediate goods. This would normally address the problem in the short-term. However, over time Iran's oil reserves deplete at a rapid rate causing oil revenue

Fig. 18 Historical data for changes in Iranian oil production 1965–2011. (BP 2012)



to decrease and the importation of intermediate goods to become limited. Since the economy cannot seamlessly substitute the production capacity of the consumption sector for the production capacity of the capital goods sector, this leads to a severe depression. Stated differently, the depletion of Iranian oil reserves shown in Fig. 17 occurs so quickly that the economy cannot react to it in a timely fashion.

Even though the modified M-model generates an internally consistent story, some aspects of its behavior are surprising. For example, there is no way that Iranian oil production could expand as quickly as is shown in Fig. 17. The sharp increase in oil production is related to an unrealistic assumption embedded in the model. More specifically, the M-model assumes that Iran is able to double its oil production in a period as short as 1 year. An examination of the historical data, however, shows that this cannot possibly be true, particularly in the postrevolution era.

Figure 18 shows the history of changes in Iranian oil production from 1965 to 2011. From an inspection of the figure it is clear that Iranian oil production has not been able to rise dramatically in any given year since the 1980s. Indeed, the last extraordinary high growth rate (23 %) occurred in 1989. Moreover, significant increases in oil production appear to occur in years following a deep *fall* in oil production. This implies that high rates of growth are due to the reutilization of an underutilized *existing* production capacity, rather than from an increase in overall production capacity.

After the 1979 revolution the expansion of Iran's oil production capacity became more difficult because of a dramatic change in the new state's foreign policies that made foreign investment problematic. Energy economists believe that the main contemporary challenge in the Iranian energy sector is the lack of funding and investment (Barkeshli 2006). It is perhaps reasonable to assume that the prerevolutionary Iran could double its oil production in 1 year, but it is not a realistic assumption for the postrevolutionary Iran.

Clearly, the surprise behavior of the M-model presented in Fig. 17 reveals a need to further modification of the M-model's structure. The next version of the model assumes that the maximum growth rate of Iranian oil production is 14 %[16]. The model is run again and the results are shown in Fig. 19.

[16] Except for 1981, the highest growth rate after the revolution is 10.98 % in 1988 (BP 2012)

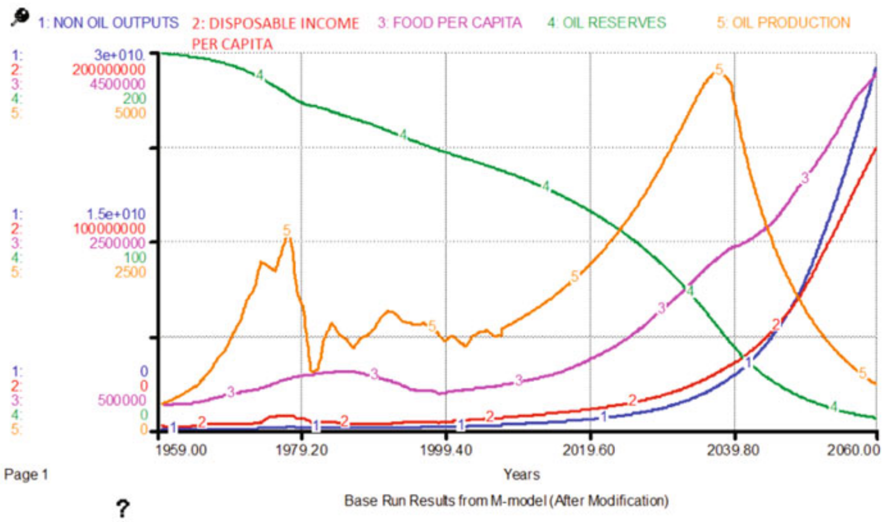


Fig. 19 Base run of the M-model from 1959 to 2060 after introducing the final modification

Figure 19 reveals that there is no severe depression in the economy from 2007 to 2060, despite the egregious depletion of Iranian Oil reserves. The reason is that Iranian oil production grows more slowly than in previous versions of the M-model (compare to Fig. 17) and the model economy, therefore, has enough time to wean itself from oil revenue. In other words, Iran's inability to absorb enough investment to develop its oil industry leads to less dependency on oil revenue. In fact, this was a policy originally proposed by *Mashayekhi* (1978) to alleviate the economic recession he had predicted for the 1990s. He had suggested that the Iranian government could slow down the production of oil *as a policy choice* so that the economy could adapt to the difficulties that would arise from the reduction in oil revenue he predicted for the 1990s. In reality, the 1979 revolution and war with Iraq *forced* Iran to slow down the production of oil. But, regardless of whether the slowdown was voluntary or mandatory its results are consistent with Mashayekhi's prediction.

