How an agent-based model can support monetary policy in a complex evolving economy *

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Abstract

This chapter sets out a central banker's perspective on the dynamics of inflation in Canada since the onset of the Covid-19 pandemic using a behavioral agent-based model developed at the Bank of Canada. The model features two crucial assumptions based on empirical evidence: first, firms use simple rules to make price-quantity decisions, and second, inflation expectations are adapted through experience. While the course of the economy in recent years has posed some new challenges about many traditional macroeconomic models, an agent-based model can explain inflation by using simple heuristics and closely tracking survey evidence. We also include an example from policymakers on how an agent-based model can be used to develop insights to support monetary policy in Canada. Finally, we suggest some future avenues for research.

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1 The advantages of an agent-based model

The COVID-19 pandemic was a watershed event for economists, especially those who work for central banks and other policy institutions. The consequences of the pandemic and related public-health policies on economies were massive and global. It was one of those rare episodes that economists describe as Knightian uncertainty—a time when risks cannot be quantified or measured because of a lack of historical data or understanding. In this chapter we discuss how an alternative agent-based model can benefit monetary policy, and thus the management of the economy, during just such a period of turmoil. Borsos et al. (2024) provides an extensive overview of the recent developments and new challenges of using agent-based model in central banks.

At the Bank of Canada, the main macroeconomic policy models used to inform monetary policy prior to the pandemic took little account of individual sectors of the economy and covered just a small cross-section of consumers. Firms' pricing behaviour was assumed not to be state contingent. The existing models assumed that expectations were fully rational and agents had perfect knowledge of the underlying model. They were estimated using data collected during the inflation targeting period. While these years were marked by cyclical fluctuations, inflation rarely fell outside the Bank of Canada's control range of 1 to 3 percent, and when it did, it did not do so for long. Inflation expectations were in line with the target range, and the target itself served as a reliable forecast for inflation a year ahead and even beyond. While the economy was subject to domestic- and foreign-sourced supply and demand shocks, swings in demand tended to be more important than swings in supply in determining excess demand.

All this changed with the onset of the pandemic. Supply shocks became at least as important as demand shocks, and each tended to have a different degree of persistence. For the first time, global supply disruptions became a critical issue, adding to firms' costs and taking an unusually long time to subside. Because of the size and expected persistence of these cost shocks, firms began to raise prices more often than in the past. Inflation accelerated rapidly beyond the Bank of Canada's target range, and stubbornly stayed there. The result was that expectations of inflation over the short and medium term followed prices as they went up but lagged on the way down.

Models with embedded supply chains, regulated pricing behaviour, and non-rational expectations proved to be valuable components of an expanded toolkit. In this chapter, we discuss the development and adoption of an agent-based model called CANVAS (Canadian Behavioural Agent-based Model) at the Bank of Canada.

By way of background, agent-based models explain the behaviour of a system by simulating the behaviour of each individual "agent" within it. These agents and the systems they inhabit could be the consumers in an economy, fish within a shoal, particles in a gas, or even galaxies in the universe. The strength of agent-based models is that they show how even simple behaviours can combine from the 'bottom up' to recreate the more complex behaviours observed in the real world. An example would be how the decisions of each individual fish create the seemingly organised and unpredictable movements of the shoal.

This "bottom-up" approach is in contrast to "top down" models which assume how agents' behaviours will combine together, sometimes by assuming that all agents are identical, or that behaviour of a single agent can represent the aggregate of the behaviour of all. The different approaches have different strengths. The agent-based approach to problem-solving began in the physical sciences but has now spread to many other disciplines including biology, ecology, computer science and epidemiology. In recent years, agent-based models have become more common in economics and several macroeconomic ABMs have been developed featuring a clear common core as discussed in Dawid and Delli Gatti (2018). One example could be that individual consumer decisions to accumulate mortgage debt could collectively cause financial market distress through too much aggregate leverage.

CANVAS is one of the first agent-based models (ABMs) used by a central bank to improve its understanding of inflation targeting and related macroeconomic forecasting and policy analysis. It builds upon the framework of Poledna et al. (2023), who pioneered the development of a small open economy ABM for forecasting and policy analysis. CANVAS offers an alternative approach by simulating at a scale of 1:100 the behavior of a diverse group of individuals to provide a comprehensive macro-level view of the economy. See Hommes et al. (forthcoming) for a detailed description of the CANVAS model.

A behavioural agent-based model offers both empirical and practical advantages. Our first objective was to design a comprehensive framework that integrates reliable household and business data in a production network for the Canadian economy. We also wanted to use a common sample to evaluate the forecasting performance of CANVAS in comparison with the more established vector autoregressive (VAR) and dynamic stochastic general equilibrium (DSGE) models. We have found that CANVAS

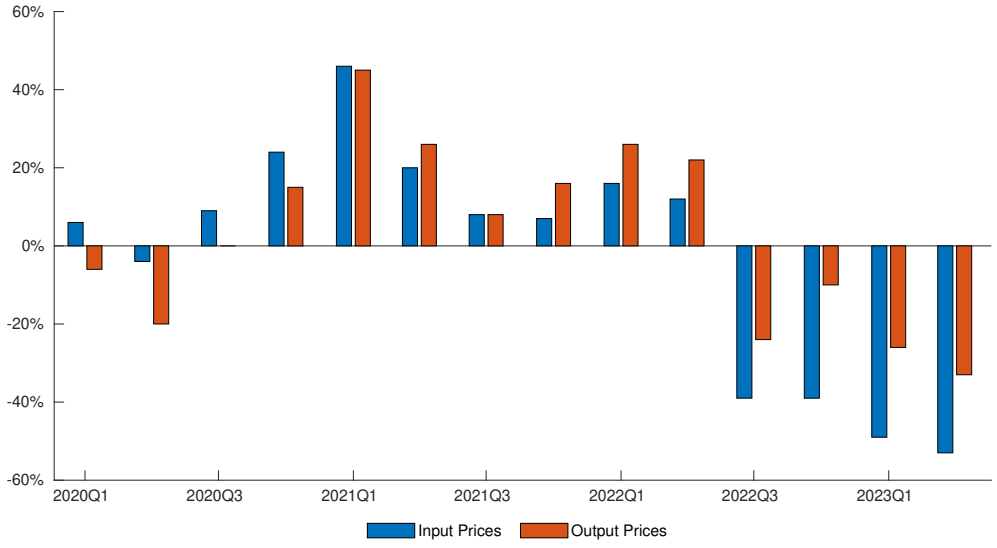
outperforms DSGE models in forecasting GDP growth and key components like consumption. This head-to-head performance is encouraging and suggests that a model based on diverse agents interacting in imperfect markets has the potential to enrich macroeconomic policy analysis. Our third goal was to improve our understanding of the interplay between evolving expectations and cost-push shocks in the context of an inflation-targeting policy regime. Finally and perhaps most importantly, we have actively applied a macroeconomic agent-based model on the front lines of monetary policy and integrated it as a new component of a central bank's toolkit.

