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Comparison of Centralised and Decentralised Pharmaceutical Manufacturing Paradigms: An Agent-Based Simulation Study

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ABSTRACT

Traditional centralised manufacturing offers efficient economies and broad market reach but faces increasing limitations with the rise of complex products requiring rapid localised delivery and greater supply chain resilience. The logistics demands of hospital-compounded therapies expose vulnerabilities in existing infrastructure, accentuating the need for rigorous evaluation of alternative paradigms. This study investigates the comparative performance of centralised and decentralised pharmaceutical manufacturing models, applying an agent-based simulation framework designed for specialised or time-sensitive drug product orders. The work implements an agent-based simulation to model both centralised and decentralised scenarios using key structural, resource, and demand parameters identified within the supply chain ecosystem. Comparison criteria include labour requirements, sustainability (as measured by environmental emissions and operational efficiency), and end-to-end supply chain lead times, informed by the geospatial distribution of manufacturers, hospitals, and clinics. The centralised case considers a single facility supplying major hospitals and several clinics from a designated hub, while the decentralised case models multiple smaller production sites supplying care centres more directly. Demand frequency, emergency inventory buffers, personnel allocations, and practical constraints are explicitly built into the simulation inputs. Preliminary simulation results reveal trade-offs between manufacturing paradigms across multiple performance dimensions. The decentralised model shows potential advantages in reducing supply chain lead times and improving responsiveness to localised demand surges, while the centralised model demonstrates efficiency gains in resource utilisation under steady-state conditions. The framework enables quantitative comparison of throughput, cost implications, delivery timeliness, and system resilience under varied operational scenarios. These findings will inform strategic design decisions for patient-centric and resilient pharmaceutical supply chains, facilitating adoption of flexible models capable of meeting modern healthcare delivery needs within the medicines manufacturing and supply ecosystem.

Keywords: Supply Chain, Modelling and Simulation, Intelligent Systems, Pharmaceutical Manufacturing

INTRODUCTION

Pharmaceutical supply chains are increasingly exposed to operational fragility, as demonstrated by recent global disruptions that have propagated rapidly through tightly coupled and inventory-lean networks. These failures highlight a structural dependence on centralised manufacturing architectures, where long replenishment paths and limited buffering capacity amplify the risk of shortages. [1-6].

Although decentralised and point-of-care manufacturing models are frequently proposed as a means of improving responsiveness and reducing logistical delays, existing literature provides limited quantitative comparison of these paradigms under realistic demand and operational conditions. In particular, there is no systematic, simulation-based evaluation of how centralised and decentralised architectures differ in inventory behaviour, coverage performance, responsiveness, and environmental impact across multiple supply-chain echelons [7-9].

An increasingly prominent part of this discussion concerns the shift from batch based centralised production to decentralised or point of care (POC) manufacturing models, enabled by advanced processing technologies. Decentralised pharmaceutical manufacturing has attracted growing attention due to its potential to reduce transport delays, shorten replenishment lead times, and enable agile response to localised demand surges. Analyses across cell and gene therapy, monoclonal antibody production, and specialised medicines have highlighted those decentralised architectures, when underpinned by modern technologies, may achieve superior responsiveness and greater operational flexibility relative to traditional centralised paradigms [6, 10, 11].

This study addresses this gap by developing a multi-tier agent-based simulation of a representative pharmaceutical supply chain in Scotland. Two contrasting manufacturing configurations, a single large centralised plant and a set of smaller decentralised plants, are evaluated under identical downstream network structures. The model enables direct comparison of echelon-specific performance across inventory, service coverage, responsiveness, and emissions. The results provide an evidence-based assessment of trade-offs between efficiency, resilience, and sustainability across alternative manufacturing paradigms [6, 7, 9, 11].

METHODOLOGY

Pharmaceutical manufacturing paradigm Assessment

The pharmaceutical supply chain examined in this study (Figure 1) consists of four primary tiers: manufacturers, hospitals, clinics, and end consumers. The flow of products and information follows a demand-driven structure, where downstream demand signals propagate upstream to guide production and replenishment decisions. This pharmaceutical supply chain problem characterized by its structural configuration, connectivity among actors, and the policies and rules of engagement governing material and information flows, can be formulated as below:

Given

- Structure and connectivity between nodes, determining flow paths and network robustness.
- Policies and rules of engagement governing ordering, replenishment, and allocation.
- Emission rate associated with manufacturing activities.
- Demand variation arising from end consumers.