Sensitivity Analysis

Sensitivity analysis reveals the robustness of a model's results with respect to changes in the values of its parameters over a reasonable range of uncertainty. There are three types of model sensitivity: "numerical," "behavior mode," and "policy." A model is numerically sensitive when a change in the values of its parameters changes the numerical values associated with its behavior. Of course, no mathematical model can be perfectly numerically insensitive. A model is behaviorally sensitive when the patterns of behavior it generates change with a change in the values of its parameters.

For instance, a model would demonstrate behavior mode sensitivity if reasonable alternative parameter values changed its behavior from, say, overshoot and collapse to s-shaped growth. Policy sensitivity exists when the impact or suitability of a suggested policy change is significantly altered by a change in the values of a model's parameters.

Since the purpose of the M-model is to determine whether or not Iran will experience economic growth during its transition from an oil-rich to an oil-poor nation, the focus of this section will be on behavior mode and policy sensitivity.

Behavior Mode Sensitivity

The behavioral sensitivity of the modified M-model will be reported in this section. To conduct the test, the values of important parameters in the M-model were systematically varied over a range of uncertainty and an examination of how the M-model's behavior changed in response was conducted. "Disposable income per capita" is chosen as the proxy for the model's overall behavior and as an example of the test.[17] Each of the parameter values was randomly altered twenty times over a range of $\pm 50\,\%$ of their base case values, using a uniform probability distribution.

The overall results of the behavior mode sensitivity test showed that, generally speaking, the modified M-model's behavior is *not* sensitive to changes in its parameters. However, a few parameters did prove to be more influential than others. The sensitivity test for five of the model's parameters is shown later.

Consider the modified M-model's two Cobb–Douglas production functions—one for the industrial sector and the other for the agricultural sector. Sensitivity testing revealed that the model is numerically *very* sensitive to the elasticity parameters for the inputs to the two functions. For example, Fig. 20 presents the sensitivity of the modified M-model to changes in "exponent of labor in agricultural sector production function" (ELA). The base value of this parameter is 0.45 and the range for the sensitivity test was 0.225–0.675. Although the modified M-model is *numerically* very sensitive to the value of *ELA*, its *behavior mode* does not change significantly. Sensitivity analysis for the parameters of the other production function in the modified M-model yields similar results.

The next parameter examined is "fraction of investment in capital equipment" (FICE). This parameter determines the portion of domestic demand that is allocated to capital goods production and the portion that is allocated to construction. The base value for FICE is set to 0.317 and the range for the sensitivity test was 0.158–0.475. Figure 21 presents the results. From a visual inspection of the figure, it is obvious that the M-model's behavior is not sensitive to the changes in *FICE*.

Another parameter which was selected for examination is "normal reserve coverage time" (NRC). This parameter determines how quickly the government depletes Iranian oil reserves. The base value for this parameter is set to 15 years. This means

[17] The behavior of all of the M-model's key variables was examined during the behavior mode sensitivity test but space limitations prevent their presentation in this chapter.

