Using counterfactuals from macroeconomic models to assess risks to accomplishment of structural innovations

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Abstract. A macroeconomic model often described as an input-output model, is specified mathematically to characterize production and consumption in an economy. Perturbations of attributes this macroeconomic model allow the examination of counterfactuals - hypothetical scenarios that run “counter to the facts” of an existing reality – to assess risks to accomplishments of structural innovations in light of plausible endogenous or exogenous shocks to the economy.

1. Introduction

Systems for risk management aim to minimize exposure to risk by lowering the probability that losses occur and by mitigating the severity of any losses that actually occur. Risk management involves assessing risks through identifying, analyzing, and prioritizing risks and controlling risks through planning, resolution, and monitoring actions [1]. Minimizing risks promotes fiscal responsibility, budget control, and on-time delivery.

Described in this paper is the use of a generally-applicable macroeconomic model to characterize production and consumption in an economy to assess risks to accomplishments of structural innovations that might involve new methods, ideas, or products introduced to markets incrementally or disruptively. The type of macroeconomic model described in our article often is described as an economic input–output model because it accounts for goods and services that are required as inputs by industries to produce outputs of goods and services to satisfy supply requirements of other industries and for delivery directly to consumers [2, 3].

The macroeconomic model described in this article forms a basis for simulating economic counterfactuals that can assist with risk assessment. A counterfactual is a hypothetical scenario that runs “counter to the facts” of an existing reality. A counterfactual condition entails “What if…?” questions that represent thought experiments about propositions that run counter to the facts. For instance, how would an economy have grown and changed if an activity or event did not occur? How do supply chain constraints or disruptions affect an innovation? The potential impact of an activity, event, or constraint is the difference between what would have happened with and, then, without the activity, event, or constraint.

Researchers long have used the counterfactual approach to consider strategic decisions, decisive acts, and paths of activity as if they had not been executed in history. For instance, in Ab Urbe Condita Libri [4], Titus Livius Patavinus, a Roman historian, contemplated an alternative 4th century BC that
questioned, “What would have been the results for Rome if she had been engaged in war with Alexander?” The modern counterfactual approach goes back at least to the 18th century Scottish Enlightenment philosopher David Hume [5], and historians, essayists, and novelists have applied counterfactual thinking productively in a variety of situations. For instance, in 1931 Winston Churchill wrote an essay, “If Lee Had Not Won the Battle of Gettysburg,” that examined the counterfactual viewpoint about what would have happened if the Confederacy (an unrecognized republic in North America that existed from 1861 to 1865) had won the American Civil War [6]. In 1962, Philip K. Dick, a novelist in the science fiction genre, published The Man in the High Castle [7], a narrative of a thought experiment that considered the consequences if Nazi Germany and Imperial Japan had won the Great Patriotic War (or the Second World War as described by many).

Counterfactuals can be examined with input–output models. The typical way to conduct such a counterfactual approach is to construct and compare two economic scenarios. The first scenario contains a possible alteration in the economy – the counterfactual – that would be pertinent to realization of a structural innovation. For instance, an alteration might result from changes in production of a strategic material, such as steel, that is a requirement necessary to sustain a structural innovation. The second scenario merely maintains the “status quo” scenario under the assumption that the economy simply grows and changes consistently according to historical trends. The difference between the first and the second scenarios is the potential economic impact of the economic alteration specified in the first scenario (e.g., the impact of decreased availability of steel on the innovation).

The results of such counterfactual economic analyses are not economic forecasts. Rather, such analyses isolate the importance only of one narrow group of changes in an economy by showing the gross effect of these changes rather than the effect of changes net of all other potential changes taken together that could affect an economy. A counterfactual used with input–output methods typically is specified under the assumption of ceteris paribus – that is, with the assumption of “all other things remaining the same” or, as is much more restrictively used in physics and other sciences [8], “if, and only if, all other things are the same and correct” In this vein, Ceteris absentibus, a term meaning literally “others absent,” probably best describes the approach for economic counterfactuals [9].

Specified in the next section of this article is the input-output macroeconomic model that forms the basis for counterfactual analysis. Then, described are classes of counterfactuals that could identify macroeconomic risks to accomplishment of structural innovations.

2. Materials and methods

2.1. Specification for a macroeconomic model. Structure
Consider an economy with \( I \) producing industries and \( J \) purchasing industries, where \( I = J \). Some of the output of industry \( i \) is sold to other \( j \) industries for use in their own production. Let \( X \) stand for a square matrix of interindustry transactions, with elements \( x_{ij} \) containing the monetary value of goods and services sold by producing industry \( i \) to purchasing industry \( j \). Sales of the product of industry \( i \) to itself – that is, \( x_{ii} \) – are possible. For instance, the coal industry also might purchase coal for use in its own production processes.

