Integrating Epidemiological Models and Hospital Resource Management – A Demonstration of the Agent-Based Simulation Tool HosNetSim

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ABSTRACT

This paper presents the design and implementation of a unidirectional data interface connecting epidemiological forecasting models with hospital resource management tools, developed within the *PROGNOSIS* project to enhance hospital preparedness for pandemics and epidemics. We demonstrate the practical application of this interface through *HosNetSim*, a novel agent-based simulation tool specifically designed to support hospital and hospital group administrators, as well as public health authorities in hospital supply chain decision-making. The interface provides standardized, geographically specific, and daily updated forecasts of hospital burden across multiple respiratory diseases and care levels, enabling what-if scenario analysis. *HosNetSim* utilizes these forecasts to evaluate and visualize critical supply chain decisions, including inventory management policies, inventory pooling, and transshipments. By simulating realistic operational scenarios, *HosNetSim* illustrates the trade-offs between service levels and associated costs from the perspectives of individual hospitals, hospital groups, and regional networks.

Keywords

Pandemics, Hospital Supply Chain Management, Simulation, Epidemiology

INTRODUCTION

The COVID-19 pandemic has exposed the vulnerabilities of healthcare systems, even in the world's wealthiest nations. Hospital capacities were overwhelmed, as they faced severe shortages of both human and medical material resources. This crisis highlighted the urgent need for hospitals and healthcare networks to enhance their resilience in the face of pandemics and epidemics (Scala & Lindsay, 2021). The *PROGNOSIS* project addresses this need as part of the funding initiative "Strengthening modelling competence for the spread of serious infectious diseases" by the German Federal Ministry of Education and Research (BMBF).

One of the main challenges during the pandemic was the strain on medical supply chains. The surge in demand for critical equipment, such as ventilators and personal protective equipment (PPE), outpaced the available supply. Hospitals had to compete with other customers, including private households, businesses, and public institutions, for these limited resources (Friday et al., 2021; Harland et al., 2021). At the same time, supply was disrupted due to factory closures, logistics bottlenecks caused by border restrictions and sick personnel, as well as a history of cost-cutting measures in supply chains at the expense of supply security (Beaulieu et al., 2024; Cohen & van der Rodgers, 2020; Spieske et al., 2022). Due to the unpredictable progression of the COVID-19 pandemic, the demand for supplies was highly uncertain. Consequently, manufacturers and suppliers faced difficulties in justifying high investments to expand their capacities without assurances of a return on investment (Dai et al., 2021). This led to critical shortages of essential medical material and drugs, jeopardizing patient safety.

The lack of adequate protective equipment for hospital staff added to the next main challenge: the strain on human resources within the hospitals. As infections amongst staff members increased, severe staffing shortages arose (Davoodi et al., 2023). This created a self-reinforcing cycle of resource scarcity, where the remaining healthcare workers became overwhelmed and exhausted due to the surge in demand and diminishing available personnel. Not only did this reduce the overall workforce, but it further heightened the emotional and psychological burden on the healthcare workers who continued to provide care, which pushed the system into a critical juncture (Hassamal et al., 2021). Hospitals must improve preparedness to respond to such capacity peaks and personnel shortages with the least possible additional burden on active healthcare staff.

But how can hospitals mitigate the cascading effects of resource scarcity during an epidemic? How can they prepare for surge capacities and uncertain fluctuations? These are questions targeted by the *PROGNOSIS* project. Partners from five academic institutions with complementary expertise in biostatistics and -informatics, epidemiology, health research, and economics have joined forces to tackle the problem of hospital capacities in pan- and epidemic scenarios with an integrated approach. It aims to provide healthcare decision makers with much-needed information on how an epidemic is affecting the overall security of healthcare services and supporting them in their decision-making to improve the hospital supply chain and human resource preparedness. Three project partners (RWTH Aachen University, TU Dresden, Leipzig University) developed data-driven short-term and mechanistic long-term models to predict hospital burden for COVID-19, influenza, and pneumococcal pneumonia at different care intensity levels. The epidemiological models span across various epidemic phases and geographic scales in Germany to enable regional forecasting. These forecasts serve as input to two hospital resource management tools developed by the other two project partners that provide effective countermeasures to cope with the expected burden. The first is a simulation tool developed by the University of Münster that supports decision-making for medical supply management within hospital networks. The second tool is developed by the University of Augsburg and entails optimization models that investigate quick-response and robust scheduling decisions for personnel management.

