Dynamic regional economic modeling: a systems approach

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DOI: 10.12846/j.em.2014.04.18

Abstract

This paper demonstrates how the insight-generating features of a static input-output model can be structurally integrated with a comprehensive system dynamics simulation model. The purpose of such integration is to add value to regional economic modeling. We examine how the constraints inherent in the traditional static model can be eliminated and/or relaxed in a dynamic model. Such constraints arise from assumptions of fixed technology, fixed combinations of labor and capital, fixed prices, and surplus factors of production. We describe how these constraints can be alleviated in a system dynamics model. Integration of the two methods enables a disciplined disaggregation of system dynamics-based macroeconomic models into interactive industrial sector submodels that facilitate economic impact studies of regions and small nations. Moreover, integration, with its elimination of constraining static assumptions, extends the applicability and value of input-output analysis.

Keywords

economic development, input-output, multiplier, system dynamics

Introduction

In this paper, we show how input-output concepts can be used in a system dynamics simulation model in ways that add value to regional economic modeling. "Regional" in this case refers not only to sub-national areas of geographical economic interest but also to small national economies where reliance on a few key industries can undermine resilience to external shocks. For example, the modeling approach in this paper utilizes data from the small Baltic economy of Lithuania.

The focus is on integrating static input-output (IO) modeling concepts into a dynamic modeling framework based on the methodology of system dynamics (SD). The value of this approach is two-fold. First, it provides a disciplined way to disaggregate SD-based macroeconomic models into interactive industrial sector submodels, based on well-established IO methodology rather than ad-hoc disaggregation. In addition, it enables eliminating some of the rigid assumptions inherent in the traditional static IO approach, thereby extending the applicability of IO analysis. The result is a dynamic regional modeling approach that integrates the powerful systemic perspectives inherent in both IO and SD.

The literature on regional economic modeling with input-output models is vast, and the limitations of static IO models are widely acknowledged (Isard et al., 1998; Armstrong, Taylor, 2000; Shaffer, Deller, Marcouiller, 2004; Stimson, Stough, Roberts, 2006). The limits stem from assumptions of fixed technology, fixed combinations of labor and capital, fixed prices, and surplus factors of production, as well as incomplete accounting for induced feedback effects on the demand side of an economy.

In the next section, we describe and analyze an SD-based economic model in which the structure of the production sector is based on the useful principles of the input-output framework without most of the inherent constraints of that framework. Early initiatives involving use of IO in SD models include Krallman (1980) and Braden (1981), with more recent work exemplified by McDonald (2005). To our knowledge, however, no previous work has taken a comprehensive macroeconomic modeling approach that seeks a synthesis of IO and SD features for purposes of regional economic impact analysis[1].

There are other approaches that address the limitations of traditional input-output models, including social accounting matrix (SAM) models and computable general equilibrium (CGE) models. SAM models typically include more extensive treatment of household income distribution and consumption, and CGE models endogenize prices and wages (Shaffer et al., 2004). Comparing SD with SAM and CGE is beyond the scope of this paper and awaits further research.

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[1] For an introduction to the simulation modeling methodology of system dynamics, consult Forrester (1961), Sterman (2000), Barlas (2002) and Ford (2010).

1. Input-Output Table

This section illustrates the static model with which the dynamic model is compared. The table in Tab. 1 is a simplified version of input-output data for Lithuania in 2010. The top four data rows contain the inter-industry transaction matrix, while rows five and six display each industry's production inputs from domestic labor and capital and imports, respectively. Reading across the first row shows that intermediate sales (measured in billions of litas/year) from the manufacturing industy went to market services (2), agriculture (1), and constuction (3), as well as throughout the manufacturing industry (4). Reading down the first column reveals that the manufacturing industry required production inputs from within its own industry (4) and from market services (2), agriculture (1), and construction (2). The remaining inputs to manufacturing production came from utilization of labor and capital within that industry (21) and imports (60). The fractions in parentheses are the inputs to the dynamic model. For example, Lithuania's manufacturing industry relied on imports for about two-thirds of its production inputs during 2010, while agriculture's import reliance was one-fourth.

Tab. 1. Simplified input-output data for Lithuania in 2010, billion litas/year (fraction of purchases)

		Purchases [billion litas/year]			
		Manufacturing	**Market Services**	**Agriculture**	**Construction**
sales (b. litas/year)	Manufacturing	4 (0.04)	2 (0.02)	1 (0.08)	3 (0.21)
	Market Services	2 (0.02)	10 (0.14)	1 (0.08)	2 (0.14)
	Agriculture	1 (0.01)	1 (0.01)	3 (0.25)	0 (0.00)
	Construction	3 (0.03)	2 (0.03)	0 (0.00)	2 (0.14)
	Labor & Capital	21 (0.23)	54 (0.74)	4 (0.33)	6 (0.43)
	Imports	60 (0.66)	4 (0.05)	3 (0.25)	1 (0.07)
	Totals	**91 (1.00)**	**73 (1.00)**	**12 (1.00)**	**14 (1.00)**

Source: adapted from data from Statistics Lithuania (2010).