Evaluate

- Holding inventory as a cost indicator.
- Inventory coverage ratio showcasing the responsiveness of the system to meet demand reliably
- Emission levels as a measure of environmental impact generated by manufacturing segment

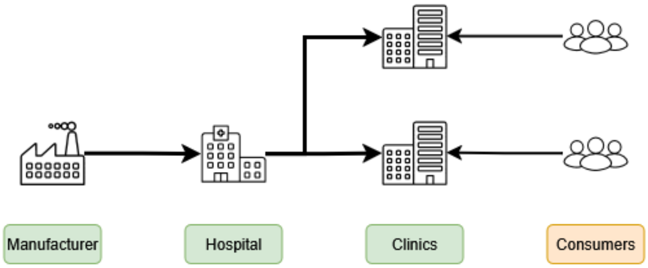

Figure 1. Conceptual model of the pharmaceutical supply chain.

Multi-Scale Agent-Based Model

The model, illustrated in Figure 2, is built on a foundational agent structure that is shared across all supply-chain entities (Figure 2-Top left). The application-level system built in the AnyLogic software (ver. 8.7.9), involves four primary agent types: manufacturer, distributor, health centre, and consumer, each instantiated from the same base agent template. As shown in Figure 2 (Top right), every agent in the logistic chain contains three core state variables: backlog, inventory, and a demand forecast, following system dynamic formulations reported in prior studies [12, 13]. Downstream demand is estimated using a first-order exponential smoothing process, and this forecast directly determines the agent's next order quantity. A set of behavioural parameters governs how each agent manages its inventory and backlog dynamics, shaping responsiveness and replenishment behaviour.

Interaction among agents occurs through order placement and shipment receipt, implemented via message-passing mechanisms that accommodate diverse ordering frequencies across tiers. Each agent type follows its own inventory policy, reflecting its position in the supply chain and influencing ordering decisions. To capture the logistics layer, the model incorporates explicit shipping and fleet components that represent transportation processes, queueing, and shipment delays, enabling a realistic depiction of material flows throughout the network.