In contrast to the challenges faced by traditional models during the pandemic, we are confident that an agent-based model like CANVAS is well-suited to interpreting micro and macroeconomic data and thus a useful tool as part of the suite of models used by central banks for forecasting key variables as well as for scenario-based policy analysis. We share some experiences below where the Bank of Canada used CANVAS to provide a variety of perspectives to support monetary policy.

2 Why pricing behavior matters to central banks

Firms' pricing behaviour is relevant for understanding how various supply and demand shocks may affect inflation, including the persistence of their impacts. Because monetary policy usually takes time to work through the macro-economy, the likely persistence of shock impacts matters. Often, monetary policy tends to "look through" high frequency movements. However, when impacts of shocks on inflation are expected to be both large and persistent, it may be appropriate for monetary policy responses to be scaled up more than proportionately in order to lean against the potential for inflation expectations to drift and slow down the return of inflation to target.

Figure 1: Asymmetry in cost pass-through



Source: Business Outlook Survey—Second Quarter of 2023, Bank of Canada

The pandemic period also revealed that it is not enough to look at measures of excess demand for understanding firm pricing. While Canadian data shows a correlation between inflation measures and estimates of excess demand, during the pandemic, cost drivers became of great importance. The most important of the supply side drivers was global supply chain disruptions that had large impacts on production, costs and availability of many products. Such details are outside the scope of the standard macroeconomic policy models.

The Calvo assumption governing the frequency of price adjustment also proved to be unrealistic. When faced with larger-than-average persistent increases in costs, firms have an incentive to change prices more frequently. This shortens the lag between developments in macro drivers (including those on the demand side) and subsequent movements in inflation. This, in turn, may influence the appropriate size and timing of policy responses to shocks.

Why does a central bank need an agent-based model (ABM)? The best motivation is to look at our recent experience over the pandemic. Our traditional structural and semi-structural models showed their limitations.

We have learned three important lessons from this experience:

- **We need to better understand how firms set their prices.** Our survey conducted during the pandemic suggests that the most relevant factors that affected Canadian firms' pricing behaviour are cost pressures, followed by labour shortages and supply chain considerations.

- **Asymmetry in cost pass-through.** There seems to be asymmetry in input costs pass-through to output prices. **Figure 1**, plots the evolution of firms response of input prices growth (in blue), along with firm's intention to adjust output prices (in red). It is interesting to see that there is a timely and significant pass-through of higher input price to output prices as inflation surges to its peak in 2022. However, despite the decline in input costs in 2023, Canadian firms appeared to have no intention and were not taking any actions to lower their output prices.

- **Agents form expectations based on experience.** It has long been accepted that, in practical terms, nominal interest rates cannot fall below an effective level (usually zero) because investors can always earn a zero nominal return simply by holding cash. This concept has been termed the "effective (or zero) lower bound" on nominal interest rates. Theoretically, the existence of this effective lower bound (thereafter ELB) limits a central bank's ability to provide further stimulus to the economy through conventional decreases in policy rates below such level. In face of large shocks and policy rate is lowered to the ELB, monetary policy needs to work through expectations to help lower real interest rates to stimulate the economy.

  The pandemic experience suggests that better modelling the formation of expectations is not just relevant near the ELB, it is something we need to understand at all times. The theory of rational inattention suggests that firms and households typically pay little attention to inflation when it is low and stable (Sims, 2003). Informational frictions make paying attention to inflation costly and simply not worth the effort. But when inflation is high and volatile, paying attention to inflation and monetary policy becomes more important—the marginal benefit is greater than when inflation is low and stable. In such situations, households and businesses benefit from incorporating views on inflation into their economic decisions and expectations. Similarly, survey and lab experiments have also shown us that people tend to learn about inflation based on their own experiences. It is more of an adaptive process.

3 Adapting models to behavior

A large body of literature documents how the formation of expectations often deviates from rational expectations. However, the relevant question for policy is whether these deviations are large enough to matter for monetary policy decisions. From the time when the inflation target was set at 2 percent in 1995 until the start of the pandemic in the first quarter of 2020, inflation in Canada tended to only fall outside the inflation control range of 1 to 3 percent for short periods of time. Inflation expectations were well-anchored on the inflation target, and assumptions on rational versus learning behaviour in the formation of expectations had only small impacts on the outlook for inflation. Thus, adjusting models to include non-rational assumptions regarding expectations formation was not a high priority. The pandemic provided an exceptional deviation from the prior 25 years. Assumptions on expectations formation became critical for economic projections and evaluations of risks.

3.1 Rational expectations are not the full story

In a complex environment of fundamental uncertainty and imperfect information, obtaining accurate forecasts is nearly impossible. Firms in such a complex environment may choose simple forecasting methods that closely monitor the relevant variables, even if such methods fail to understand the complete model of the economy. This approach fits within the concept of procedural rationality (Gigerenzer, 2015). Lab experiments with human subjects show that in an environment that is too complex to fully understand subjects use simple forecasting rules, such as adaptive expectations, low order autoregressive (AR) processes, trend-following rules (Hommes, 2021). A forecasting method that meets these requirements is the AR(1) forecasting rule: this is a simple procedure, based on the observed mean and persistence, for projecting past trends into the future while its forecasting capabilities are relatively high.

Under adaptive learning, that is, recursive updating of parameters, the gaps between expected and realized values of state variables will close gradually. Learning ensures that the unconditional mean and autocorrelations of the unknown non-linear stochastic process—which describes the actual law of motion of the model economy—concur with the unconditional mean and autocorrelations of the AR(1) process in the long run. In fact, adaptive learning with the AR(1) rule leads to convergence to a behavioral learning equilibrium where agents learn to use an optimal AR(1) rule in the complex ABM economy, one of the simplest types of misspecification equilibrium put forth in the adaptive learning literature (Hommes and Zhu, 2014).

3.2 A behavioural agent-based model based on lab insights

In this chapter we only present the structure and main assumptions underlying the CANVAS model. For details of the CANVAS agent-based model, see Hommes et al. (forthcoming). The CANVAS model economy is structured into six sectors: (1) non-financial corporations (firms); (2) households; (3) the general government; and (4) financial corporations (banks), including (5) the central bank. These four sectors interact with (6) the rest of the world through imports and exports. Each sector is populated by heterogeneous agents whose balance sheets and economic flows are set according to data from national accounts.

The firm sector is made up of 19 industries (The North American Industry Classification System (NAICS) by Canada's national statistical agency), where each industry (firm) produces a perfectly substitutable good using labor, capital, and intermediate inputs with Leontief technology. Firms, subject to fundamental uncertainty, use a simple AR(1) rule to form expectations of the output and (producer price) inflation. Given these, they set prices and quantities. Output is sold to households, to other firms, or is exported. Firm investment is conducted according to the expected wear and tear on capital.