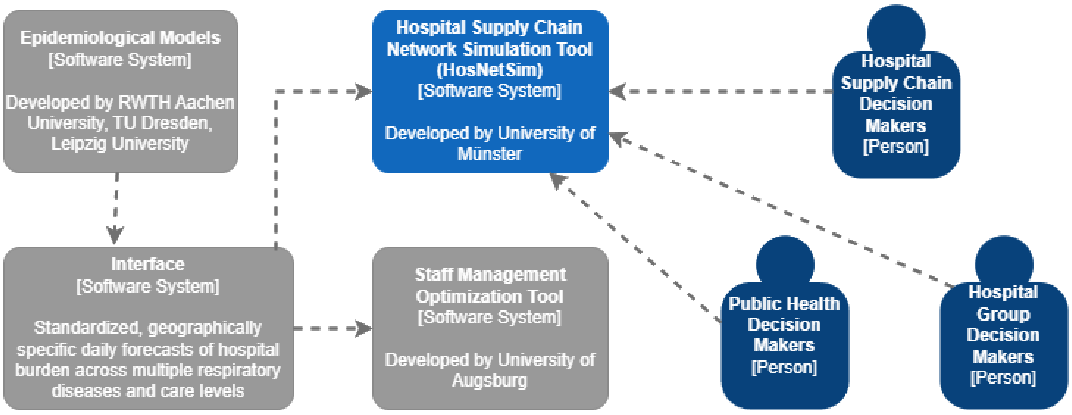


Figure 1 - C4 Level 1 Depiction of Interface, Hospital Resource Management Tools, and Users of the Simulation Tool

This Work-in-Progress paper presents the interface from the epidemiological models to the hospital resource management tools. Further, it demonstrates the simulation tool for medical supply chain management showing how input data is processed to provide support for hospital supply chain decision makers. **Figure 1** depicts the connections of models, interface and tools, as well as the users of the simulation tool. More detailed information on the overall concept of the *PROGNOSIS* project, the epidemiological short- and long-term models, and the personal management optimization tool will be presented in separate publications.

INTERFACE BETWEEN EPIDEMIOLOGICAL MODELS AND HOSPITAL RESOURCE MANAGEMENT TOOLS

The successful integration of epidemiological forecasting with the hospital resource management (HRM) tools requires a carefully defined data interface between these systems. To establish this interface, the project partners first approached the issue from two directions: the two HRM teams conducted requirements analyses to identify their essential input needs, while the three epidemiological modeling teams mapped their potential output capabilities. Through collaborative workshops between all project partners, the separate analyses were synthesized into a unified set of specifications that ensures seamless data flow between the forecasting models and HRM tools. An example for the structure of the interface is given in **Table 1**, while **Table 2** summarizes the interface requirements alongside their rationale and resulting design decisions.

ID 74XQED 18.05.2025 17:53:45 Forecast Period: 01.01.2022 – 28.02.2022

Date	**Disease ID**	**Intensity**	**District ID**	**Forecast**	**Lower B.**	**Upper B.**	**Actual**
01.01.2022	3	2	05515	14	10	18	15
01.01.2022	2	1	05515	35	28	42	37
…	…	…	…	…	…	…	…
28.02.2022	3	2	05515	67	51	83	60

Table 1. Example Entries of PROGNOSIS Forecast Data for the District Münster (05515)