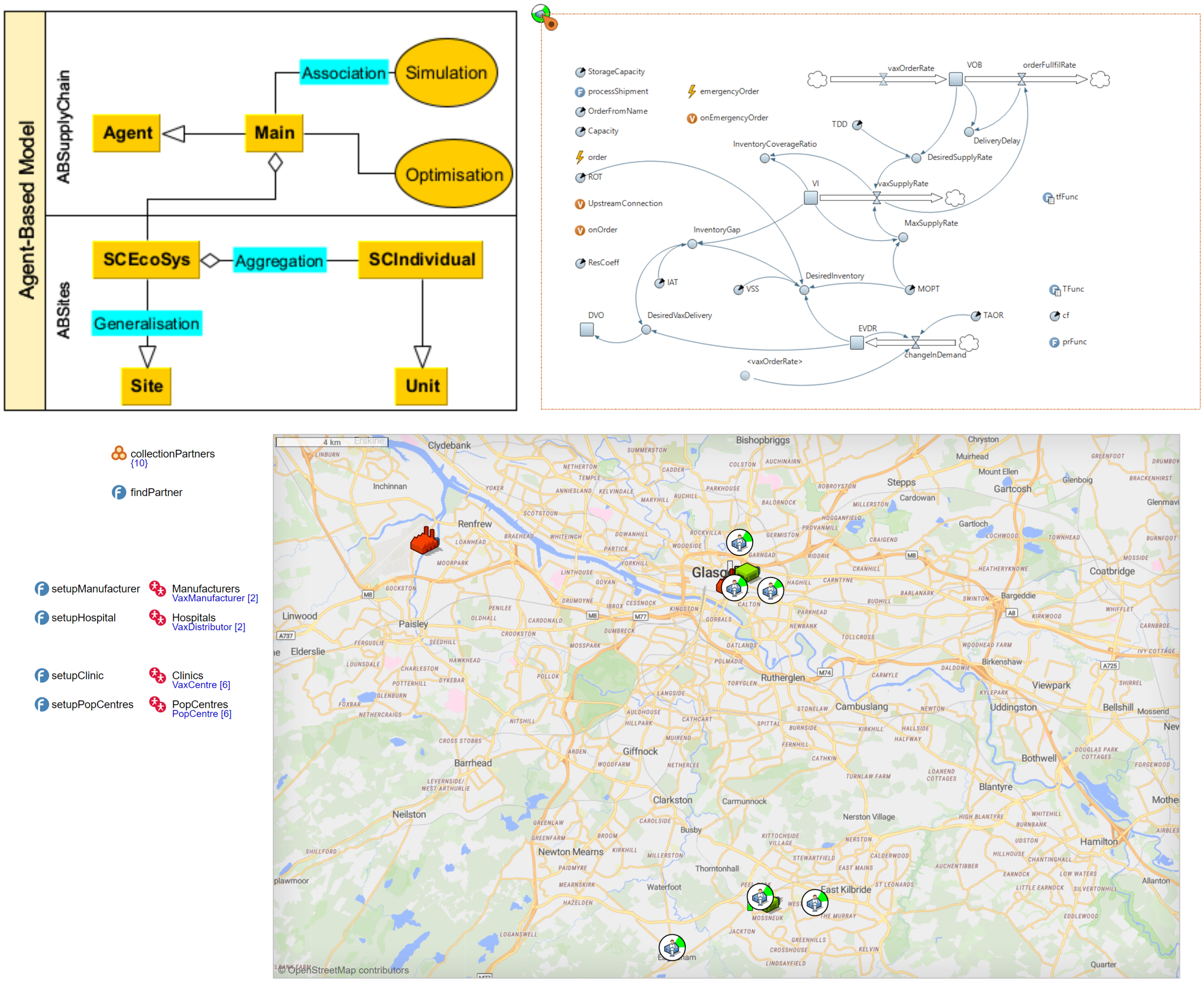

Figure 2. (Top left) The foundational representation of agent-based model (Top right) Dynamic agent behaviour representation (Bottom) Simulation model for Greater Glasgow pharmaceutical supply chain.

To represent the geographical distribution of supply chain entities, the model incorporates Geographic Information System (GIS) capabilities available within AnyLogic. These tools allow the spatial layout of manufacturers, distributors, and health centres to be embedded directly into the simulation environment, ensuring that distances, travel paths, and regional clustering are reflected in the system's behaviour. By linking agent locations to real or stylised geographic coordinates, the model captures spatial dependencies that influence shipment times, fleet utilisation, and overall logistics performance. This spatial layer complements the behavioural and structural components of the base model, enabling a more realistic depiction of how geography shapes SC dynamics.

The model uses a compact set of input data describing demand behaviour, operational policies, manufacturing capabilities, logistics characteristics, and sustainability factors. Demand inputs define the average and variable requirements of hospitals and clinics; operational inputs specify ordering rules, replenishment timings, and transport delays; manufacturing inputs capture production rates and process characteristics for both centralised and decentralised plants; and sustainability inputs include the emission factors associated with each manufacturing technology. Together, these inputs provide a consistent basis for comparing the two manufacturing paradigms under equivalent conditions.

Case study

The case study focuses on a pharmaceutical supply chain located in Scotland, modelled using two alternative manufacturing paradigms: a centralised configuration with a single large production plant, and a decentralised configuration with two smaller plants. In both scenarios, the downstream structure remains identical, consisting of two hospitals, six health centres, and six consumer centres. The overall supply-chain layout follows the structure

