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COVID-19 supply chain resilience modelling for the dairy industry

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Abstract

Precipitated by the COVID-19 pandemic, the extant global supply chain is transitioning from an efficiency fixated system to a system orientated on resilience. Key factors advancing this transformation include localisation and digitalisation. A system dynamics model is formulated to facilitate the investigation of the aforementioned factors impact on the cost structure of the dairy sector. A 3 level, 2 factor experiment reveals the confounding effect of the two factors to be a decrease in the mean cost across the system mediated primarily by the cascading benefits of digitalisation on innovation, continuous improvement and the concomitant efficiency enhancement. Analysis of the simulation results establishes that employment is augmented by digitalisation and localisation but constrained by skills scarcity. An extended model incorporating a more comprehensive description of the dairy sub-sector would be indispensable to informing policy and strategic and tactical decision making for resilience based designs.

Keywords: localisation; digitalisation; cost; resilience

1. Introduction

The propagation of the coronavirus pandemic has exposed shortcomings in the extant global supply chain obliging a review in which the localization and digitalization of supply chains is a key consideration [6]. Further, resilient, as opposed to efficient, businesses will survive the crisis resulting in consolidation post pandemic.

This localization and digitalization of inbound supply chains is expected to impact local communities and businesses. An understanding of these impacts will direct the decision-making process of business leaders, local and national government planning, skills development providers and investors and entrepreneurs.

This paper evaluates the impact of "re-shoring" and digitalization on the efficiency and resilience of dairies operating in South Africa with specific focus on implications to the cost structure as a function of employment and inventory variations. The analysis is conducted using a systems dynamics model predicated on the nascent data emerging from literature. The objective of the analysis is to develop a systems dynamics forecasting model to ascertain the impact of the anticipated post COVID-19 inclination to more resilient supply chains specifically with regards the

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cost structure of the dairy subsector. The research incorporates the effects of skills capacity, inventory, employment, and innovation.

2. Background

2.1 Global Supply Chains

Post-World War 2, globalization remedied persistent food security issues simultaneously stimulating food safety and diversification [3]. The increasing sophistication of the global supply chain network was accompanied by an emerging fragility [9] exposed as the pandemic swept from east to west, compelling authorities to institute containment strategies that disrupted economic activity on an unprecedented scale.

Being constituted of factories, suppliers, distributing networks and transportation links, global supply chains are particularly vulnerable to persistent disruptions and uncertainty [7]. Short term survival has compelled organisations to adopt intermediate strategies to contend with upstream and downstream disruptions including pricing adjustments and shifting demand to products that are more accessible [5].

2.2 From efficiency to resilience

In the medium term the pre-eminence of efficiency in erecting supply chain networks will be subordinated by considerations of resilience, for example revisiting lean Just In Time (JIT) strategies in favour of maintaining higher inventory levels and increased investments in redundancy [17].

With organisations adopting diversification as a risk mitigation strategy post pandemic, the two factors that constantly emerge in the literature as key enablers of the mind-set shift arising from the backlash against globalization are geography and technology. Penrod (2020), Kirk (2020), Cappelli (2020) and Farlow (2020) all predict localization of supply chains both as an adaptation to the post pandemic uncertainty and necessitated by regulatory interventions by authorities. This migration to shorter food supply networks must be facilitated by investments in capacity development, technical solutions and research exploring the substitution of scarce inputs with abundant locally accessible materials.

Accelerated adoption of technology driven by a need for innovation to improve resilience involves the integration of digitization into supply chain network optimization and development. Big data analytics, cloud computing, automation, the internet of things [5], 3D printing and Blockchain [9] will ultimately lend significant competitive advantage by enhancing the management of relationships in the supply chain network, overcoming restrictions on the movement of people, streamlining supplier selection processes, facilitating the in-house production of key components, and enhancing product quality systems.

3. Literature

The fundamental structure describing the shift in supply chain configurations remains inchoate in the extant literature. The incipience of the current transition in the global supply chain network necessitates urgent study to evaluate the outcomes of post COVID-19 strategies.

3.1 Supply Chain

The advent of the Fourth Industrial (4IR) revolution has hastened enormous change in the manufacturing of food and beverages. These 4IR technologies are particularly suited to resolving the peculiar challenges confronting food and beverage manufacturers: demand for differentiated Stock Keeping Units (SKU's), regulatory compliance, production scale, complex planning requirements and high variation in seasonal demand (McNamara 2017). In the midst of this transition, a new seismic shift precipitated by the Novel Coronavirus (COVID-19) pandemic is compelling organisations to restructure the prevailing lean models to contend with unprecedented demands in the midst of intermittent production and disrupted supply and distribution networks [19].