Households earn income and consume in markets characterized by search and matching processes. Employed households supply labor and earn wages; unemployed households receive unemployment benefits; investor households obtain dividend income; and inactive households receive social benefits. Additional social transfers are distributed equally to all households. Similar to firms, households also form AR(1) expectations about the expected growth rate and expected inflation.

The government collects taxes, distributes social as well as other transfers, and engages in government consumption. The banking sector obtains deposits from households as well as from firms and provides loans to firms. Bank profits are calculated as the difference between interest payments received on firm loans and deposit interest paid to holders of bank deposits, as well as write-offs due to credit defaults. (5) The central bank sets the policy rate according to a generalized Taylor rule, provides liquidity to the banking system, and takes deposits from the bank in the form of reserves. Furthermore, the central bank purchases government bonds, acting as a creditor to the government. To model interactions with (6) the rest of the world, a segment of the firm sector is engaged in import–export activities. As we model a small open economy whose limited volume of trade does not affect world prices, we obtain trends of exports and imports from exogenous projections based on national accounts.

Interactions between agents in the model take place on decentralized markets, characterized by search and matching. These interactions are governed by explicit behavioral rules that depict the micro behavior and institutional design of the considered economic system. This search and matching mechanism depends on the probability of a firm being chosen by a customer, which is determined by (1) the offering price of the firm and (2) the size of the firm. The purchased amount then depends on the consumer's consumption budget and the seller's supply. Markets do not necessarily clear; however, the ABM constantly tends towards an approximate equilibrium state and markets, in general, tend to be close to an equilibrium between supply and demand.

3.2.1 A fresh understanding of growth and inflation

In our model, there are two variables that agents need to form expectations over the expected output and producer price inflation. We assume agents form expectations in a homogeneous way: they are boundedly rational and use AR(1) rules to forecast variables in the model economy[1]. This rule is misspecified as it ignores cross-correlations and nonlinearities. However, agents continuously learn and update the parameters of their AR(1) forecasting rule and, in the long run, converge to a so-called misspecification

[1]This modelling choice is comparable to other adaptive mechanisms, such as VAR expectations as used in the US Federal Reserve's FRB/US macroeconomic model (a large-scale estimated general equilibrium model of the U.S. economy that was developed at the Federal Reserve Board) (Brayton et al., 1997), or expectations according to an exponential moving average (EMA) model, as in Assenza et al. (2015a).

equilibrium where agents have learned an optimal AR(1) rule consistent with the mean and first-order autocorrelation (a behavioral learning equilibrium as introduced by Hommes and Zhu (2014) and Hommes et al. (2023)).

Equation (1) summarizes the firm's expectations of the real GDP growth rate ($\gamma^e(t)$) and inflation ($\pi^e(t)$), measured by the log first difference of the GDP deflator:

$$\gamma^e(t) = \mathrm{e}^{\alpha^\gamma(t-1)\gamma(t-1)+\beta^\gamma(t-1)+\epsilon^\gamma(t-1)} - 1 \tag{1a}$$

$$\pi^e(t) = \mathrm{e}^{\alpha^\pi(t-1)\pi(t-1)+\beta^\pi(t-1)+\epsilon^\pi(t-1)} - 1\,, \tag{1b}$$

where parameters $\alpha^\gamma(t-1)$, $\alpha^\pi(t-1)$, $\beta^\gamma(t-1)$, and $\beta^\pi(t-1)$ are re-estimated every period with the time series of output growth $\gamma(t')$ and inflation $\pi(t')$ where $t' = -T', -T'+1, -T'+2, \ldots, 0, 1, 2, \ldots, t-1$. $\epsilon^\gamma(t-1)$, and $\epsilon^\pi(t-1)$ are random shocks with zero mean and variance re-estimated every period from past observations over the last $T'+t-1$ periods.

3.2.2 The production network

The production network in traditional DSGE models is often simplified and doesn't have sufficient granularity to analyze the impact of shocks in specific sectors. The introduction of a detailed Canadian production network follows the lines of Smets et al. (2019b) and Afrouzi and Bhattarai (2023) and considers how shocks to individual sectors could permeate throughout the economy. Naturally, the effect of shock propagation depends on the input-output linkage, the degree of substitutability of intermediate inputs and the complex price and quantity adjustments of individual firms when responding to shocks.

We use a detailed Canadian input-output database to calibrate the production network based on Canada's classification as a small open economy. **Figure 2** suggests that there exists important domestic production linkages through supply and demand of intermediate inputs across the 19 sectors. The energy commodity sector (including mining, quarrying, and oil and gas extraction), for example, is a key sector of the Canadian economy at the aggregate level. As the world's fourth largest oil producer in 2018, investment in the oil and gas sector accounts for about 30 percent of total business investment. Canada is also a net oil exporter, with about 75 percent of commodity production being exported. As a result, the sharp energy price increase had a significant impact on the Canadian economy through terms of trade effects.