The interface design follows a unidirectional flow of information, where epidemiological models generate forecast data that feeds into the HRM tools for analysis and decision support. Potential feedback loops from the HRM tools to the epidemiological models, for instance, to reflect how PPE shortages might influence infection rates, were deliberately excluded early in the design process. Such a feedback mechanism would require additional context data as well as multiple computational cycles at each forecast time interval. This would substantially increase the system's complexity, while its effects on infection dynamics would remain highly uncertain, thus decreasing applicability for practitioners. Feedback loops between the HRM tools, e.g., how absence of personnel influences material demand, were also excluded for the same reason. To ensure efficient operation of the unidirectional design, *all outputs from the epidemiological models are structured in a standardized format*, e.g., via a relational database, enabling automated processing and consistent interpretation across different forecasts.

Since the epidemiological models encompass multiple respiratory tract infections including COVID-19, influenza, and pneumococcal pneumonia, along with their variants, *each forecast entry must incorporate a standardized disease identifier*. These identifiers need to be consistently defined and implemented across both the epidemiological models and HRM tools to prevent misclassification. The severity of illness of a patient vary significantly based on patient characteristics such as age, sex, and pre-existing conditions like obesity or chronic diseases (Killerby et al., 2020). The severity directly determines the required care intensity and associated resource consumption that the HRM tools must manage. Although the detailed patient characteristics also have an impact on patient requirements, they would make the prediction more complex and less accurate. Thus, they are not included. To enable accurate resource planning, *forecast data must specify a standardized care intensity level*. The levels must be discrete because resource requirements are not linearly proportional to care intensity; for instance, an ICU patient on ventilation demands substantially different resources than a patient on a regular ward.

The impact of infections and hospital burden can vary significantly across geographical regions, resulting in regional hot spots while other areas remain relatively unaffected during the same period (Gimpel & Schröder, 2021). Effective hospital resource management is therefore crucial to ensure optimal distribution across different locations in response to varying needs. This applies particularly to supply chain management because the mobility of medical supplies offers more flexibility compared to healthcare staff, who typically remain anchored to specific hospitals. From a public health perspective, a key challenge for hospitals is maintaining an equilibrium in resource distribution to prevent simultaneous overstocking in some facilities while others face shortages (Spieske et al., 2022). To address this challenge effectively, *epidemiological models need to incorporate geographically specific forecasting at standardized spatial scales*.

Hospital burden from infections can fluctuate significantly on a daily basis, requiring rapid operational responses in both personnel management and supply chain management. These dynamic conditions make daily forecasting necessary to allow quick decision-making, particularly adjusting staffing levels and modifying order quantities and frequencies. The HRM tools model these processes as a continuous daily sequence to enable analysis of dynamic shifts across operational and tactical time horizons. To generate reliable results, these tools require an *uninterrupted series of daily patient arrival forecasts*.

Inherent uncertainty characterizes all forecasting efforts, with prediction accuracy diminishing over longer time horizons. To account for this variability, the *epidemiological models must provide uncertainty indicators* that enable comprehensive scenario analysis. If the forecast interval is in the past, *the actual hospital burden should be included*. These indicators allow decision-makers to evaluate a spectrum of possibilities, from worst- to best-case scenarios, and optimize resource allocation decisions accordingly.

Each forecast dataset represents a distinct scenario for analysis, requiring *robust metadata management* for effective utilization. By incorporating unique identifiers and creation timestamps, these forecasts become traceable, which ensures that decision-makers can systematically evaluate and compare outcomes across multiple scenarios while maintaining clear documentation of their analytical process.