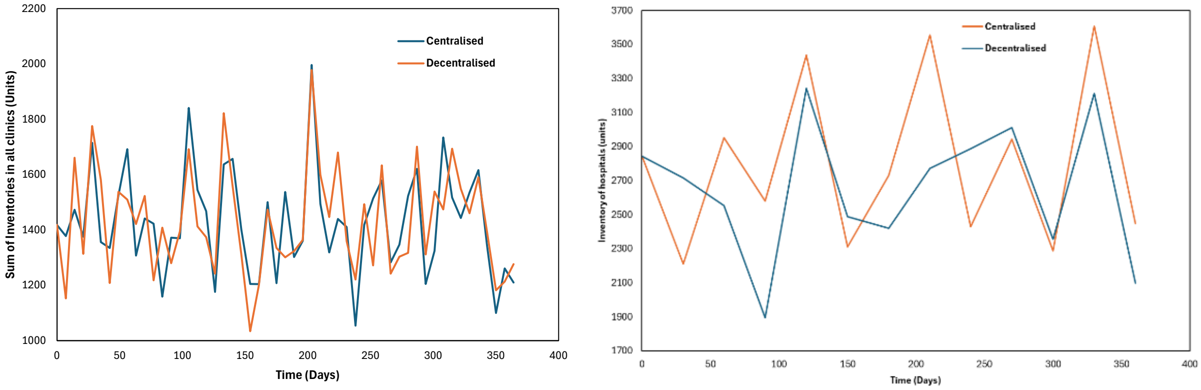

Figure 3: (left) Sum of inventory units in all clinics, and (right) Inventory of hospitals (Glasgow Royal Infirmary and Haimyres) in centralised and decentralised cases.

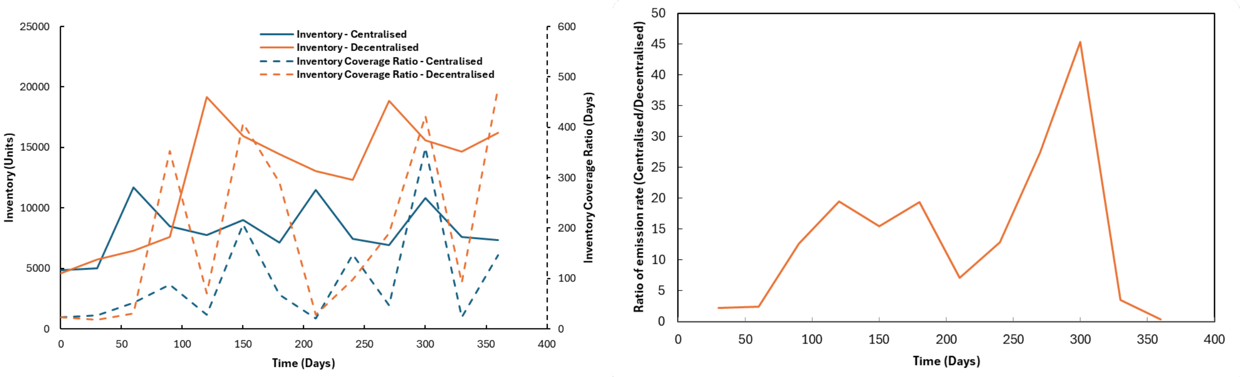

Figure 4: (left) Inventory units and inventory coverage ratio in centralised and decentralised cases, and (right) Ratio of emission rate of centralised over decentralised manufacturing cases.

reported in du Plessis, van Vuuren [14]. Under the centralised paradigm, hospitals place orders directly with the large plant, whereas in the decentralised paradigm each hospital orders from its corresponding small plant. Operational and logistical parameters for all tiers, as well as demand-variation characteristics, are taken from du Plessis, van Vuuren [14], ensuring behavioural realism. Emission parameters for manufacturing activities are also drawn from Hindiyeh, Altalafha [15] to capture sustainability impacts accurately. All agent locations in the model reflect their actual geographic coordinates, enabling spatially realistic routing, travel distances, and logistics performance within the Scottish context.

RESULTS AND DISCUSSION

The simulation outcomes reveal a structured set of performance differences between the centralised and decentralised pharmaceutical manufacturing paradigms. Performance differences emerge because clinics, hospitals, and manufacturers operate under distinct replenishment cycles, buffering rules, and demand-propagation dynamics. These structural differences cause each echelon to respond uniquely to changes in manufacturing configuration, leading to divergent inventory and coverage behaviours across the network. The analysis therefore demands a tiered interpretation rather than a monolithic comparison.