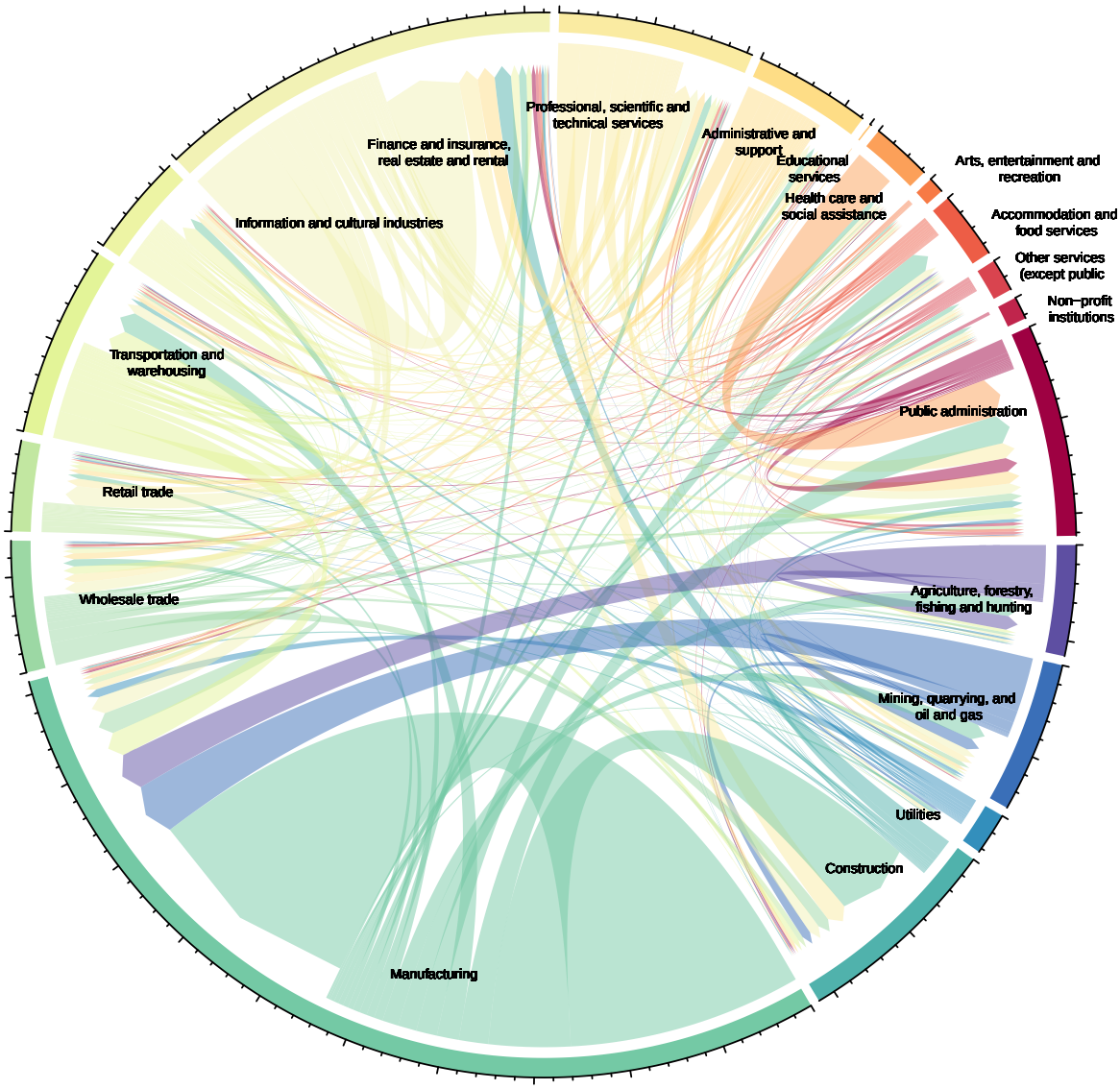
What's worth highlighting is that both the energy commodity sector and the non-energy commodity sector play important roles in the Canadian production network because they are critical inputs for manufacturing goods sector. Since the manufacturing sector supplies nearly all parts of the economy, any fluctuation in commodity prices would naturally have effects that propagate throughout the Canadian economy.

Each firm uses labor input for production measured by the number of persons employed. Demand for labor during each period is determined according to the firm's desired scale of activity and its average labor productivity.

Each period, each firm chooses real investment, which adjusts the real capital stock. As in standard DSGE models, capital adjustment in CANVAS is not immediate and is time-consuming. The firms' investment decision process is modelled by a simple heuristic that accounts for both expectations of the aggregate economy and firm-specific conditions. Every period, each firm observes realized demand and makes a forecast of future demand according to the expected rate of economic growth. Conditional on demand for business investment, the firm's capital stock adjusts accordingly when accounting for depreciation. Under adaptive learning, should realized growth rates surpass growth expectations, investment in subsequent periods will adapt to the approximate trend equilibrium level, and vice versa. As a result, the resulting trend of business investment tends to approximate the trend equilibrium path of this model economy.

Each firm also needs intermediate inputs for production. We assume that each firm holds an inventory stock of each type of input goods. Each period, the firm follows a heuristic of maintaining its inventory stock in positive supply and choosing the desired amount of intermediate goods and raw materials to avoid shortfalls of material input that would impede production. The realized demand for intermediate goods depends on a search-and-matching process. If this firm does not succeed in acquiring the materials it intends to purchase, it will be limited in its production possibilities.

Figure 2: Canadian Production Network



Note: The transactions between industries is shown for the sectors: Agriculture, forestry, fishing and hunting [11]; Mining, quarrying, and oil and gas extraction [21]; Utilities [22]; Construction [23]; Manufacturing [31-33]; Wholesale trade [41]; Retail trade [44-45]; Transportation and warehousing [48-49]; Information and cultural industries [51]; Finance and insurance, real estate and rental and leasing [52-53]; Professional, scientific and technical services [54]; Administrative and support, waste management and remediation services [56]; Educational services [61]; Health care and social assistance [62]; Arts, entertainment and recreation [71]; Accommodation and food services [72]; Other services (except public administration) [81]; Non-profit institutions serving households [NP000]; Public administration [91].

Source: Statistics Canada, authors' calculation

We define the cost-push inflation $\pi_i^c(t)$ as:

$$\pi_i^c(t) = \underbrace{\frac{(1+\tau^{SIF})\bar{w}_i}{\bar{\alpha}_i}\left(\frac{\bar{P}^{HH}(t-1)}{\bar{P}_{g=s}(t-1)}-1\right)}_{\text{Unit labor costs}} + \underbrace{\frac{1}{\beta_i}\left(\frac{\sum_g a_{sg}\bar{P}_g(t-1)}{\bar{P}_{g=s}(t-1)}-1\right)}_{\text{Unit production material costs}} + \underbrace{\frac{\delta_i}{\kappa_i}\left(\frac{\bar{P}^{CF}(t-1)}{\bar{P}_{g=s}(t-1)}-1\right)}_{\text{Unit capital costs}} \quad (2)$$

$\forall i \in I_s$

where, $\bar{P}_{g=s}(t)$ is the average price among competitors of firm i, $\bar{\alpha}_i$ indicates the average labor productivity and $\bar{w}_i$ is the average real wage, defined as gross wages, which include both salary costs and employers'

contributions to social insurance charged with a rate τ^{SIF}. $\frac{1}{\beta_i}\sum_g a_{sg}$ is real unit expenditures on intermediate production input by industry s on good g, weighted by the average product price index $\bar{P}_g(t)$. δ_i/κ_i are unit capital costs, conditional on the average price of capital goods ($\bar{P}^{CF}(t)$) and capital depreciation relative to productivity growth (where δ_i is the firm-specific capital depreciation rate and κ_i is the productivity coefficient for capital).

3.2.3 Price-quantity decisions based on a simple rule

As discussed above, we assume each firm is boundedly rational and uses a simple AR(1) rule to forecast output growth and (producer price) inflation. Every period, the firm sets both the supply of its product and related price based on its expectation for the aggregate economy, firm-specific cost structure and market demand conditions.

In each period, a firm from an industry produces real output of a principal product with Leontief technology that combines intermediate inputs, labor, and capital. A firm's supply choice depends on its expectations of the aggregate economy and individual supply/demand versus pricing power. It is driven by three sources: (1) its product supply from the previous period; (2) the expected, economy-wide economic growth rate; and (3) the realized, firm-specific growth rate of demand from the previous period.[2]

Firms set product prices and determine supply based on both aggregate expectations for overall economic conditions as well as firm-specific conditions for cost pressures and market demand.