	Requirement	Rationale	Design Decision
1	*The forecast data shall be structured in a standardized format*	Automated processing and consistent interpretation	Forecasts have a tabular format (see **Table 1**).
2	*Each forecast entry shall include the identifier for the disease type*	Multiple disease types and variants	Models use a mutually agreed map of disease types and ids
3	*Each forecast entry shall include a standardized care intensity level*	Care intensity level influences the associated resource consumption	Models use a mutually agreed levels of care set
4	*The forecasts shall be geographically specific*	Resource management must factor in the regional heterogeneity of hospital burden	Forecasts are provided for every district separately, identified by the legal municipality key (AGS)
5	*Forecasts shall be provided per day and consecutively*	Rapid fluctuation of hospital burden and continuous HRM process modelling	Forecasts are provided in an uninterrupted series for every tuple of day, disease type, level of care, and district
6	*The forecasts include indicators of uncertainty*	Comprehensive what-if scenario analysis and optimization	Forecasts include the precise value, upper and lower bounds of the 95% confidence interval
7	*The actual hospital burden shall be included, if available*	Comparison of forecast and actual data	If the forecast interval is in the past, the actual data is included
8	*The forecast data shall provide robust metadata*	Documentation and comparability	Forecast data includes generation timestamp and identifier

Table 2. Interface Requirements

APPLICATION OF THE INTERFACE FOR HOSPITAL SUPPLY CHAIN MANAGEMENT

In the following, we demonstrate the application of the interface using the hospital supply chain network simulation tool *(HosNetSim)* developed as part of the *PROGNOSIS* project. We present the tool development methodology, problem description and motivation, and the decisions that are targeted by the tool, as well as how accurate forecasts from epidemiological models can help to improve the decision making.

Methodology

The development followed a Design Science Research approach by Wieringa (2014), which encompasses three phases: problem investigation, treatment design, and treatment validation. The problem investigation phase began with interviews of healthcare practitioners across multiple domains, including hospital materials logistics, pharmacy operations, nursing staff, and medical professionals, to understand their existing processes and experiences with supply shortages. The key insights and take-aways from the interviews are listed in **Table 3.** These insights informed a targeted literature review examining both the current state of research in hospital supply chain resilience and analytical techniques in hospital supply chain management. Through business process modeling, we identified relevant operational and tactical decisions that significantly influence supply availability on the hospital level as well as critical agents that execute and influence these decisions. The treatment design phase commenced with the development and practitioner validation of requirements for an analytical decision support tool. After a thorough assessment revealed no existing tools sufficiently met these requirements, we proceeded with the conceptual design and implementation of a novel tool. We started by defining a minimum viable product, that is supplemented by additional relevant features during development iterations. The treatment validation phase incorporated internal validation methods, particularly sensitivity analyses, and will be extended to include external evaluation by practitioners from hospital groups.