The competitiveness of contemporary organisations is inextricable linked to the global supply chain which has become extremely sophisticated as a result of its interconnected and global characters, a product of significant investment in cost minimisation, inventory reduction and asset utilisation [8]. The attendant efficiency gains translated into differentiation in a marketplace defined by more discerning customers. With efficiency elevated to an existential issue for organisations participating in the global marketplace focus is maintained on resolving the issues of risk management, information sharing, supplier competence, sub-optimal levels of buyer-supplier trust and collaboration, uncertainties in demand [16] making supply chains longer, leaner and geared for just in time supply [9].

Demand forecasting in the midst of a pandemic is plagued with the uncertainties concomitant with the prediction of the extent and frequency of containment measures. "Shortage Gaming" is the phenomenon whereby users artificially inflate demand creating the well documented "bullwhip effect" which is exigency amplification upstream in the value chain [19]. These factors expose the fragility of contemporary supply chain networks eroding confidence in long term sustainability.

On 07 January 2020 a novel strain of the coronavirus was isolated from a patient in Wuhan, China [18]. By mid-July 2020 over 12.5 million people have been infected globally despite authorities instituting unprecedented containment measures globally; the impacts of which have severely curtailed economic activity and decimated business and consumer confidence. Many countries or regions have reopened economies only to experience a resurgence in infections [18]. The daily infection rates increases obstinately dispelling notions that the impact will be sharp and short lived [5].

Seifert (2020) submits that supply chains have thus far met the demands imposed by the pandemic through resourcefulness and adaptability but anticipates a fundamental restructuring of supply chains. The efficiency / resilience trade-off will provide impetus for geographic diversification of operations [5], development of agile production and distribution networks and digitalisation to facilitate reconfiguration [8]. Due to the prevailing local constitution of food and beverage supply networks, the modifications to food supply chains will not be as extensive as sectors such as automotive. Kirk (2020) anticipates shorter supply chains albeit characterised by tiered complexity with companies preferring to incorporate resilience into supply chain networks rather than depend on authorities to prevent and manage seismic disruptions.

Like the rest of the world, the South African dairy industry is consolidating with the number of producers decreasing from 3 551 to 1 253 in the ten years from 2009 to 2019 [21]. This transition to larger producers was accompanied by the introduction of technology (automated milking, phenotypic profiling for genetic progression) and more sophisticated supply networks. In South Africa, the dairy supply chain is constituted of the producers (large, medium and small), importers, bulk milk collectors, dairy processors, exporters, transporters, retailers, informal traders and consumers. With respect to volume, milk is South Africa's third most produced agricultural good, split into liquid (milk, yogurt, buttermilk) and concentrates (butter, cheese, condensed milk) [13]. The market is forecasted to grow by 2% compounded annually in the period 2018 to 2023. The top four processors in South Africa controlled 54% of the total milk market value in 2018 [11].

3.2 Experimental Methodologies

Systems Dynamics is more suitable to evaluate the high level interdependencies predominant in global supply chains as compared to discrete event simulation or agent-based modelling [20]. Using a macro focussed, top down approach, Systems Dynamics reproduces system level behaviour exposing counterintuitive emergent phenomena indispensable to decision making when confronted with complex, intricately woven and dynamic systems, like global and local supply chains [15]. Further the architecture of systems dynamics models enhances predictive capabilities to complement superior explanatory features [14].

Global Supply Chains (GSC's) are intricately woven rendering GSC's susceptible to action from a multitude of factors. Any successful model of such a system must be able to evaluate the individual contributions of each factor on the system, the extent of the effect on the response and establish the interaction between factors. The Design of Experiments (DoE) Methodology is a stochastic systematic approach to mapping multiple responses across a range of factors simultaneously [1]. A feature of the DoE methodology is the capability to identify significant effects irrespective of confounding factors [4].

4. Method

The impact of localisation and digitalisation on the dairy industry in South Africa remains under-investigated primarily due to the absence of impetus compelling such a transformation; a situation rendered obsolete by the onset of the COVID-19 pandemic. Of particular interest are the implications for the cost structure across the dairy sub-sector which regulates the magnitude of post pandemic evolution to increasingly resilient structures. In order to anticipate the effect of the localisation and digitalisation on employment and inventory levels in the South African dairy industrial sub-sector, a systems dynamics model is constructed incorporating a multitude of contributing parameters to facilitate a quantitative exploration.