2. System Dynamics Model Structure

The dynamic economic model described here is an extension of the original *Macro-Lab* model of the U.S. economy (Wheat, 2007a, 2007b), which Yamaguchi (2013, p. 11) cites as "the first complete (system dynamics) macroeconomic model ever presented to the public"[2]. A full discussion of *MacroLab* is beyond the scope of this paper but Fig. 1 provides an overview of the basic structure of the current version, which differs from the original version in several significant ways. The revision of particular relevance to this paper is the disaggregation of production among industry sectors and the linking of those sectors according to the conceptual framework of input-output analysis – a principal method for conducting regional economic impact studies.

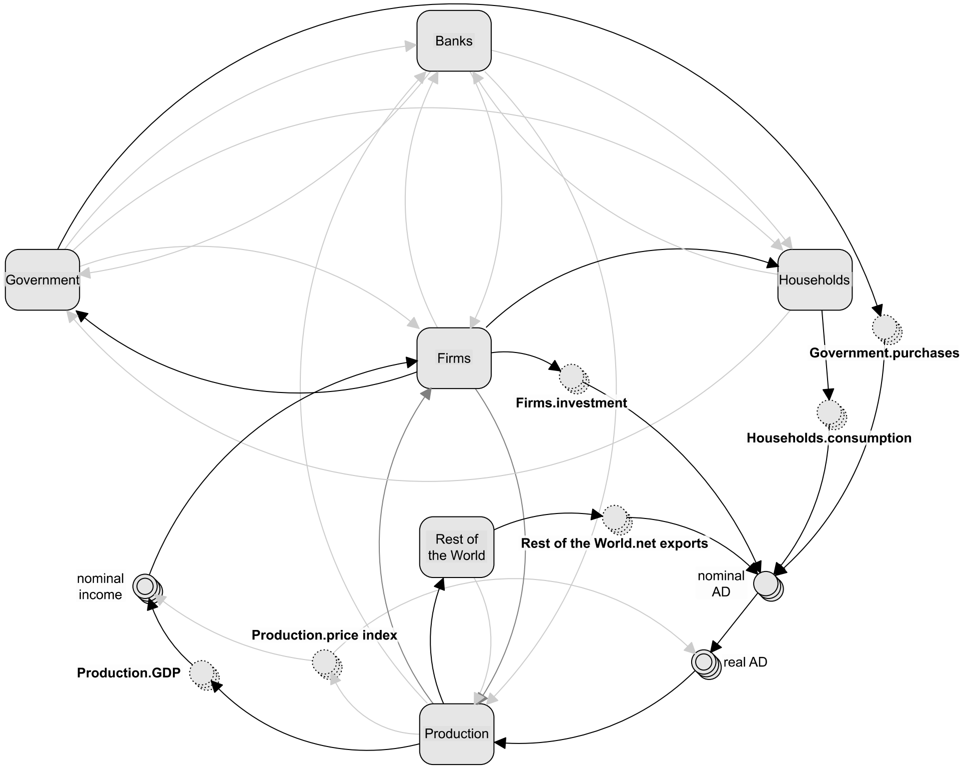

Fig. 1. Overview of economic sector of MacroLab

Source: model developed by Wheat with Stella® Professional Modeling & Simulation Software (version 1.0, http://www.iseesystems.com).

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[2] Nathan Forrester's SD-based macroeconomic model (Forrester, 1982) was not as comprehensive as *MacroLa*b but motivated its development. An SD model of business cycles published by Mass (1975) was also an inspiration for *MacroLab*.

Five input-output submodels (agriculture, construction, manufacturing, market services, and public services) are contained within the Production sector displayed in the Fig. 1 diagram. The circular symbols with a multi-dimensional appearance are arrayed variables that contain one or more vectors of information. The nominal income variable, for example, contains information about income earned by factors of production within the five industry categories of the model. The nominal AD (aggregate demand) variable is a 4x5 array that contains information about four categories of aggregate demand, each with its own final demand for the five industry categories. A prefix on a variable identifies the submodel where its value is determined. For example, the arrayed variable Production.price index, contains price indices for the five industries and is calculated within the Production submodel. When nominal AD is divided by Production.price index, the result is the arrayed variable real AD, which is an input to the Production submodel.