Problem Description and Motivation

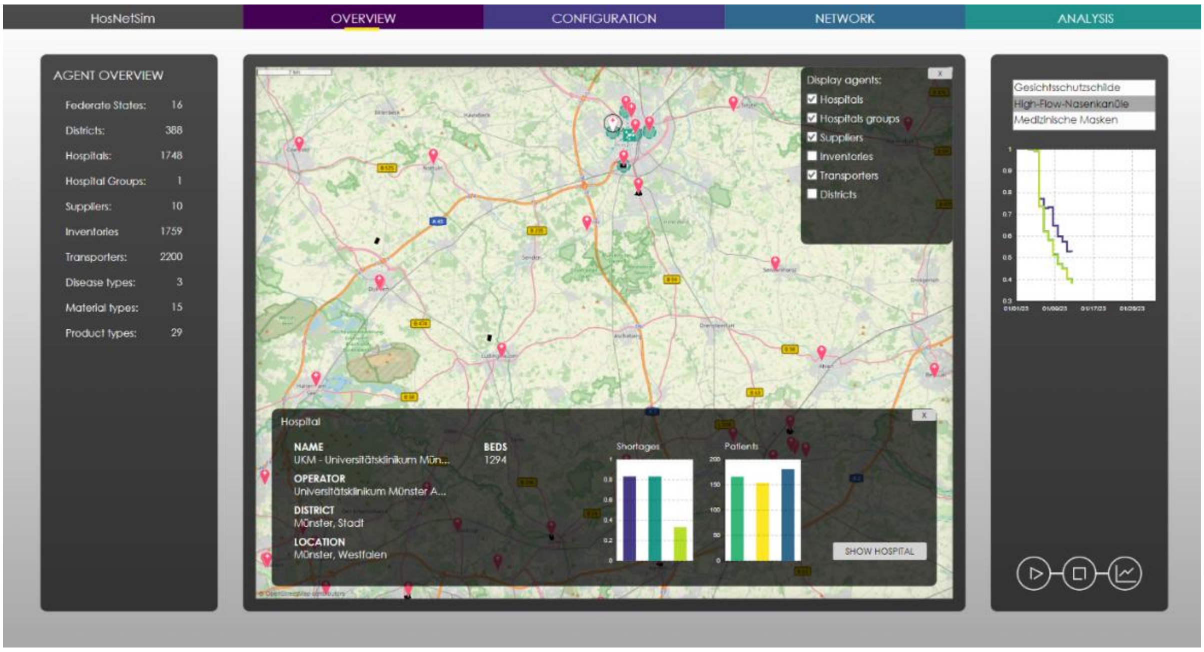
Hospitals face distinct challenges in supply chain management, particularly during epidemics that are characterized by highly uncertain fluctuations in both demand and supply. They must navigate dual imperatives: balancing public health interests with individual organizational needs. On one hand, hospitals have a moral and legal obligation to maintain a high service level, ensuring the best possible patient care. On the other hand, they must consider their economic viability as organizations. The competitive environment in which hospitals operate adds another layer of complexity. The high number of diverse actors and item types involved and the regional heterogeneity of hospital burden intensifies the uncertainty of supply and demand and the challenge of maintaining sufficient supplies to meet patient needs (Chtioui et al., 2020). The conflict between public and individual interests constrains hospitals' actions in ways that differ from other industries. Moral and legal frameworks prevent hospitals from competing in a completely free market, limiting their ability to pursue purely individual and economic interests. Ideally, from a public health perspective, all hospitals would collaborate and coordinate fully to maximize their overall service level. However, this ideal is hindered by missing individual incentives, lack of trust, and the absence of collaborative infrastructure between the hospitals (Friday et al., 2021). Effective and efficient measures must be identified that work in favor of both, individual and public interest.

Despite these challenges, the COVID-19 pandemic has demonstrated the potential for increased collaboration among hospitals. Collaborative measures such as inventory pooling, shared inventories, transshipments, emergency deliveries, information sharing, and collaborative forecasting, planning and replenishment have shown promise, particularly in high-uncertainty scenarios (Friday et al., 2021; Rojas et al., 2021; Spieske et al., 2022; Wang et al., 2022). However, the barriers to permanent effective collaboration remain. One major obstacle is the lack of technical infrastructure. Many hospitals do not have centralized digital inventory systems, making immediate data sharing challenging. Information about supplies is often scattered across different departments, each operating with individual processes, hindering the ability to quickly assess and share information about resource availability (Gimpel & Schröder, 2021). Inventory sharing between hospitals is also constrained because staff are typically trained on specific products, which means they cannot easily switch to alternative materials (Spieske et al., 2022). Additionally, the traditionally isolated nature of hospital operations has resulted in a lack of established trust and communication standards among institutions, creating a social infrastructure barrier. To overcome these barriers, investments in both technical systems and trust-building mechanisms are necessary. For instance, the government could implement safety nets for collaborating partners that help initiate collaboration even in the absence of previously established trust.