In addition to setting price and quantity based on aggregate expectations and cost pressures from the production network, each firm also chooses to alter its previous period's quantity or price based on its perceived market conditions. We assume that due to different information and search costs, each firm has a certain degree of pricing power in its local market, so that the law of one price does not apply. We also assume that firms cannot change their quantity and price at the same time.[3]

As a reflection of firms' expectation error concerning demand, "excess supply" is defined as the difference between production and sales. Firms form their expectations of market conditions using two indicators that both rely on observed information from the previous period $t-1$: (1) the level of excess supply, which is the difference between the previous period's supply $Q_i^o(t-1)$ and realized demand $Q_i^d(t-1)$; and (2) the deviation of the firm's price $P_i(t-1)$ from the average price among competitors $\bar{P}_g(t-1)$ for product g. Each firm considers four possible price-quantity setting scenarios (depicted in **Figure** 3).

Effectively, the firm-specific growth rate of demand only differs from zero in scenarios (b) and (c):

$$\gamma_i^d(t) = \begin{cases} \frac{Q_i^d(t-1)}{Q_i^o(t-1)} - 1 & \text{if } Q_i^o(t-1) \leq Q_i^d(t-1) \text{ and } P_i(t-1) \geq \bar{P}_g(t-1) \\ & \text{or if } Q_i^o(t-1) > Q_i^d(t-1) \text{ and } P_i(t-1) < \bar{P}_g(t-1) \\ 0 & \text{otherwise.} \end{cases} \tag{3}$$

Each firm's supply choice depends on its expectations of the aggregate economy and individual supply/demand versus pricing power. In our model, it is driven by three sources:

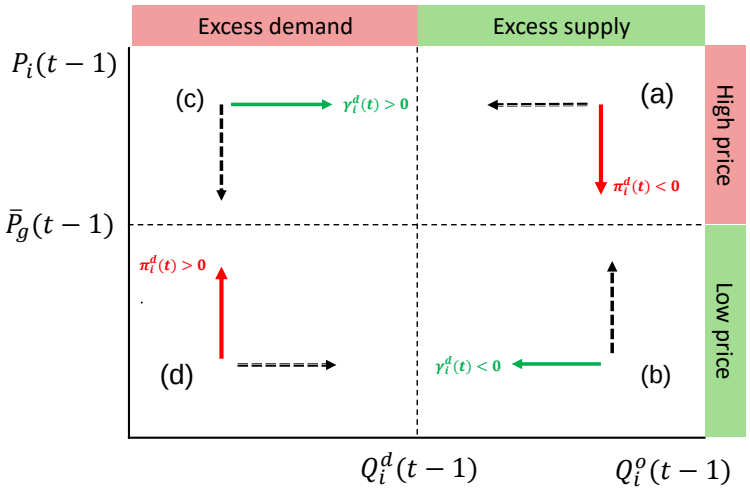
- product supply from the previous period $Q_i^o(t-1)$;
- the expected, economy-wide economic growth rate ($\gamma^e(t)$); and
- the realized, firm-specific growth rate of demand from the previous period, $\gamma_i^d(t)$:

$$Q_i^s(t) = Q_i^o(t-1)(1+\gamma^e(t))(1+\gamma_i^d(t))\,. \tag{4}$$

[2]The assumption of Leontief production technology is consistent with the data and is in line with the literature (Assenza et al., 2015a). Moreover, as our explicit aim was to derive the simplest possible ABM that has the features we desire, we relegate all further extensions of the model, such as assumptions on technological progress that change technology coefficients, to further research.

[3]This modeling choice is adapted from Delli Gatti et al. (2011), who use a similar price-quantity heuristic and is motivated by empirical surveys of managers' pricing and quantity decisions; see, e.g., Kawasaki et al. (1982) and Bhaskar et al. (1993). Dawid et al. (2024) also provides a detailed discussion of the price-quantity rules in macroeconomic agent-based models. Moreover, there is empirical evidence from laboratory studies showing subjects use similar price-quantity settings heuristics in monopolistic price-quantity settings (see, e.g., Assenza et al. (2015b)).

Figure 3: Firm quantity and price setting



Similar to Equation (3), in scenarios (a) and (d) firms adjust their prices in the following manner:

$$\pi_i^d(t) = \begin{cases} \frac{Q_i^d(t-1)}{Q_i^o(t-1)} - 1 & \text{if } Q_i^o(t-1) \leq Q_i^d(t-1) \text{ and } P_i(t-1) < \bar{P}_g(t-1) \\ & \text{or if } Q_i^o(t-1) > Q_i^d(t-1) \text{ and } P_i(t-1) \geq \bar{P}_g(t-1) \\ 0 & \text{otherwise.} \end{cases} \tag{5}$$

Thus depending on the scenario, firms either change prices or quantities (at the same rate) to ensure that supply (in nominal terms) matches expected (nominal) demand. Notice that $Q_i^d(t-1)/Q_i^o(t-1) - 1$ is a dimensionless quantity and is equal to the nominal relative change $(P_i(t-1)Q_i^d(t-1))/(P_i(t-1)Q_i^o(t-1)) - 1$, which can be reduced to $Q_i^d(t-1)/Q_i^o(t-1) - 1$.

3.2.4 Inflation determination

With some aggregation and simplification, firm i's nominal price $P_i(t)$ in our model can be decomposed into three components: (1) expectations of economy-wide inflation $\pi^e(t)$ (aggregate inflation expectation); (2) the cost structure of the firm $\pi_i^c(t)$ (cost-push inflation); and (3) the firm-specific growth rate of demand $\pi_i^d(t)$ (demand-pull inflation):

$$P_i(t) = P_i(t-1) \cdot \underbrace{(1+\pi_i^d(t))}_{\substack{\text{Demand-pull} \\ \text{inflation}}} \cdot \underbrace{(1+\pi_i^c(t))}_{\substack{\text{Cost-push} \\ \text{inflation}}} \cdot \underbrace{(1+\pi^e(t))}_{\substack{\text{Aggregate} \\ \text{inflation expectation}}} \tag{6}$$

This specification is broadly in line with business survey evidence in Canada found in (Asghar et al., 2023). In normal times, firms' input costs are the key driver of their output prices. When there is broader input cost pressure, the pass-through of input costs to output prices could increase. During such times, inflation expectations could also further influence the way a firm sets its prices.