Also visible in Fig. 1 are several feedback loops involving Production on the "supply side" and the components of aggregate demand (consumption, investment, government purchases, and net exports) on the "demand side" of the model economy. Those loops are the transmission channels for what the input-output literature calls the induced effect of a production stimulus; i.e., the feedback effect of additional production on additional income and final demand. Within the Production sector, a portion of each industry's production constitutes value added, and the total value added is Production.GDP. Within the business Firms submodel, most of nominal income is distributed to the Households and Governments submodels in the form of wages and taxes; the rest is retained earnings. The dark arrows trace the return flow of spending in the form of consumption, investment, government purchases, and net exports[3].

Within the Production submodel, there are five industry submodels, each linked with one another. The four private sector submodels are identical in structure but differ in their parameter values. Fig. 2, for example, displays the Agriculture submodel and its input-output structure[4].

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[3] The light arrows indicate other linkages (e.g., transfer payments from Government to Households, bond sales from Government to Households, planned investment information from Production to Firms, and interest rate information from Banks to Production).

[4] Equations for the Fig. 3 diagram are available upon request.

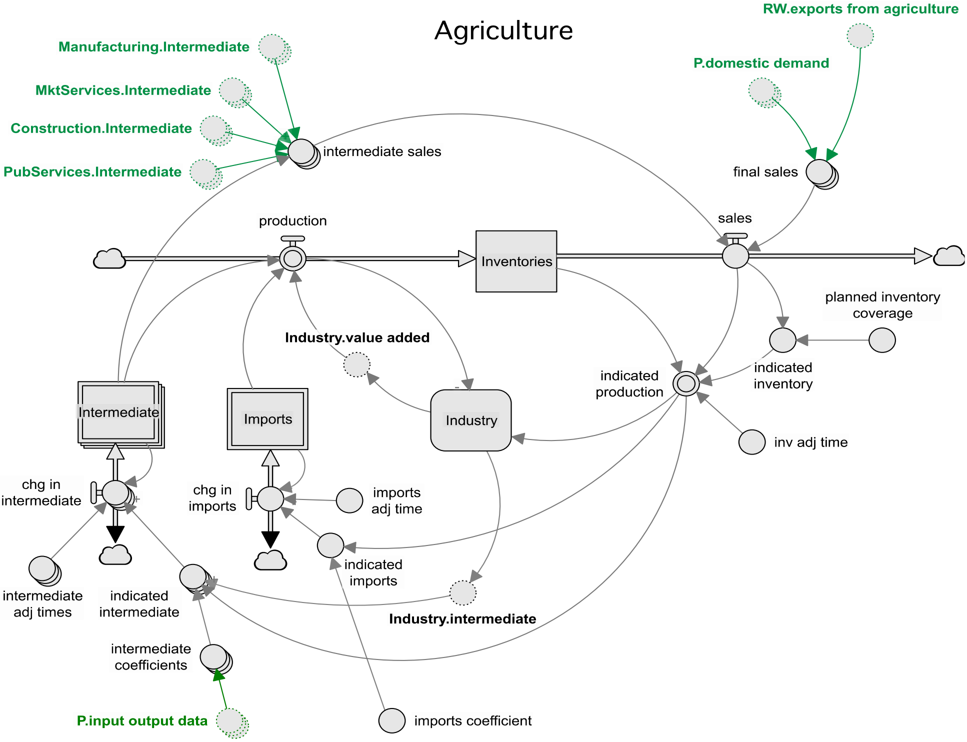

Fig. 2. Typical input-output structure within a production submodel

Source: model developed by Wheat with Stella® Professional Modeling & Simulation Software (version 1.0, http://www.iseesystems.com).

Final sales within the agriculture submodel is the sum of domestic demand and agriculture exports. The intermediate agriculture sales are governed by the data on other industry's purchase fractions in Tab. 1. The agriculture industry provides approximately 1 per cent of the production inputs to both manufacturing and market services, and 25 per cent to additional agriculture production[5].

The pipeline symbols represent flows; e.g., production and sales (b. litas/year). The rectangular boxes represent stocks. Inventories is a material stock which is measured in currency units that reflect the value of physical inventory items. Another type of stock in system dynamics models is an accumulation of information about

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[5] To simplify the presentation, all public service transactions were assumed to be confined to the public service industry (i.e., government) in both the IO model and the SD model.

flows, such as Imports and Intermediate purchases in Fig. 2, measured in b. litas/year. The Industry submodel contains the structure of labor, capital, productivity, and prices within the agriculture industry. The output of that structure consists of value added by the domestic agriculture industry, with the remainder sold to other domestic industries. The agriculture production flow is the sum of the value of imports, intermediate purchases, and value added by the domestic agriculture industry.