CLINIC LEVEL PERFORMANCE

Figure 3-Left shows the sum of all inventories at the clinic level in the centralised and decentralised cases. At the outermost tier (the six clinics) the two manufacturing architectures display no substantive divergence in overall inventory behaviour or service attainment. Although the decentralised system occasionally offers marginally tighter control of coverage during transient spikes, the broader simulation horizon demonstrates that clinics ultimately experience comparable stock levels and service stability under both paradigms. This is consistent with the observation that clinic level performance is heavily buffered by upstream nodes in the centralised case, while in the decentralised case it is moderated by shorter replenishment paths rather than by increased local inventory. Although decentralised manufacturing shortens physical

delivery distances, clinic-level performance remains comparable across both scenarios because clinics are heavily buffered by upstream inventory. In the centralised case, hospitals carry larger safety stocks to compensate for longer replenishment paths, while in the decentralised case shorter delivery routes offset lower upstream inventory. These opposing mechanisms result in similar clinic-level stability despite architectural differences.

Hospital Level Inventory

A more differentiated behaviour emerges at the hospital tier, where the simulation tracks the aggregated inventory of Glasgow Royal Infirmary and Hairmyres Hospital. The results show that the centralised scenario consistently yields slightly higher combined hospital inventories (Figure 3 - Right). While the magnitude of this increase is modest, its operational implications are not. Hospitals, as high cost stockholding environments, are disproportionately affected by incremental increases in buffer requirements. The elevated stock levels observed under the centralised architecture arise from the longer replenishment lead times from a single remote hub, compelling hospitals to hold additional safety stock. In contrast, under the decentralised configuration, more responsive resupply from CMAC and NMIS enables hospitals to operate with leaner inventory profiles, thereby reducing their holding cost burden.

Manufacturing Level Inventory

Figure 4-Left shows the inventory and coverage ratio over time for the manufacturers in the centralised (MMIC) and decentralised (CMAC + NMIS) cases. It can be seen that for the majority of the period considered, the decentralised case sees a higher total inventory (and therefore coverage ratio) maintained. This reflects the potential for greater fluctuations in order size in the decentralised case as a result of interactions between the larger number of participants. In the centralised case, the manufacturer is required to meet the demand of each hospital and so maintains an inventory sufficient to fulfil this requirement. In the decentralised case, each manufacturer could receive orders from either hospital, and does not know the orders placed to the order manufacturer. As a result, larger inventories are maintained as a means of ensuring resilience against downstream demand shocks. This effect is representative of a fundamental supply chain principle: the loss of risk pooling when production is divided across multiple smaller facilities. Each decentralised site must individually buffer against local variability, leading to a structurally heavier stock profile. The centralised facility, by contrast, benefits from statistically aggregated demand and can therefore operate more efficiently with lower safety stock requirements. Accordingly, while decentralisation may offer logistical and resilience benefits (as discussed below), it does so at the cost of increased working capital and reduced inventory efficiency at the manufacturing tier.

Coverage Ratios and Responsiveness

Despite its higher manufacturing inventory, the decentralised system exhibits stronger inventory coverage ratios, particularly during demand intensification periods. This reflects the inherent advantage of shorter physical and operational distances between production and consumption nodes. In practice, the decentralised units can respond more promptly to emergent demand fluctuations, thereby mitigating the risk of stockouts despite their smaller individual production capacity. This does not, however, translate into dramatically superior outcomes at the clinic tier (as previously noted), because the centralised system compensates through largescale throughput capability. Nevertheless, the decentralised architecture clearly delivers greater temporal responsiveness, and this confers a form of operational resilience that is particularly relevant for time sensitive or specialist pharmaceutical products.

Sustainability Metrics

Figure 4-Right shows the ratio of emissions in the centralised and decentralised cases. It can be seen that for the majority of the period considered, the centralised emissions are significantly greater than for the decentralised case. This is a result of the improved technologies used, but the variation in this ratio over time also shows a story of changing production rates. Spikes in the emissions ratios correspond to instances where centralised manufacturing increases in response to a low coverage ratio (see Figure 4-Left) whilst dips correspond to the inverse case with increased decentralised manufacturing.