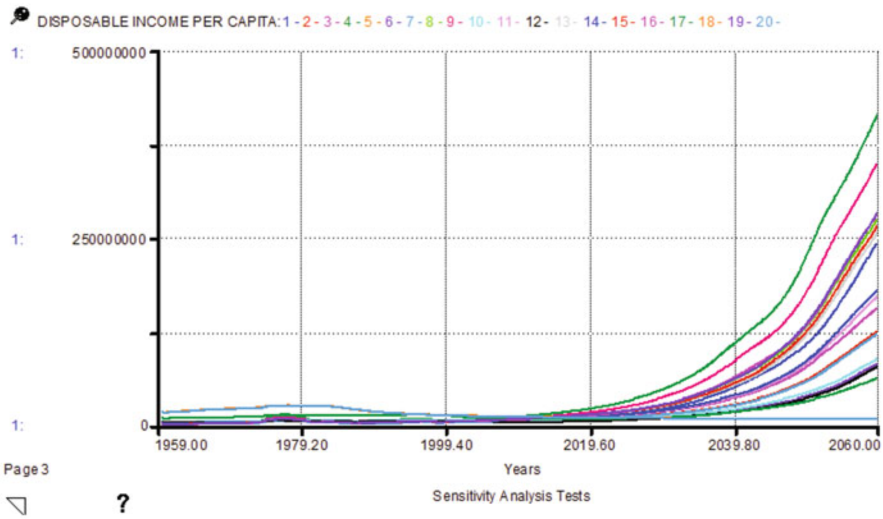


Fig. 20 Behavioral sensitivity of disposable income per capita in the modified M-model to changes in ELA

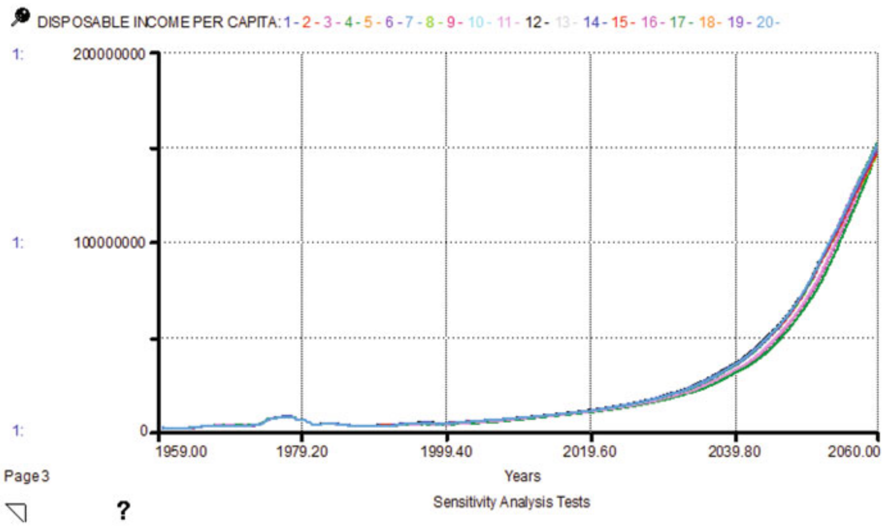


Fig. 21 Behavioral sensitivity of disposable income per capita in the modified M-model to changes in fraction of investment in capital equipment (FICE)

that the Iranian government adjusts its oil production rate such that existing oil reserves will last 15 more years. The range of values for the sensitivity test was chosen to be between 8 and 22 years. The results of the test are shown in Fig. 22. Again, from a visual inspection of the figure, it is obvious that the modified M-model's behavior is insensitive to changes in NRC.

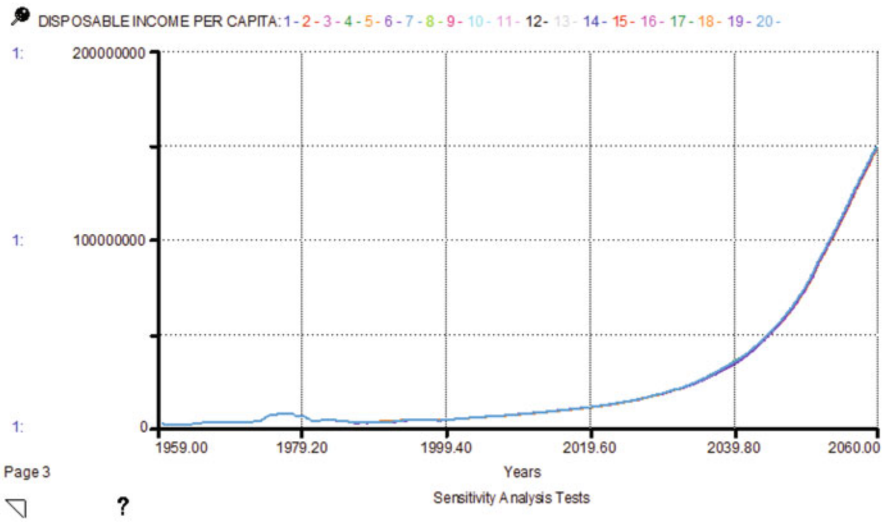


Fig. 22 Behavioral sensitivity of disposable income per capita in the modified M-model to changes in normal reserve coverage time (NRC)

The next parameter selected for presentation is "normal industrial output per capita" (NIPC). In the population sector, the birth and death rates depend on the level of industrialization in the country. NIPC provides a base value against which industrial output per capita generated by the model can be compared. This comparison provides an indication of the rate of Iranian industrialization. The base value of NIPC is 1,015,272 rials and the range of its value during the sensitivity test is 507,636–1,522,908 rials. Figure 23 presents the results of the test. Once again there is no evidence that the modified M-model is behaviorally sensitive to changes in NIPC.