The production theory implicit in the Fig. 2 diagram is that the industry has a norm for inventories called indicated inventory, which is a function of planned inventory coverage (assumed to be about three months in this case) and sales (initially 12 b. litas/year, based on Tab. 1 data). When the model is initialized in equilibrium for analytical purposes, initial production is also 12 b. litas/year until the model is shocked. Based on data from the input-output matrix in Tab. 1, about one-third of agriculture production will be generated by domestic labor and capital, about one-fourth will be imported, and manufacturing and market services will each contribute production inputs amounting to about eight per cent of agriculture's requirements. The indicated imports and indicated intermediate purchases will eventually be realized, but not immediately; thus, the average adjustment time assumption of six months for each.

The domestic industry production within the Industry submodel is based on a Cobb-Douglas production function, and the stocks of labor and capital utilized depend on wage rates, cost of capital, and the varying productivity of labor and capital. Moreover, an industry-specific price index is calculated within the submodel, based on demand pressures, cost pressures, and attainable mark-ups.

Information about the labor stock employed within the Industry submodel is transmitted up to the Production submodel, where total employment is calculated for the entire economy. When compared with the full labor force, an economy-wide unemployment rate is calculated. The unemployment rate information is transmitted back down to each Industry submodel, and the corresponding wage pressures influence the desired capital-labor ratio and the hiring rate for each industry. In a similar manner, information about the capital stock and desired investment within each Industry submodel is transmitted to the Firms submodel and, in conjunction with interest rate information received from the Banks submodel, decisions about investment take into account retained earnings, dividends policy, and borrowing costs. The cost of capital information feeds back to the Industry submodel and influences the desired capital-labor ratio and the desired capital.

3. SD Model Behavior

The primary purpose of this paper is to discuss the structure of a system dynamics model that integrates IO features while removing static constraints. In this section, however, we take a brief look at the behavior of the model. Fig. 3 illustrates the response to an export demand shock. Two hypothetical scenarios are tested, each with the same sudden and permanent step increase in exports equal to 1 b. litas/year (1 percent of GDP). In one scenario, the additional export demand is for manufactured products; in the other scenario, the additional export demand is for agriculture products. Measured behavior includes GDP and the unemployment rate.

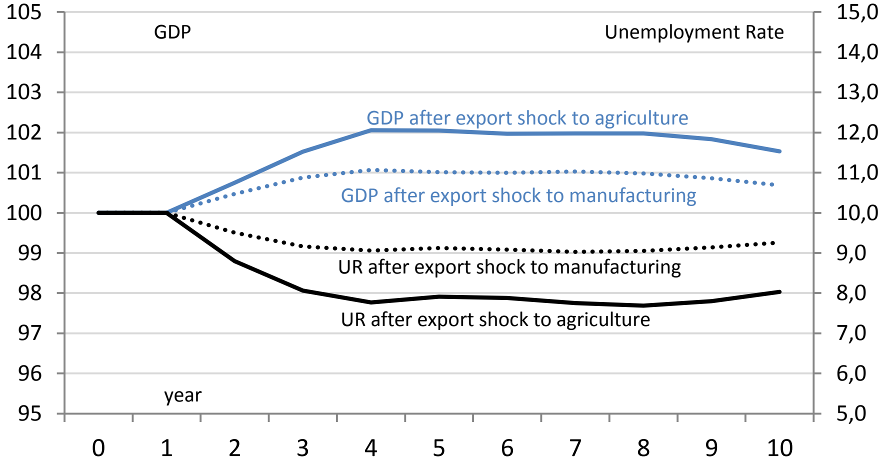

Fig. 3. Simulated effects of two export demand shocks of equal magnitude

Source: simulation results with model developed by Wheat.

Both shocks have favourable impacts on the model economy, with GDP rising and the unemployment rate falling. However, the "better" outcome occurs when the export demand is directed towards agriculture rather than manufacturing. The explanation stems from the input-output data: compared to the agriculture industry in this illustrative model, the manufacturing industry is more reliant on imports for its inputs to production. Thus, relatively less of the increased export demand for manufacturing goods translates into value added production within that industry because of the substantial "leakage" to pay for imported inputs. Without the IO structure, the

SD model would be incapable of revealing the differential effects of shocks identical in magnitude but targeted at different industries.