Interview Insights	**Take-Aways for Tool Design**
Information silos on material availability hamper an integrated view of hospital supplies.	Implement a multi-agent architecture representing hospitals, hospital groups, and suppliers as distinct entities. Compare centralized vs. decentralized strategies to highlight potential benefits of investing in collab. infrastructure.
Collaboration between hospitals (e.g., transshipments) occurs reactively during crises. There is a lack of formal agreements.	Provide functionality to model inter-hospital resource sharing (e.g., transshipments). Enable scenario comparisons that show how collaboration might reduce shortages and raises service levels, giving grounds for formalizing agreements.
Demand surges for supplies happen suddenly during crises, leaving little room for proactive planning.	Integrate daily patient-arrival data to simulate rapid fluctuations in demand. Allow real-time configuration of inventory policies to simulate ad-hoc manual adaptation to surges. Include automatic forecast-based policies to demonstrate the advantages of improved epidemiological forecasting.
Hospital internal processes are highly individualized, even between wards.	Focus primarily on external supply-chain processes to maintain feasibility and reduce complexity for decision-makers.
Cost-efficiency moves into background during emergencies yet remains a priority under normal conditions.	Incorporate collaborative-infrastructure costs for regular demand periods. Allow scenario-based assessments to illustrate trade-offs between cost efficiency and crisis preparedness.

Table 3. Insights from Interviews and Take-Aways for Tool Design

In light of these complex dynamics, hospital and public health decision-makers require a sophisticated tool to support their decision-making processes and to provide evidence-based justification for investments (Araujo et al., 2023). This tool must provide accurate demand predictions for better supply estimation and analyses of effective measures. Such analyses need to address both high-demand periods, focusing on securing service levels, and regular demand periods, emphasizing cost optimization. Moreover, they should offer perspectives from both individual hospital or operator viewpoints and broader public health network-level considerations. The development of such a tool is rather complex due to the high number of potential countermeasures, different permutations of collaborative networks, diverse interests and objectives, and uncertain application scenarios. There is no one-size-fits-all solution. Furthermore, it is not feasible to create a model that perfectly resembles reality due to the lack of data and too high implementation costs. Decision-makers thus need a tool that can easily adapt to their specific requirements, application contexts and scenarios of interest. A technique that was identified as appropriate for such problems is agent-based simulation. It allows the creation of customizable models of agent networks that are tested against different scenarios to perform what-if-analyses. Based on prior work in the areas of humanitarian logistics and blood supply chains (see Horstkemper et al., 2021; Widera et al., 2017), the *Hospital Supply Chain Network Simulation Tool (HosNetSim)* was developed as part of the *PROGNOSIS* project.



AGENT OVERVIEW

Federate States:	16
Districts:	388
Hospitals:	1748
Hospital Groups:	1
Suppliers:	10
Inventories	1759
Transporters:	2200
Disease types:	3
Material types:	15
Product types:	29

Display agents:
☑ Hospitals
☑ Hospitals groups
☑ Suppliers
☐ Inventories
☑ Transporters
☐ Districts

Hospital

NAME
UKM - Universitätsklinikum Mün...

BEDS
1294

OPERATOR
Universitätsklinikum Münster A...

DISTRICT
Münster, Stadt

LOCATION
Münster, Westfalen

Gesichtsschutzschilde
High-Flow-Nasenkanüle
Medizinische Masken

Figure 2. HosNetSim - Main Agent View of a Simulation Run

HosNetSim is designed not as a tool that produces directly implementable, optimal solutions, but rather as a decision support system that enhances understanding of complex hospital supply chains for individual hospitals and hospital groups. This approach acknowledges the inherent uncertainties and data limitations in hospital supply chain management. For instance, transforming hospital burden to material demand is imprecise due to the variability in individual patient treatment needs. Moreover, the lack of comprehensive visibility into total available materials across hospital networks and suppliers further complicates precise optimization. Instead, *HosNetSim*'s primary value lies in its ability to compare and visualize the potential impacts of various countermeasures, with a particular emphasis on incorporating forecast data. By allowing users to explore different model configurations and scenarios, the tool facilitates a deeper understanding of the system and potential outcomes. If the simulation model is understood, the simulation results can provide evidence about whether (and to what extent) investments in collaborative infrastructure between hospitals might be beneficial. Comparing scenarios with or without collaboration can show when resource sharing reduces shortages or costs. Due to the diversity of internal hospital logistics processes, *HosNetSim* currently focuses solely on the external supply chain, spanning from first-tier suppliers to the hospital's central inventory.