The next test of model sensitivity involves the parameter "non-oil output per capita normal" (NOOPCN), which provides a base value against which non-oil output per capita (NOOPC) can be compared. If the ratio of NOOPC to NOOPCN is greater than 1 Iranian education capacity expands. Alternatively, if the ratio is less than 1 Iranian education capacity shrinks. The default value of NOOPCN is 3,555,739 rials per year per person (RPYPP) and the range of values explored during the sensitivity test is 1,777,870–5,333,608 RPYPP. The results of the sensitivity test are shown in Fig. 24.

Clearly, the behavior of the modified M-model is insensitive to this parameter. For the last example presented in this chapter, all five of the parameters discussed earlier are varied simultaneously. Figure 25 shows that the modified M-model is *numerically* sensitive, but *behaviorally* insensitive, to the combined set of changes. Indeed, all but one of the simulation runs generates exponential growth in disposable income per capita.

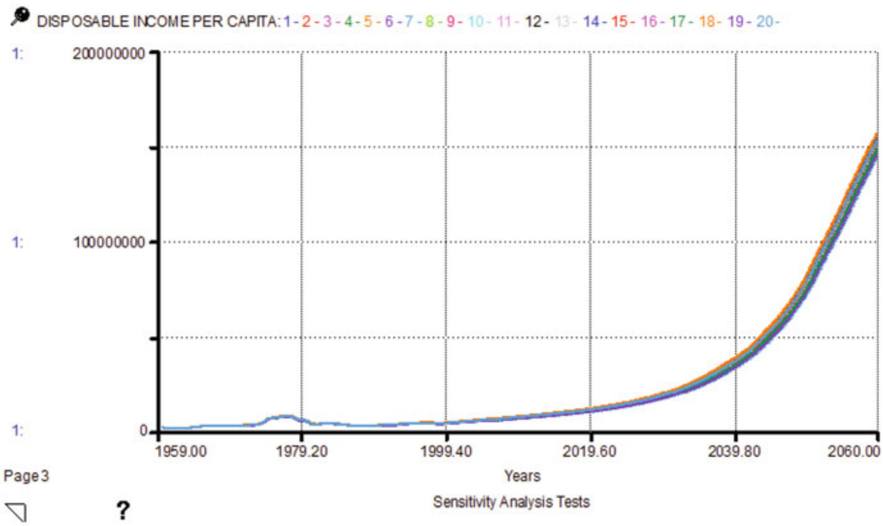


Fig. 23 Behavioral sensitivity of disposable income per capita in the modified M-model to changes in normal industrial output per capita (NIPC)

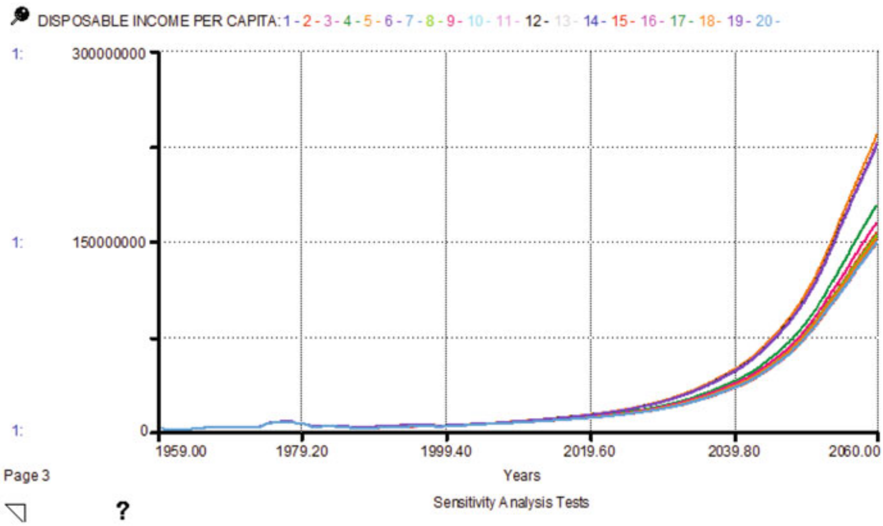


Fig. 24 Behavioral sensitivity of disposable income per capita in the modified M-model to changes in non-oil output per capita normal (NOOPCN)