Establishing the causal relationships necessarily preceded the model design in order to identify the key parameters influencing the factors being investigated. Figure 1 demonstrates the balancing loop identifying the causal connections regulating the relationship between localisation and employment. The rationality implicit in the casual relationships show that an increase in localisation (local content of total procurement spend causes an increase in the number of suppliers in the marketplace resulting in an increase in employment which causes costs to rise (due to more regulated local labour markets) resulting in a decrease in localisation.

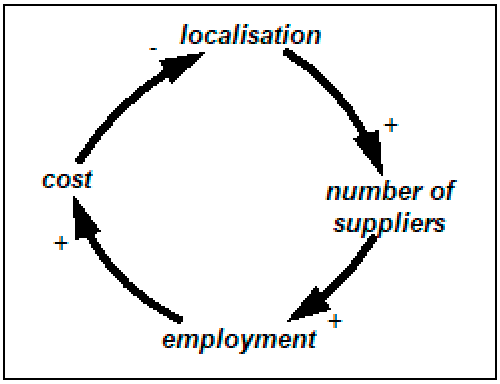

Figure 1: Causal loop diagram – localisation and employment

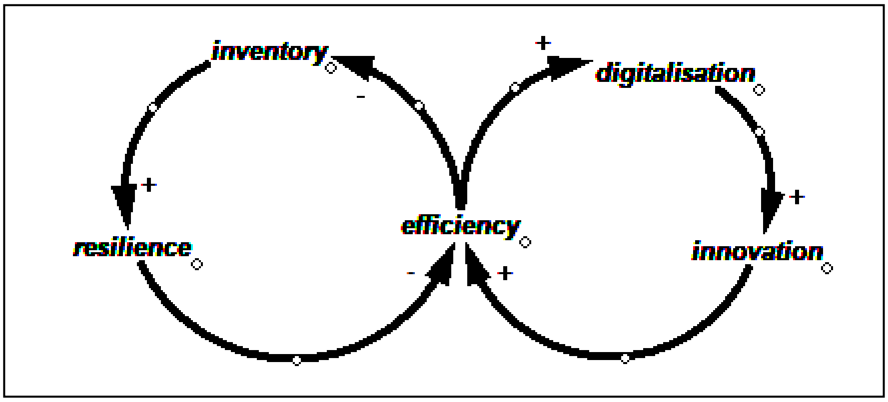

Figure 2: Causal loop diagram – digitalisation, efficiency and resilience

In Figure 2, the causal loop diagram reveals how digitalisation promotes innovation resulting in increased efficiency, which correspondingly reduces inventory which has a proportional relationship with resilience. The loops displayed in Figure 1 and 2 are the most critical considerations in the analysis, however this is not an exhaustive demonstration of the sub-systems constituting the model.

The simulation model is built using the Vensim software which is purpose-built for system dynamics. The software is selected based on Bures' (2015) comparative analysis of several systems dynamics simulation packages. The

Vensim model is selected for its accessibility and superior functionality arising from its solitary focus on systems dynamics modelling and simulation.