Demonstration of HosNetSim

HosNetSim is an agent-based simulation tool that runs a discrete-event process. In this multi-method modeling approach, diverse agents with distinct behaviors and individual parameters interact within the simulated environment during an event-based process. The agent structure is organized into three main categories: Network Agents (Hospital, Hospital Group, and Supplier), Infrastructure Agents (Inventory and Transporter) and Configuration Agents (District, Disease Type, Material and Product Type). **Figure 2** shows a glimpse of the main window of a simulation run, while **Figure 3** depicts the agents as well as their relationships and cardinalities. The collective arrangement of the agents and their interconnections defines a customizable model upon which one or multiple simulation runs can be executed. The tool does not only allow a static set of agents, but lets the user flexibly choose and create agents. Each simulation run can represent a distinct scenario with a unique trajectory of input parameters, such as hospital burden per disease type and district, or available supply of items per product type at the supplier level.

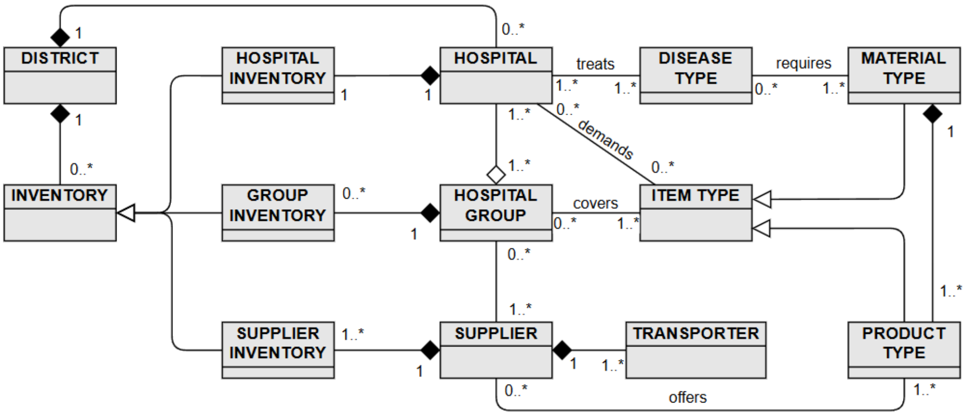


Figure 3. HosNetSim Agents and Relationships

The simulation operates through two distinct event-based processes (see **Figure 4**). The first process handles item consumption. It starts with the daily hospital burden that is provided by the interface. Each district agent allocates patient arrivals from the interface among hospitals based on factors such as hospital size or available capacity, determining each hospital's daily patient burden. This burden is then translated into material demands specific to each disease type and care intensity based on the disease type's parameters. The system checks current inventory levels, identifies shortages, and processes the consumption of items.

The order process is the simulation tool's primary focus, as it reflects various supply chain management decisions. In this process, hospital inventories generate item-specific demands based on their inventory policies and submit these to the hospital, which then places orders with the hospital group responsible for the respective material type (which may be the hospital's own proprietary group). The hospital group consolidates these orders and submits an aggregated request to its connected suppliers. Depending on the supply scenario, supply shortages might occur. If this is the case, suppliers allocate items among hospital groups and send corresponding offers. The hospital groups then distribute the promised items among their member hospitals and confirm the allocation with the supplier, after which transporters deliver the allocated items to the respective inventories. While this order process is initiated daily, the complete cycle from order to delivery typically spans several days due to the lead time and potential backorders. Order quantities are determined by inventory policies, including parameters such as order period, which will be depicted in the following section.