4 Using CANVAS to manage the inflation challenge

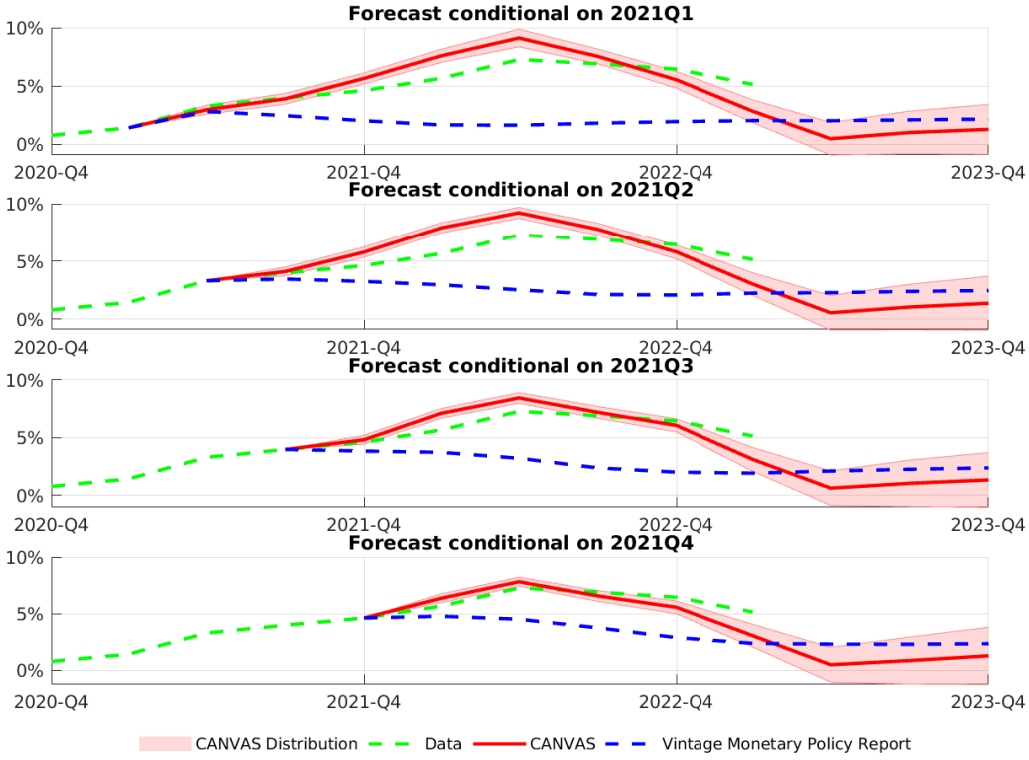
Before introducing CANVAS for policy analysis, we have conducted formal forecasting performance evaluation of the out-of-sample forecasting performance of CANVAS in comparison with standard macroeconomic models such as a VAR and a DSGE model (see Hommes et al. (forthcoming)). The DSGE model is ToTEM, an estimated large-scale multi-sectoral model that is used for projection and policy analysis at the Bank of Canada (see Corrigan et al. (2021)). Relative to both alternative models, CANVAS has richer heterogeneity in both households and firms. On the demand side, CANVAS models households of varying income levels, and persons in the labor force are associated with additional characteristics such as their age, sex, and occupation. On the supply side, each of the 19 industries is populated by firms that differ in market share, balance sheet conditions, and ownership structures.

CANVAS shows great strength and outperforms the DSGE model in forecasting GDP growth and key components like consumption. This competitive forecasting performance is encouraging, suggesting that a macroeconomic ABM that encompasses rich household and firm heterogeneity where agents interact in incomplete markets has the potential to enrich macroeconomic forecasting.

The learning mechanism helps align theoretical work on behaviour with new survey evidence on Canadian firms' pricing behavior observed through the pandemic (Asghar et al. (2023)). These enhanced features provide us confidence in using CANVAS to help understand the economic impact from the COVID-related lockdown measures within particular industries and specific populations.

4.1 CANVAS has richer framework to understand inflation

Figure 4: Conditional forecast would have pointed to significant upside risk to inflation surge



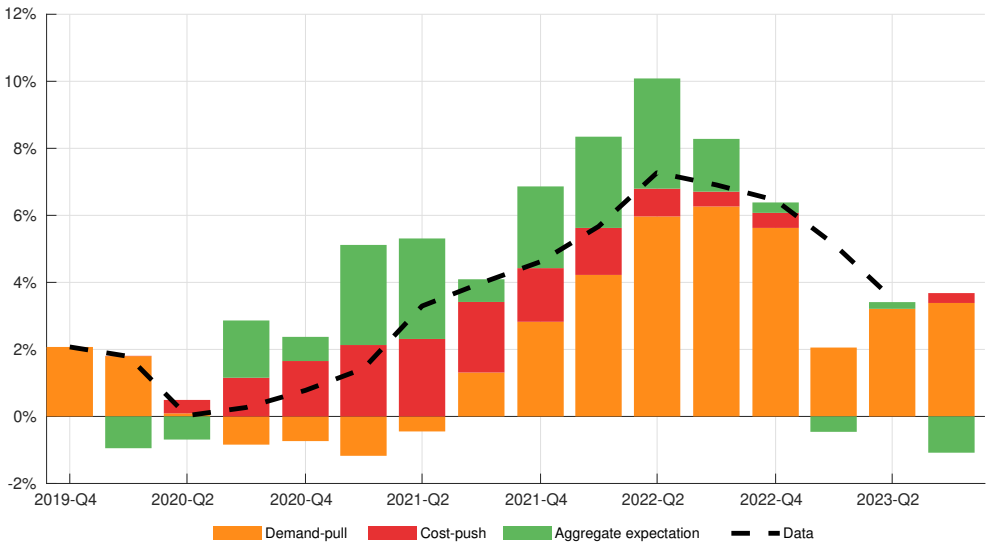
Source: Statistics Canada, authors' calculation

Conditional on the state of the economy in 2019Q4, we use the model to conduct a counterfactual exercise of eight-quarters-ahead out-of-sample projections until 2021Q4. The dashed green line in **Figure 4** shows inflation data, the mean model-implied inflation projections under this scenario are shown in red. In contrast to the benchmark cases from the Bank of Canada's Monetary Policy Reports (blue dotted line), CANVAS predicted a surge in inflation in 2021 and 2022.

Key drivers behind inflation surge On the one hand, the cost-push mechanism characterizing inflation in 2021 is intuitive. An increase in production inputs costs leads firms to increase their prices. Such a mechanism can be found in most macroeconomic models. On the other hand, the demand-pull mechanism characterizing inflation in the post-restrictions period in 2020 is less obvious. Firms increase prices, not because the *level* of demand is high — in fact, the level of real GDP in 2020Q3 in Canada is still below its pre-pandemic value — but because the *growth* of demand is high. This mechanism is specific to the heuristic assumed in Eq. (6) and has a well-defined implication.

Figure 5 provides a decomposition of the GDP deflator inflation in Canada from a CANVAS simulation. The model suggests that higher costs is the primary driver of inflation during 2020-2021 as shown by the red bars. As soon as inflation surpasses the 2% target, inflation expectations start contributing

Figure 5: Inflation surge explained by three key drivers



Source: Statistics Canada, authors' calculation

to higher inflation as illustrated by the green bars. While both expectations and cost considerations remain relevant, since the second half of 2022 when the Canadian economy gradually reopens, demand has become an important driving force to the inflation surge. To this end, the notion that firms could have exploited their market power to raise prices by more than increased input costs could be the mechanism at play, similar to the recent discussion (e.g., Glover et al. (2023); Hansen et al. (2023)). When consumer demand is less sensitive to prices, or when there is reduced market competition, firms' market power increases which could lead them to set higher prices to gain greater markups. In our model with adaptive expectations, it is clear that there is a rotating contribution among the three drivers of inflation. When costs increase, firm may increase their prices by allowing for greater cost pass-through but not necessarily increase their markups because of the concern for competitors. Firms' expectations play a crucial role in determining inflation dynamics since firmspay greater attention to the inflation data to assess how long the higher cost situation may persist. When inflation perception starts to rise, even current costs decline since mid-2023, markups may continue to increase as firms are concerned about their future costs.