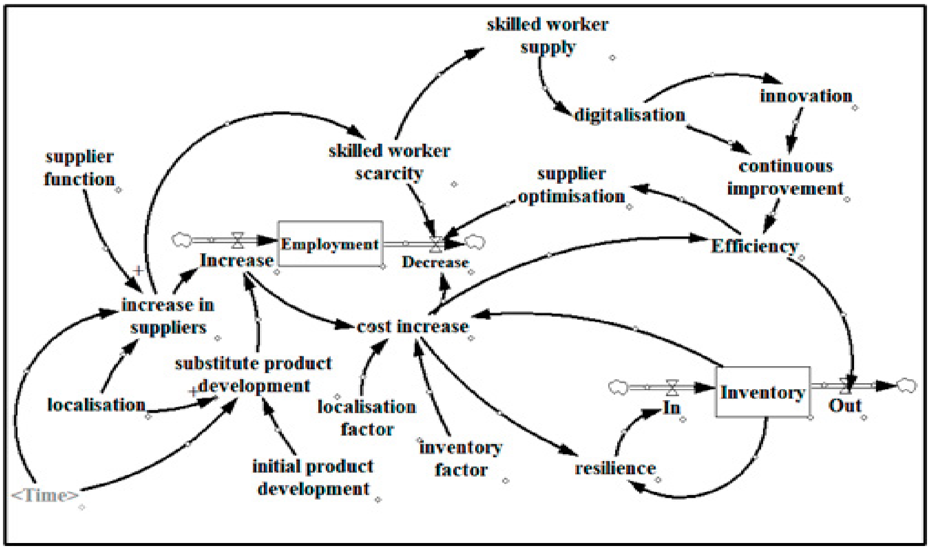

Figure 3: Stock and Flow representation of dairy system

The stock and flow diagram shown in Figure 3, created from the various causal loop diagrams constituting the system, is inserted into the software and subjected to mathematical and structural validation. A verification of the model structure in comparison to descriptions of the system is conducted to corroborate its structural validity. The model's mathematical validity is authenticated employing extreme condition testing.

Obtaining a functional model necessitated incorporating several assumptions into the model structure. In this model of the dairy sector, it is assumed that resilience is directly proportional to inventory levels whilst exhibiting an inverse relationship with cost. The variation in cost is constrained due to the confounding effects of localisation and digitalisation and the collective subordinate influences on the expansion in the local supplier network, inventory levels and the stimulus of substitute material development, innovation, continuous improvement and efficiency. Employment levels are attenuated by the well-established skills scarcity in the South African labour market, in addition to cost increases and the downstream implications of digitalisation within the system. Efficiency is propelled by digitalisation and innovation and instigated by increasing costs. The costs are dependent on localisation effects and inventory variation on a ratio of 1:2.

The model assumed an initial digital proliferation (which is the amount of functions within the system that are digitalised or automated) of 30% attaining maximum levels between 40% (DL) and 60% digitalisation in the dairy sub sector. The localisation (which represents the amount of goods and services appropriated locally) is modelled as a non-linear function increasing from 85% to between 90% (LL) and 94% in a 104 week period.

A three level, two factor experiment (3^2) using a full factorial design is adopted to establish the significance of the relationship between the localisation and digitalisation of the dairy system and employment and inventory levels. The study is conducted using a methodology involving a stepwise incrementation of the pertinent percentages in order to discern the quantitative relationships primarily because this technique can be accomplished as a dimensionless analysis and realises the objective of the research. The aforementioned baseline scenarios (DL and LL) are designated as the low-level scenarios.

Table 1: Experimental Levels for 3 factor analysis

Factors	Low Level	Mid-Level	High Level
Localisation	90%	92%	94%
Digitalisation	40%	50%	60%

The levels per factor are identified from the extreme condition testing abetted by trial simulations identifying significant inflection points of the selected response (cost).

The validated model is simulated on the Vensim software in accordance with the experimental schedule in Table 2.

Table 2: Experimental Design

Trial	Localisation	Digitalisation
1	90%	40%
2	90%	50%
3	90%	60%
4	92%	40%
5	92%	50%
6	92%	60%
7	94%	40%
8	94%	50%
9	94%	60%

The interaction and dependencies between the factors and responses are determined from the responses obtained after 104 weeks from the model start time. The data thus obtained is analysed using Minitab, a data analysis software package equipped with DoE functionality.

5. Discussion of results

The systems dynamics model of the dairy system is simulated with the Vensim software compliant with the experimental setup and the responses for the cost variable are obtained as presented in Table 3.

Table 3: Response Table for Inventory

Trial	Localisation	Digitalisation	Cost(units)
1	90%	40%	111.2
2	90%	50%	110.5
3	90%	60%	49.5
4	92%	40%	96.7
5	92%	50%	96.3
6	92%	60%	95.5
7	94%	40%	96.4
8	94%	50%	95.8
9	94%	60%	95.2

The data is input into Minitab using the Design of Experiment tool for a 3 level (low, mid and high) and 2 factor analysis. That a relationship exists between the factors and the cost variable is implicit in the design of the model, however this investigation is concerned with the magnitude of the impact and the interaction between the factors in the variability of the response.