Policy Sensitivity

If decision makers are to have confidence that the policy prescriptions generated by a system dynamics model are likely to yield the same results in the real system as they do in the virtual world, the policy prescriptions have to be robust. That is, the

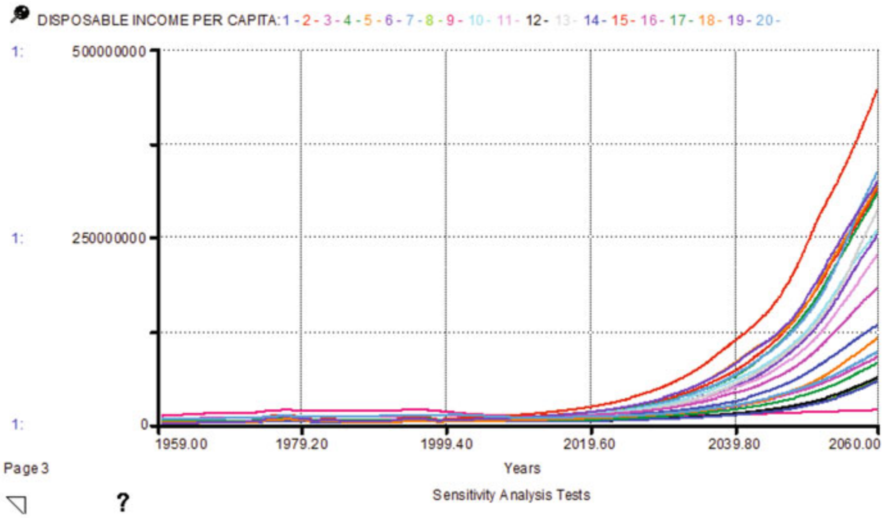


Fig. 25 Behavioral sensitivity of disposable income per capita in the modified M-model to simultaneous changes in all five parameters

policy prescriptions should not change when a model's parameters are varied over a reasonable range of values.

This section will present the results of policy sensitivity tests run on the modified M-model. As a prerequisite, however, some policy conclusions need to be drawn from the model.

Recall that, although the M-model has the potential to be a foundational platform for Iranian macroeconomic modeling, its current structure is quite limited. More specifically, its current structure is appropriate for examining issues related to the oil dependency of the Iranian economy, but not for answering broader macroeconomic questions in the areas of fiscal, monetary, or income redistribution policies.

Recall also that one of the counterintuitive conclusions drawn from simulations of the M-model is that *slowing down* or *limiting* investment in Iranian energy production will yield long-term benefits for the economy. This conclusion is in sharp contrast to the viewpoint held by many energy experts who believe that the Iranian government should attract *more* investment to speed-up Iranian oil and gas production (Barkeshli 2006).

The "more investment now" viewpoint is principally based on two perceptions. First, most of Iran's proven oil reserves are in the second half of their life cycles (MOE 2008). As a result, if secondary or tertiary oil recovery methods are not brought on-line, it will become increasingly difficult to exploit these reserves in the future (Ahmed 2006). To bring these methods on-line, however, Iran will have to invest more in its energy sector. Second, Iran shares some of its oil and natural gas fields with its neighbors (e.g., Qatar). If these jointly-owned reserves cannot be exploited in a timely fashion, they will impose some opportunity costs on the Iranian economy. Investing more in its energy sector now, rather than later, will increase the probability that the jointly-owned reserves can be utilized by Iran.