This behaviour mirrors the technological assumptions embedded in the model: MMIC represents a traditional batch-based facility with correspondingly high emissions intensive cycles, whereas CMAC and NMIS operate small manufacturing processes with materially lower per unit emissions. The data confirms that even when emissions from both decentralised sites are combined, total environmental impact remains substantially below the centralised equivalent. This establishes that decentralisation provides a robust and widening sustainability advantage, conditional on the adoption of advanced continuous technologies rather than scaled-down legacy batch operations.

Beyond emissions, the manufacturing tier labour burden could also be compared across centralised and decentralised architectures, since site level carbon footprints can be translated into indicative fulltime equivalent (FTE) requirements using established energy and process intensity correlations. This linkage provides an additional operational lens, suggesting that lower emission continuous manufacturing sites may also exhibit reduced labour intensity relative to traditional batch-based facilities of equivalent throughput.

Synthesis and Implications

The findings reveal that the comparative merits of centralised and decentralised manufacturing are multidimensional and echelon specific. The centralised architecture optimises inventory efficiency, while the decentralised architecture optimises responsiveness and sustainability. For strategic planning, this implies that pharmaceutical supply chains must prioritise between cost efficiency, resilience, and environmental performance, recognising that these objectives are not simultaneously maximised by any single configuration.

The results show that centralised manufacturing benefits from statistical risk pooling, which reduces total manufacturer-level inventory and stabilises upstream stock levels. This efficiency, however, comes at the cost of longer replenishment paths that require hospitals to maintain higher safety stocks and accept slower response during demand surges.

Decentralised manufacturing exhibits the opposite behaviour. Shorter transport distances and geographically distributed production enable faster recovery from demand spikes, as reflected by higher coverage ratios during high-demand periods. This responsiveness is complemented by significantly lower emissions due to continuous manufacturing technologies used at decentralised sites.

These patterns confirm that no single architecture is universally optimal. Centralisation minimises inventory, decentralisation maximises responsiveness and sustainability, and each performance dimension emerges from structural features of the network rather than parameter tuning alone.

CONCLUSIONS

This study demonstrates that the comparative performance of centralised and decentralised pharmaceutical manufacturing is echelon dependent rather than monolithic. At the periphery of the network (the clinics) both architectures converge to broadly similar service outcomes, indicating that geographical proximity alone does not yield decisive gains in routine delivery performance. At the hospital tier, the centralised configuration imposes a modest but persistent inventory uplift relative to the decentralised case, implying a higher holding cost burden in an inherently expensive stockkeeping environment. The effect is operationally material despite its limited magnitude and is consistent with longer replenishment paths from a single remote hub. At the manufacturing tier, the trade-off reverses. Decentralisation raises total upstream inventory, particularly pronounced at individual sites, reflecting the expected loss of risk pooling when capacity is fragmented across multiple smaller facilities. This escalates working capital requirements even as it improves responsiveness.

Critically, decentralisation delivers stronger inventory coverage ratios and greater temporal responsiveness during demand intensification, strengthening resilience against localised shortages. However, this advantage does not translate into a dramatic superiority at the clinic level, because the centralised system offsets through high throughput.

The environmental signal is unambiguous. The ratio of emissions intensity (centralised/decentralised) remains above unity throughout and increases as the simulation progresses, establishing a clear and widening sustainability advantage for decentralised production, conditional on the adoption of modern continuous processes rather than scaled down legacy batch operations.

There is no single dominant architecture. Centralisation minimises aggregate inventory via pooling, while decentralisation optimises responsiveness and sustainability. Strategic design must therefore be explicit about priorities: cost efficiency (inventory), resilience (coverage and surge handling), or environmental performance. A balanced network strategy may combine a limited number of advanced, decentralised nodes to secure responsiveness and carbon performance, while retaining selected centralised capabilities to preserve pooling efficiency, were economically critical.

The results should be interpreted within the bounds of the modelled demand cycles and behavioural rules. Extending the analysis to alternative demand regimes, richer disruption scenarios, and technology pathways would further illuminate design envelopes where hybrid architectures outperform either extreme. Incorporating explicit costings for transport, quality systems, and regulatory overheads across sites would allow a fuller economic assessment to complement the inventory, coverage, and emissions metrics reported here.

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