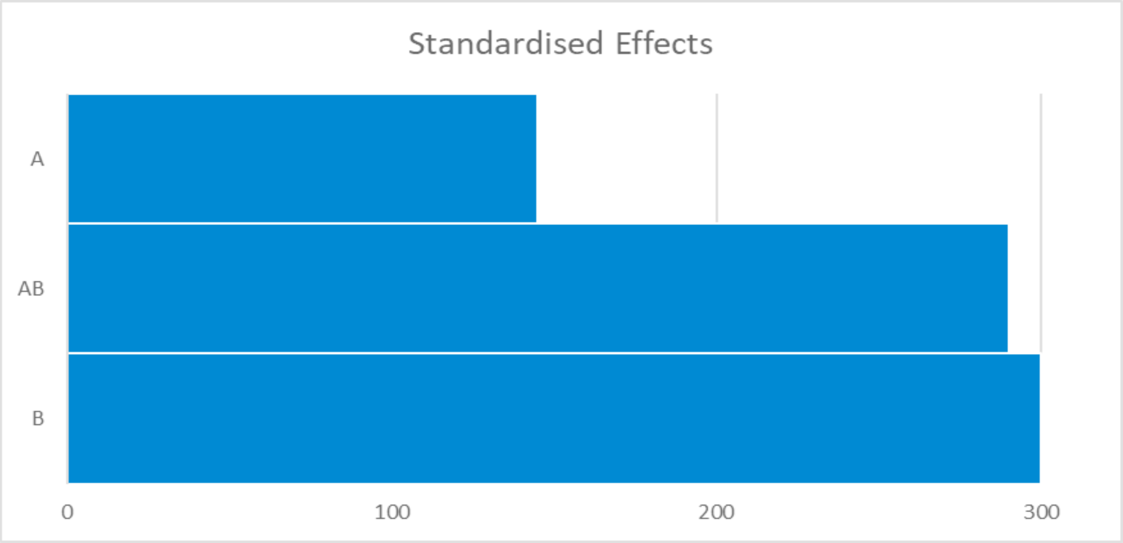

Figure 4: Pareto Chart of Standardised Effects

Allocating the nomenclature of A for localisation, B for digitalisation and AB for the combined effect of these parameters on the response, it is evident from Figure 4 that digitalisation exerts a substantially more significant effect on the costs within the system than does the effects of localisation. The interaction between the two factors show the attenuating impact of localisation on the effect of digitalisation on cost. The standardised effect conveys the relative significance of the factors under investigation, not the direction of the impact.

The effects of the individual factors on the system cost is shown in Figure 5. Localisation has the effect of increasing the mean cost, and this effect is countered by digitalisation of the dairy industry.

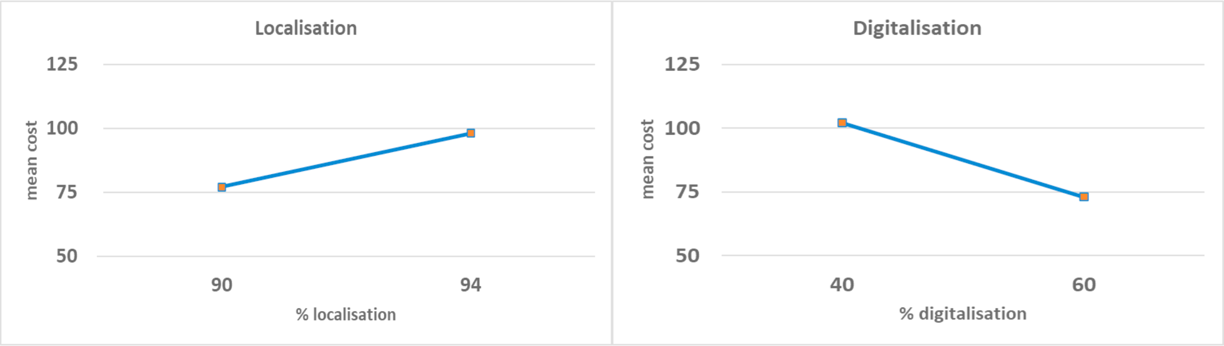

Figure 5: Pareto Chart of Standardised Effects (a) localisation (b) digitalisation

The mean cost is increased from its baseline value by the 104-week transient point only at the lowest values of digitalisation and localisation.

In addition to the effects of the factors under investigation, the model demonstrates that employment levels will increase under the combined effects of the two factors, and that cost increases arising from elevated inventory levels will be mitigated by the cascading effect of digitalisation on innovation and continuous improvement. It is anticipated that the proliferation of digitalisation will be limited by the scarcity of skilled workers but the improvements precipitated by the digitisation of the dairy sector will negate any deleterious effects on cost.