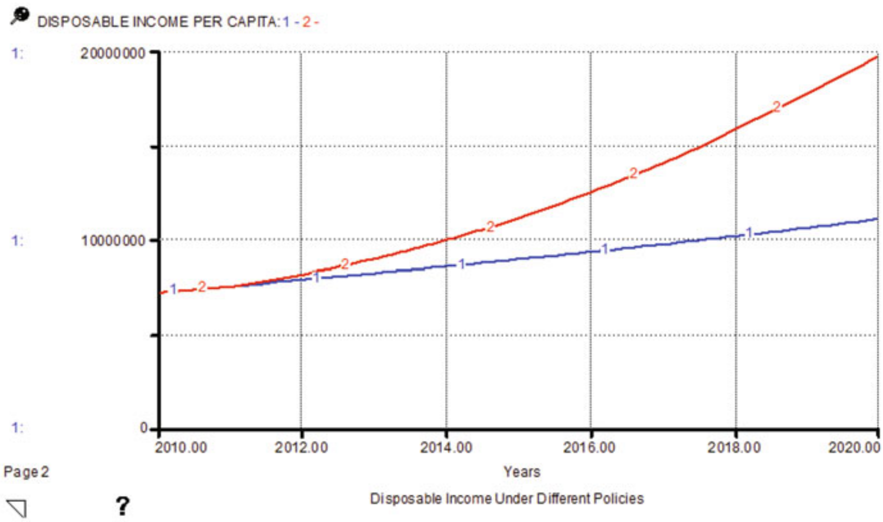


Fig. 26 Time paths for disposable income per capita from 2010 to 2020 under the "slow investment down" and "more investment now" strategies

The implications of the "more investment now" versus the "slow investment down" strategies can be tested with the modified M-model by simulating a change in Iranian foreign policy. To test the "more investment now" strategy, the assumption is made that the Iranian government improves its relationships with the developed countries and, as a result, is able to accelerate its production of oil. More precisely, it is assumed that this about-face in foreign affairs will allow Iran to double its oil production in as little as 1 year.[18] The simulation run embodying this assumption can be compared with an earlier one in which the maximum oil production growth rate was assumed to be 14 %. This is the "slow investment down" strategy. The short-term and long-term implications of these strategies can be compared separately. Figure 26 shows the time paths for "disposable income per capita" in the short-term (2010–2020).

Curve 1 represents the "slow investment down" strategy and curve 2 represents the "more investment now" strategy. Over this narrow period of time it is clear that increasing Iranian oil production capacity at a faster rate can yield higher economic welfare.

Figure 27, on the other hand, shows that the story is different in the long run. Although superior in the short-term, the "more investment now" strategy leads to an economic depression in the long-term because the economy cannot adjust to a lack of oil revenue caused by depletion.

The robustness of this policy conclusion can now be examined. To conduct this sensitivity test the protocol from section "Behavior Mode Sensitivity" will again be

[18] Recall that this was an assumption in the original M-model.

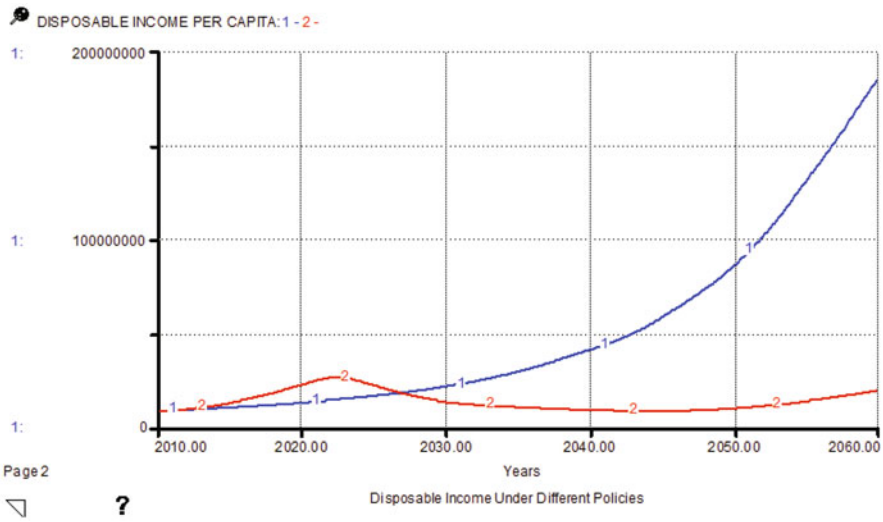


Fig. 27 Time paths for disposable income per capita from 2010 to 2060 under the "slow investment down" and "more investment now" strategies

utilized. Further, the same parameters that were varied in section "Behavior Mode Sensitivity" will be changed with the only difference being that, for each sensitivity run, each parameter is given only one new value. Similar to the results presented in Fig. 25, all of the parameters will be altered simultaneously.