In this conception of an economy, industry output is produced by firms. A number of firms can comprise an industry. Firms might own or manage multiple establishments at which industry production occurs. To add complexity, some firms produce output of goods and services that are classified in multiple industries, which is, then, accounted separately for each industry. The fundamental rule is that accounting for economic output is by industry, which is an aggregation of highly similar good or services, and not by firm or within establishments run by firms. Also, the macroeconomy is understood as an open system in the sense that it can gain or lose income or products from outside its boundaries through trade. Moreover, any aggregations such as firms, cities,
geopolitical regions, countries, or the entire world could form the boundaries of the macroeconomy examined.

Further, output of industry \( i \) not purchased by industries for their own production instead is sold directly to consumers to meet demands for personal consumption in households, government purchases of defense and non-defense goods and services, fixed investments such as housing and other structures, and exports net of imports. Let \( y \) indicate an \( I \)-length vector whose elements display the monetary value of goods and services delivered by producing industry \( i \) to fulfill demands of the economy. Vector \( y \) represents the “final demand” for goods and services in an economy and is known commonly in the parlance of national income and product accounting practice as “gross domestic product” [2].

2.2. Direct requirements
Quantities in \( X, y \), and \( x \) are most commonly expressed as monetary values (e.g., as dollars, rubles, or some other form of currency used as a medium of exchange) rather than as quantities of goods and services, although some energy and resource input–output models are scaled in physical quantities such as megawatts of electricity, kilograms of waste, hectares of land, or litres of water [10].

The production sector of the economy, then, is defined by \( X \), and \( y \) is the consumption sector. The total output of the economy by producing industry, contained in \( I \)-length vector, \( x \), is equal to the sum of production and consumption, or

\[
x = X + y.
\]

Define \( A \), a direct requirements matrix with elements \( a_{ij} = x_{ij} / x_i \), showing the proportion of industry \( i \) output required for production by industry \( j \). Equation 1 now becomes

\[
X = Ax + y.
\]

Elements in \( A \) are assumed to be fixed, homogenous, and linear within purchasing industries. In particular:

- Inputs required by purchasing industry \( j \) from producing industry \( i \) do not change over time, or, more technically, zero elasticity of price or quantity substitution exists among inputs to purchasing industry \( j \) (i.e., fixed);
- All firms in purchasing industry \( j \) use the same proportion of industry \( i \) inputs (i.e., homogenous);
- Neither economies nor diseconomies of scale are manifest as producing industry \( j \) output increases or decreases (i.e., linear).

These three assumptions are, of course, highly restrictive and probably are unrealistic in a longer view of most economies. Yet, even without adding additional complexity to detail the simple model represented by equation (2), these assumptions have proved tenable within limits and useful for economic analysis in static contexts. However, the use of the model does not rest on the full verisimilitude of its assumptions. Rather, many analysts have relied on the pragmatic view that these assumptions are close enough to short-term reality to allow answers to economic problems that do not lend themselves to other analytic techniques [11].

2.3. Total requirements: The Leontief Inverse
Introducing for mathematical convenience an \( I \)-by-\( J \) identity matrix, \( I \), and algebraically rearranging terms in equation 2, the relationships among production, consumption and economic output is expressed as

\[
x = (I - A)^{-1} y,
\]

2 Although the notation seems awkward to have an element of matrix \( X \) indicated by the scalar \( x \) and the column vector of total output indicated by \( x \), we are following notation conventions that are common in the field of interindustry analysis.
where \((I - A)^{-1}\) is a total requirements matrix, which shows the additional dollar value of output from industry \(i\) needed directly or indirectly to deliver a dollar’s worth of output from industry \(j\) to final demand in the economy. The total requirements matrix, \((I - A)^{-1}\), often is referenced as the Leontief Inverse, acquiring its name after its originator, Wassily Leontief [12, 13], who won the 1973 Nobel Prize in Economic Sciences largely for the development and application of this technique [14]. Actual economies can have large numbers of industries, so \(A\) often is large. As a consequence, \((I - A)^{-1}\) usually is solved numerically by Laplace transform techniques.

Taking the difference between the total requirements matrix and the direct requirements matrix produces an indirect requirements matrix. Indirect requirements are generated from the long string of transactions among industries representing intermediate production that must occur to generate a final product for consumption. The addition of households as both a row and column in \(X\) allows inclusion of the effects of household production and purchasing into the model. This addition augments the total requirements matrix to include not only direct and indirect requirements but also to show induced effects of household spending on the economy as it stimulates purchases of goods and services. The difference between the total requirements matrices, net of the indirect requirements matrix, including household spending produces an induced requirements matrix.