Also of interest is a comparison of the behavior of the dynamic model with the static IO model that relies on the same inter-industry production coefficients (in Tab. 1). First, we acknowledge that the static model also predicts that an import-dependent manufacturing industry would contribute less to GDP than the agriculture industry in the simulation experiment described above. The static model, however, is not capable of suggesting the pattern of dynamic response for either industry. In Fig. 3, the response patterns in both scenarios underscore the significance of delays that are intrinsic to the dynamic model; the maximum impact takes nearly three years to be realized. The impact is then sustained for about five years before stabilizing below the maximum impact. A static outcome is timeless, by definition, but the implicit future projection would be a flat line based on a static calculation of a constant multiplier effect – hardly a realistic scenario, but an inevitable one given the constraints of a static model.

Conclusions

Let us now summarize how the dynamic model described in this paper eliminates or relaxes key constraints inherent in traditional IO models. First, a fixed combination of labor and capital is no longer assumed. As described above, labor and capital vary within each industry submodel based on the target capital-labor ratio within that industry, a target that itself varies according to changes in productivity of labor and capital and changes in wages and the cost of capital. Second, traditional IO models not only assume fixed proportions of labor and capital, but also assume surplus productive capacity that can fully respond to exogenous increases in demand. In the dynamic model, however, labor and capital shortages can occur and can limit the capacity of supply to respond to changing demand. Third, the changing costs, as well as changes in demand pressures, cause prices to change in the model, thus eliminating another IO constraint. Moreover, the price changes are industry-specific, and the economy-wide price index is a weighted-average of the industry price indices. Fourth, the dynamic model contains a comprehensive set of feedback loops on the demand side that channel household consumption, business investment, and government spending in response to changes in income, in contrast to the static "induced" demand effects calculated by treating households as a sector in an IO table.

A fifth constraint in IO models the assumption of a fixed technology that governs the inter-industry inputs is not yet eliminated in our dynamic model. The technical coefficients of the original IO table (Fig. 1) are used to allocate the source of inputs to the overall production process in each industry submodel. Nevertheless, within the industry submodels, most of the production is generated by labor and capital that are endogenous to that industry. And that production process is not based on a static production process, as noted above regarding the dynamics of labor, capital, productivity, and pricing. Thus, it is fair to say that the rigid production process assumption in IO models is relaxed in our dynamic model. Future research will be aimed at dynamic modeling the influences on the coefficients in the IO table, with the goal of eliminating the remaining constraint.

In addition, the next round of model development and evaluation will consider how the SD-based model compares with SAM and CGE models. One important question is whether the nonlinear feedback approach of SD treats income distribution and final demand in more satisfactory ways than SAM methods. We will also investigate whether an SD model endogenizes prices and wages in more plausible ways than the market-clearing approach of CGE models.

Notwithstanding the limitations of the current model, the approach described in this paper indicates considerable potential for improving dynamic regional economic modeling. The approach is based on integrating two methods – SD and IO – that use complementary systemic lenses to view the operation of real-world economies. The input-output framework enables SD models that would otherwise be too highly aggregated to answer important questions about regional economic development and policy design. The system dynamics framework enables IO analysts to embed their methodology in a dynamic model and be relieved of constraints that raise questions about the external validity of their analysis.

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Dynamiczne modelowanie regionalnego rozwoju: podejście systemowe

Streszczenie

W artykule zaprezentowano sposób strukturalnego integrowania wewnętrznie generowanych właściwości statycznych modeli wejścia – wyjścia z ogólnym symulacyjnym modelem dynamiki systemu. Celem takiej integracji jest dodanie nowej wartości w regionalnym modelowaniu ekonomicznym. Autorzy badają, w jaki sposób ograniczenia związane z tradycyjnym modelem statycznym mogą zostać wyeliminowane i/lub pomniejszone w modelu dynamicznym. Te ograniczenia wynikają z założeń przyjętej technologii, ustalonych relacji nakładów pracy i kapitału, stałych cen i dodatkowych czynników produkcji. Wyjaśniamy, jak te ograniczenia mogą być zminimalizowane w modelu dynamiki systemu. Integracja dwóch metod pozwala na metodyczne rozgrupowanie modeli makroekonomicznych opartych na dynamice systemu oddziaływujących na siebie sektorów submodeli gospodarki, które ułatwiają badania wpływu gospodarczego regionów i mniejszych krajów. Okazuje się, że poprzez integrację, która eliminuje ograniczające założenia statyczne, ulega rozszerzeniu zastosowanie i jakość analizy wejścia – wyjścia.

Słowa kluczowe

rozwój gospodarczy, wejście – wyjście, mnożnik, dynamika systemów