Figures 28 and 29 show representative results from the policy sensitivity test in both the short and long runs, respectively. In both cases, curves 2 and 4 repeat the same results shown in Figs. 26 and 27 while, curves 1 and 3 show the time paths generated by the modified M-model with new, randomly chosen, parameter sets. In both, the short and long runs, the *behavior modes* are insensitive to the parameter changes. The overall conclusion of the test is that the modified M-model's policy recommendations are robust—that is insensitive to changes in model parameters.

System Improvement Tests

Solving a problem in an actual system is the ultimate goal of a system dynamics modeling project. A system improvement test is designed to determine whether or not the modeling process led to the achievement of this goal.

There are three parts to a system improvement test: (a) the model must generate policies which can improve the behavior of the system; (b) those policies must be applied in reality; and (c) the policy changes should enhance the performance of the real system in the ways suggested by the model. However, evaluating the impact of a model in practice is almost impossible. As Sterman (2001, pp. 887–888) explains:

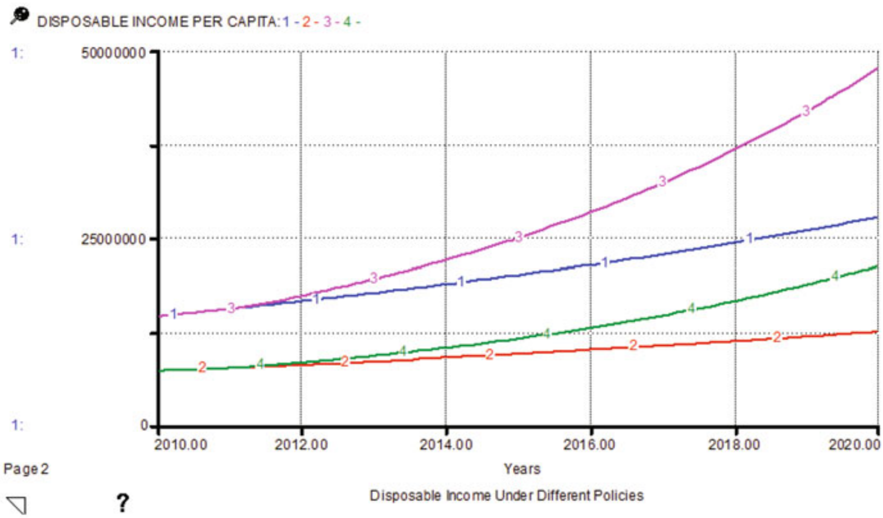


Fig. 28 Sensitivity of time paths for disposable income per capita from 2010 to 2020 under the "slow investment down" and "more investment now" strategies

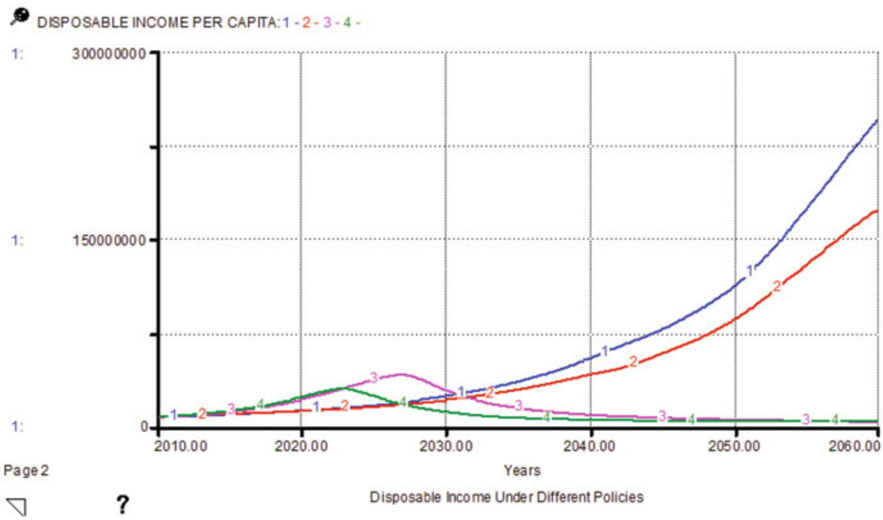


Fig. 29 Sensitivity of time paths for disposable income per capita from 2010 to 2060 under the "slow investment down" and "more investment now" strategies

It is hard to assess the extent to which the modeling process changed people's mental models and beliefs. It is rare that clients adopt the recommendations of any model promptly or without modification. When new policies are implemented, it takes a long time for their effects to manifest. Many other variables and conditions change at the same time new policies are implemented, confounding attempts to attribute any results to the policies. Performance improvement following a study does not mean the model-based policies were responsible; the system may have improved for reasons unrelated to the modeling process. Likewise, deteriorating performance after policy implementation does not mean the model failed since the outcome could have been even worse without the new policies.