2.4. Multipliers

Indirect and induced requirements matrices show how each dollar spent on goods and services delivered to consumers multiplies itself throughout the economy. Ratios such as \([\text{direct requirements} + \text{indirect requirements}] / \text{direct requirements}\) as well as \([\text{direct requirements} + \text{indirect requirements} + \text{induced requirements}] / \text{direct requirements}\) are called Type I and Type II multipliers, respectively [15] and are common metrics used to account for system-wide change evoked from changes in particular sectors of an economy. Pre-multiplying the direct, indirect, and induced requirements matrices by, say, total employment parses the impact of delivery of final demand to consumers into direct, indirect, and induced employment components. In a similar manner, multipliers for other economic indexes, such as income or taxes, can be computed.

3. Results and Discussions

3.1 Classes of counterfactuals to macroeconomic model for assessing risk

A potential impact of a counterfactual is computed by calculating the difference between (a) an economic scenario created by a counterfactual condition exemplifying a production or consumption shock and (b) a status quo scenario representing an economy anticipated under historical trends in growth and change. Shown in Table 1 are three classes of counterfactuals that are possible in a hypothetical case for the production and consumption of so-called transparent aluminum.

Transparent aluminum, a ceramic composite technically known as aluminum magnesium oxyxnitride, is an extremely durable, sintered crystalline material composed of magnesium, aluminum, oxygen, and nitrogen \((AlN-MgO-MgAl_2O_4)\) that is optically transparent (\(\geq 80\%\)) in the near-ultraviolet, visible, and midwave-infrared regions of the electromagnetic spectrum. The name of this material comes from its similarity to a material referenced in the science fiction movie, Star Trek IV: The Voyage Home. This promising building material is four times harder than fused silica glass, 85% as hard as sapphire, and resists corrosion, radiation, and oxidation [16]. Products requiring both durability and transparency – such as armored glass, windshields on airplanes and sea vessels, windows for laser and infrared communications, personal protective gear, smartphone and watch screens, and sensor components – are among the potential uses for transparent aluminum.
Table 1. Three hypothetical macroeconomic counterfactuals specified to assess risk to production and consumption of transparent aluminum

| Counterfactual description                                      | Change specified in macroeconomic model                                      |
|----------------------------------------------------------------|---------------------------------------------------------------------------|
| Change in consumption of transparent aluminum                 | $\Delta y_{i'}$, where element $y_{i'}$ is total final demand for industry $i'$, the transparent aluminum industry ($i' \subseteq I$). |
| Change in production function for the transparent aluminum industry | $\Delta a_{i'}$, where vector $a_{i'}$ is a column vector representing the proportion of inputs from I industries purchased as inputs to the transparent aluminum industry ($j' \subseteq J$). |
| Change in production function of a purchaser of transparent aluminum | $\Delta a_j$, where vector $a_j$ is a column vector representing the proportion of inputs from I industries purchased as inputs to the any industry other than the transparent aluminum industry ($j' \neq j$). |

3.2. Change in consumption of transparent aluminum
Using equation (3), implementing this counterfactual involves substitution of $y_{i'}$ for $y_i$ and solving for $x = (I - A)^{-1} y_{i'}$, where $y_{i'}$ is a new column vector of total final demand for industry $i'$, the transparent aluminum industry ($i' \subseteq I$). The result is a direct change in transparent aluminum output, along with indirect and induced changes of the total output of all industries to the extent that they have direct or indirect interindustry linkages to the transparent aluminum industry.

3.3. Change in production function for the transparent aluminum industry
Changing a production function involves altering the proportion of total products from other industries purchased by the transparent aluminium industry. This change could result from efficiencies affected in the production of transparent aluminium. Or, supply chain constraints or shortages might have required changes in the manner that transparent aluminium is produced. Such a change is manifest in alterations in $A$. As a result, $(I - A')^{-1}$ also is altered, reestablishing the input-output identity to $x = (I - A')^{-1} y$, where $A'$ is $A$ altered by $a_j$, a column vector representing the proportion of inputs from I industries purchased as inputs to the transparent aluminum industry ($j' \subseteq J$). The result observed, holding transparent aluminum output constant, is indirect and induced changes of the total output of all industries to the extent that they have direct or indirect interindustry linkages to the transparent aluminum industry.

3.4. Change in production function of a purchaser of transparent aluminium
The consequence of this scenario is a similar change similar to changes in the production function for the transparent aluminium industry. However, the result observed, holding output constant in the industry making the production function change, is indirect and induced changes of the total output of all industries, including the transparent aluminum industry, to the extent that they have direct or indirect interindustry linkages to the industry making the production function change.

4. Conclusion
Examination of consequences of counterfactual macroeconomic scenarios holds potential for estimating risks to accomplishment of structural innovations. Some other useful non-economic models for identifying risk involve understanding [17-19] or modifying [20-22] the performance of people in innovation processes.
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