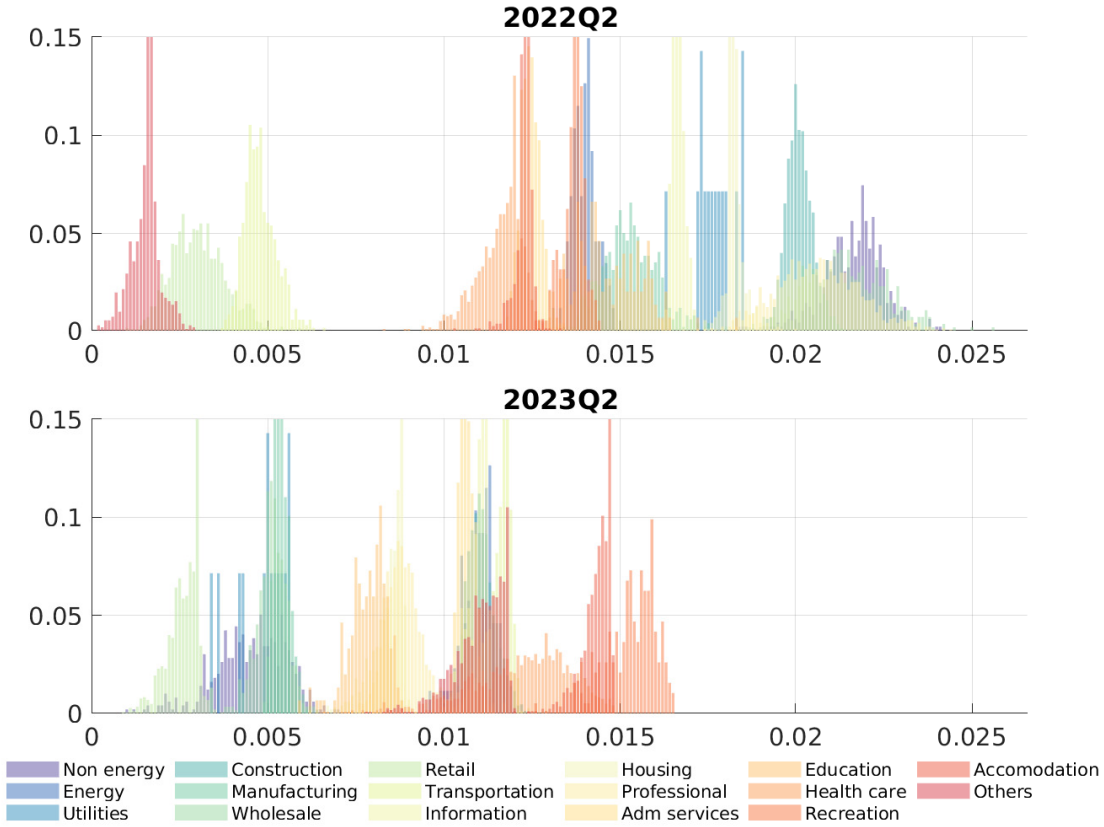
Granular level of inflation dynamics Since CANVAS models firm heterogeneity, it helps expand the capacity of macroeconomic analysis with its ability to model dynamics at the firm and industry levels. We construct a counterfactual scenario and illustrate the firm-level inflation distribution within each sector in **Figure 6**.

In this scenario, firms react to the sharp increase in individually perceived demand observed in the post-lockdown period by increasing their prices. As a result, demand-pull inflation explains most of the inflationary pressure in Canada over 2020-2021. As global activity rebounds since mid-2021, an increasingly high share of firms expect demand to grow quickly. As they observe higher inflation following the global supply chain disruption, a greater share of firms would also expect increased inflation persistence. For an individual firm that relies on utilizing labour, capital and intermediate inputs from other suppliers, the rebound of global activities implies more firms would experience rising input costs pressure, which directly affects production costs and price setting.

We show a snapshot of sectoral inflation distribution when inflation was at its peak in summer 2022. In the simulation, the means of inflation of the commodity, manufacturing and transportation sectors are relatively higher than other sectors. Since the commodity sector supplies the critical inputs for the manufacturing goods sector, when there is large and persistent surge in commodity prices, coupled with port strikes that hinders functioning transportation sector, sectoral inflation surge and the production and distribution of manufacturing goods is jammed. Since manufacturing sector supplies nearly all parts of the economy, such disruption would have effects that propagate throughout the Canadian economy.

Interestingly, the simulated distribution of firm-level inflation shows large dispersion. This type of information is particularly useful for policy makers to better understand the implications of the oil price movement and its impact on Canada.

Figure 6: ABM provides granular insights beyond traditional models



Source: Statistics Canada, authors' calculation. Note that the x-axis indicates sectoral producer price inflation (Y/Y), and the y-axis indicates distribution

4.2 Monetary policy decision-making in times of uncertainty

The inflation mechanism in CANVAS is closely related to new lab experimental evidence. Salle et al. (2024) show that recalled experiences of inflation by individuals affect their forward-looking expectations about inflation. In particular, experience with high inflation leads to more attentive behaviour and less central bank credibility while experience with low inflation leads to more credibility. Furthermore, experience with rising inflation leads to higher inflation expectations. The authors also find that there is asymmetric behavior as individuals tended to overreact to their forecast errors in the case of rising inflation treatment.