In the present case, the ability of the M-model to pass a system improvement test is even more difficult to assess because it was never used by Iranian decision makers. Nevertheless, a case can be made that the M-model is able to pass this test. First, as was argued earlier in this chapter, the political conflict between Iran and Western countries after 1979 led to the reduction of Iranian oil production, which was one of the policies that Mashayekhi had suggested in his study. In other words, one of Mashayekhi's policy recommendations stemming directly from the M-model was implemented in the actual system, albeit accidentally rather than deliberately.

Second, after the publication of M-model's conclusions in Iran (Mashayekhi 1984) the topic of oil dependency came to the forefront in the academic arena. It also turned out to be an appealing subject in Iranian presidential elections. Indeed, all presidential candidates during and after the 1990s have emphasized the need for Iran to become independent of oil revenues and have promised, if elected, to implement policies that will lead this outcome (Katouzian 2009). Since other publications devoted to the topic of Iranian oil dependency appeared during the same period of time,[19] it is difficult to say which study had the greatest impact on Iranian society, but Mashayekhi's study had two advantages: (1) a version of it was published in Farsi, and (2) it was very easy to read and understand. It can be argued therefore that, although the M-model was unable to change the government's behavior regarding the oil dependency issue, it may have contributed to changing the mental models of the Iranian people.

Conclusions

In this chapter, a classic system dynamics model developed by Ali Naghi Mashayekhi in 1978 was resurrected, updated and revalidated. The goal of the model is to investigate the issue of Iranian oil dependency. The original model had predicted that Iran would face a harsh economic recession during the 1980s due to a steep fall in oil revenue caused by natural resource depletion. Thirty-five years later, however, Iran's oil reserves remain intact and the country has not encountered the sort of severe depression that was predicted.

An examination of the original M-model showed that it did not contain the structure necessary to capture the dynamics of the Islamic revolution or the war with Iraq that occurred during the 1980s. Updating the M-model's exogenous variables, modifying some of its assumptions, and recalibrating some of its parameters significantly improved its ability to reproduce Iranian economic history.

Revalidation of the M-model has shown that it is fairly robust and generally reliable. Although it is an excellent tool for analyzing questions directly related to the issue of Iranian oil dependency, however, due to its relatively narrow boundary it

[19] For example see Mahdavy (1970); Vakil (1977); Katouzian (1978); and Amuzegar (1983).

is an inadequate platform for analyzing many contemporary Iranian macroeconomic policies. Broadening the boundary of the M-model by adding sectors such as a financial market, a foreign exchange market, a labor market, and an energy market would greatly enhance its versatility. As such, it can be argued that the M-model can serve as a foundational platform for future Iranian macroeconomic modeling efforts.

Finally, this chapter can serve as a starting point and archetype for those who wish to develop a system dynamics macroeconomic model of a resource-dependent developing nation. Future research involving the use of the M-model for this purpose should, therefore, address the following issues:

1. As previously mentioned, the boundary of the M-model should be broadened to include a financial market, foreign exchange market, labor market, and an energy market.
2. The energy sector of the M-model should be revised to address energy–economy interactions. For example, the original M-model and its current modified version contain only one source of energy—oil. The boundary of the energy sector needs to be broadened to include alternative sources of energy and the economics of their substitutability.
3. The importation of energy is impossible in both the original M-model and its current modified version. This is not acceptable, particularly when the purpose of the model is to analyze energy–economy interactions.
4. The production functions in both the original M-model and its current modified version are very sensitive to their elasticity parameters. The formulation of these functions should be modified to eliminate this fragility.
5. The modified M-model should be recalibrated to see if it can reproduce the behavior of other "capital-deficient" oil exporting nations such as Nigeria, Algeria, Indonesia, Venezuela, Ecuador, or Mexico that have large populations and significant agricultural sectors.

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