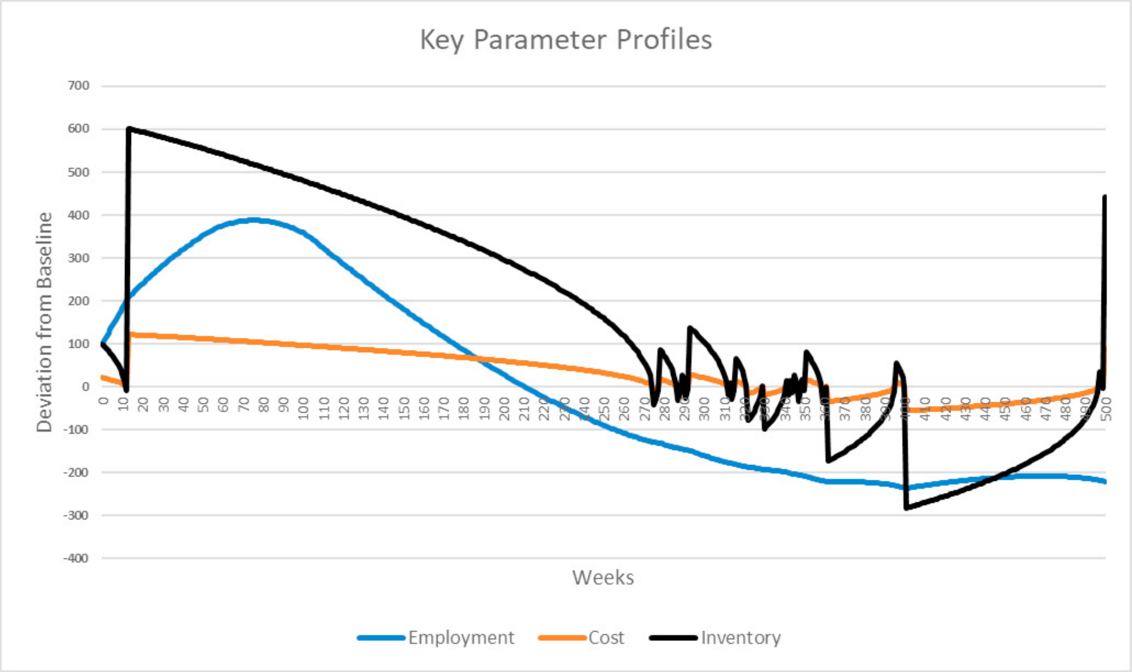

Figure 6: Employment, Cost and Inventory trend at maximum localisation (94%) and digitalisation (50%)

As per the model, the levels of employment in the dairy supply chain will also increase appreciably in the 200-week period subsequent to initiating resilience measures but will be reduced as the efficiency gains from digitalisation proliferate through the supply chain. The trends also reveal medium term benefits on inventory levels and cost, the key factors to achieving supply chain resilience. This result requires interpretation within the context of the assumptions of the model and the parameters included therein, which have been selected to provide elucidation on the impacts of the specific factors being investigated. As such the model is limited in articulating scenarios exceeding the scope of this study.

6. Conclusion

The imposition of the stresses associated with the COVID-19 pandemic on global supply has necessitated a review of the current “efficiency at all cost” systems that constitute contemporary integrated and vulnerable supply chain systems. The remedy is the creation of “resilient” supply chains able to withstand shocks. Achieving resilience in the supply chain is achieved by localisation and inventory adjustments. Digitalisation is a key enabler of achieving resilience arising from its propensity to mitigate cost escalation by facilitating innovation and continuous improvement.

A systems dynamics model of the dairy subsector simulated on Vensim revealed that localisation increases costs within the system whilst digitalisation has the opposite effect. The confounding effects of the two factors result in an overall decrease in mean cost across the system consequent to the implications of digitalisation. The increase in localisation and digitalisation increases employment and inventory levels across the sub-sector but the effects are contained by the scarcity of skilled workers and the increased innovation and continuous improvement catalysed by digitalisation.

The model is limited in that it is designed to exclusively evaluate the effects of localisation and digitalisation on cost and does not provide a comprehensive representation of the dairy sub-sector.

Notwithstanding the aforementioned considerations, the qualitative features of the model can contribute to an understanding of the post COVID-19 restructuring of the dairy sub-sector and opportunities exist to extend the scope of the model to inform policy and strategic and tactical decision making beyond localisation and digitalisation. The application of systems dynamics to illuminate emergent properties arising from the transition from efficient to resilient supply chains is novel.

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