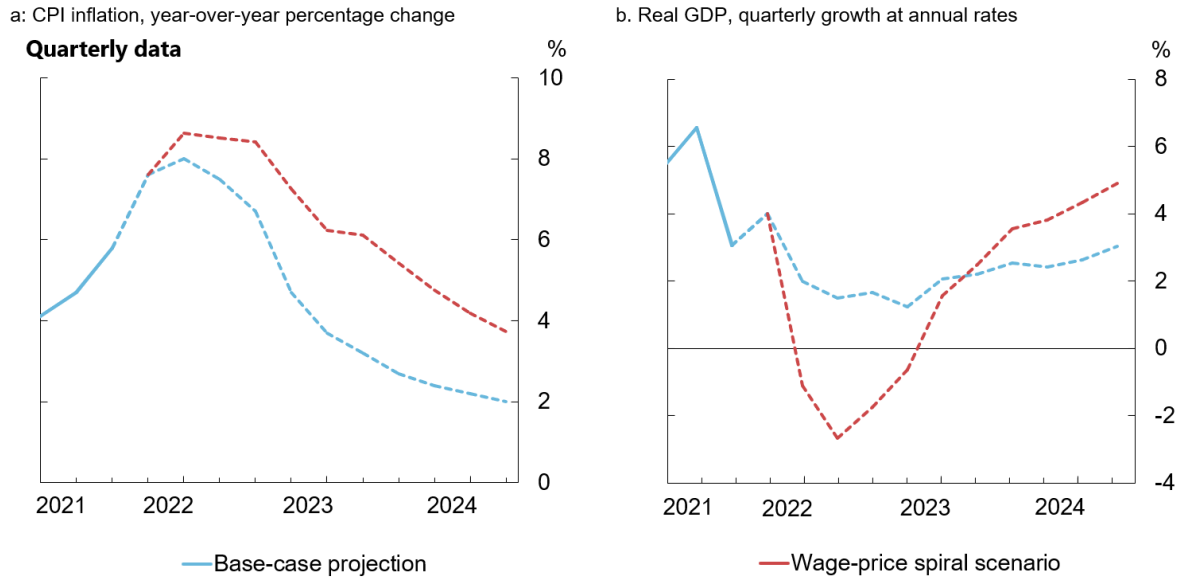
Making monetary policy decisions amid such a high degree of uncertainty is a challenge. The baseline economic projection models used in the Bank of Canada's Monetary Policy Report generally assume that inflation expectations are well anchored on the 2% inflation target. However, in July 2022, inflation was climbing and broadening, inflation expectations moved upward, it became important to consider the upside risk to inflation. If these rising inflation expectations occur while the labour market is tight and wage growth is strong, there is an increased risk that a self-reinforcing wage-price spiral could raise the inflation outlook.

We developed a "wage-price spiral" scenario in CANVAS to illustrate the uncertainty when inflation was approaching its peak level in July 2022. In this risk scenario, when inflation remains persistently high, more households and firms base their inflation expectations only on the most recent inflation data. As a result, longer-term inflation expectations become de-anchored and stay above the target.

De-anchored inflation expectations lead firms to set prices even higher. Similarly, in response to higher expected inflation, workers bargain for persistently higher wage growth to protect against anticipated losses in purchasing power. The resulting stronger wage growth feeds into production costs and prompts firms to raise prices even further. This process boosts inflation expectations, perpetuating the spiral.

While the likelihood of a wage-price spiral was assessed to be negligible, policy makers are keenly aware of the risks associated with a wage-price spiral. Concerns about a worst-case scenario like this can lead to amplification in the optimal monetary policy response (e.g., Giannoni (2002); Onatski and Stock (2002); Tetlow and Von zur Muehlen (2009)). To break this vicious circle, monetary policy needs to tighten more than in the base case to create additional excess supply so that long-run inflation expectations remain well-anchored. This is illustrated in **Figure 7**, where in the wage-price spiral scenario, considerably weaker real GDP growth is required to bring inflation down, and even so the decline in inflation is delayed and more gradual than in the base case. This scenario was included in the Bank of Canada's Monetary Policy Report of July 2022 accompanying the policy announcement at the time.

Figure 7: In the wage-price spiral scenario, inflation is higher and growth is slower



Source: Monetary Policy Report, July 2022, Bank of Canada

5 The way forward

Macroeconomic models play an essential role in the conduct of monetary policy and the Bank of Canada has a long history of using them for projections and policy analysis (Poloz, 2017). The models have grown vastly more sophisticated through the years and have many benefits. But while they tend to feature a rich demand side, they have performed less strongly in analyzing supply—a shortcoming that became clear during the COVID-19 pandemic.

For policy models used to support real world decision making for an inflation-targeting central bank, it is important to have inflation equations that are effective at explaining and forecasting inflation. Given challenges before and during the pandemic, a better understanding of inflation determination is a focus for research and development by an inflation-targeting central bank. CANVAS helps bridge modelling gaps at the Bank of Canada in three main areas:

- The individual firm's cost structures of integrate critical domestic and global input-output linkages in Canadian production networks. During the nearly 30 years of the "great moderation" era prior to the pandemic, supply shocks (such as energy prices fluctuations) typically had temporary effects on inflation. As demand rebounded following the reopening from pandemic lockdowns, the economy experienced a series of large negative supply shocks such as a negative labour supply shock, the disruption of global supply chains, and the subsequent surge of commodity prices. Traditional models that only focus on demand as the main driver of aggregate imbalances between supply and

demand in the economy were insufficient in gauging inflationary pressures to guide policy actions. These experiences triggered a critical need for a more granular, multi-sector model to help better understand inflation dynamics when the costs of production depend crucially on the economic structure and linkages.

- Inflation expectations depart from rational expectation assumptions. Agents are boundedly rational. In the discussion in this chapter, we have emphasized adaptive learning of simple AR(1) rules, but the models can easily be extended to switching between heterogeneous forecasting rules. As a result, the persistence of inflation and central bank credibility become endogenous, and inflation expectations could become deanchored in the absence of an aggressive monetary policy response. The experience of applying CANVAS to help understand the formation and importance of inflation expectations during a high inflation episode has taught us to be more agile in considering alternative ways to understand how the complex economic system is evolving. Our household and corporate surveys have provided new evidence on how people and firms form expectations during stable inflation time as well as when inflation fluctuates. New lab experimental evidence shows that experience with high inflation leads to higher inflation expectations. Inflation memory could potentially explain the persistence of inflation expectations and the perception gap not explained by the structural models. These are areas future macroeconomic agent-based models could explore to allow us to fill important gaps in our understanding of the inflation psychology.

- While many central banks have emphasized the joint role played by both persistent input cost pressure and excess demand in contributing to an inflation surge, there is little direct role in traditional DSGE models in capturing excess demand and how a central bank uses its instrument and communication in managing it. Similarly, there is little emphasis in acknowledging the role of the central bank in providing confidence and managing inflation expectations under enormous uncertainty. Detailed macroeconomic agent-based models that encompass heterogeneity, a realistic supply side of the economy and behaviour into one framework can offer some promising performance in the Canadian experience. Yet, the journey of effectively integrating ABM into our policy toolkit is not smooth. It is complicated by the level of investment policy makers would need to make to fully understand the ins and outs of the model and clearly communicate model uncertainties to the public. When inflation expectations are high and central banks are under tight scrutiny in effectively restoring price stability, how to use the intuitive narrative from the models to connect with a broader audience has become critical. In our experience, we have resorted to using effective data visualization to get to the story behind model simulations, introducing interactive "what-if" type tools to allow the model insights to be more accessible, and explain the models in plain and simple languages to make sure the key messages get through.

The pandemic presented an excellent opportunity to better understand the dynamics of inflation with the help of an agent-based model. While we have learned a great deal, we are still learning. Our work will not be done without more experiments and greater clarity. However, one conclusion is already clear: policy scenario analysis using agent-based models based on microeconomic data will become essential tools for central banks and many other policy-making institutions around the world. We hope our work will enhance the collective knowledge of these models, helping us to get a firmer grip on inflation—whatever it may throw at us.

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