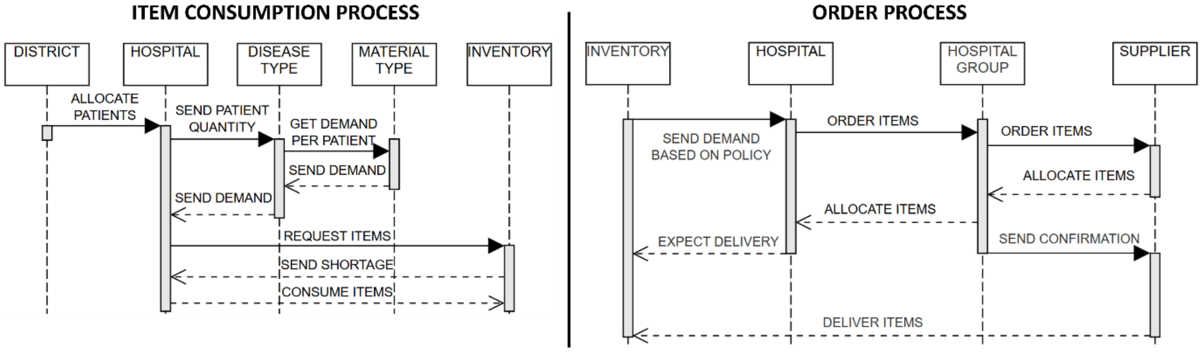


Figure 4. Daily Item Consumption and Order Process Sequence Diagrams

Supply Chain Decisions

In addition to defining agents and scenario parameters, users can configure supply chain decisions by hospitals and hospital groups. This flexibility enables two primary modes of tool utilization: (1) evaluating the resilience of a given decision configuration across multiple scenarios, and (2) analyzing the impact of varying supply chain decisions within a single scenario. The key supply chain decisions available for customization by hospitals and hospital groups are outlined below:

Inventory Policies: The simulation tool enables testing of various inventory replenishment policies. The choice of policy significantly impacts both supply security and operational costs. The performance is highly context specific. For example, while lean inventory management mechanisms yield optimal results during periods of stable demand, they become ineffective during irregular surge periods that require buffer stocks (Rehman et al., 2023). Thus, it is important to test policies against different scenarios to understand their impact. This includes setting parameters such as order period, reorder point, lot size, target level or the required safety stock, depending on the policy. The user can choose between static policies with fixed values or dynamic policies that regularly adapt based on both *PROGNOSIS* forecast data or traditional demand forecasts, e.g., exponential smoothing. For instance, dynamic policies may increase lot sizes in anticipation of higher demand. By comparing *PROGNOSIS* forecasts against historical data, decision-makers can quantify how improved predictive accuracy enhances overall performance. The simulation supports both decentralized control at individual hospitals and centralized management at the hospital group level. This allows hospital group decision makers to try out different decisions more easily. Furthermore, centralized inventory policies allow the hospital group to get more control over the even allocation of items between their hospitals as presented in the following.

Centralization: Centralization is a strategy that involves implementing a hospital group as an intermediary between suppliers and individual hospitals, potentially enhancing resource allocation efficiency. By aggregating demand forecasts, the centralized entity can reduce the bullwhip effect caused by inaccurate estimates at the hospital level. It enables more accurate forecasting of aggregate demand, allowing proactive reallocation of supplies in times of shortages before they are delivered to the hospitals. Centralization offers several additional benefits, including economies of scale through bulk purchasing, strengthened negotiating power with suppliers, and improved supply chain visibility (Kriegel, 2012). A specialized form of centralization is inventory pooling, which utilizes shared warehouses at the hospital group level. This mechanism mitigates uncertainty risks associated with demand fluctuations at individual hospitals, enabling centralized warehouses to maintain safety stocks for low supplier availability and emergency situations. Inventory pooling can also lead to improved inventory turnover, reduced warehousing costs, and enhanced supply chain resilience (Rojas et al., 2021).

Transshipments and Emergency Deliveries: Transshipments are the transfer of items between agents within a hospital group to balance inventory discrepancies across the network. Transshipments between hospitals occur in two primary forms: economically-driven transfers aimed at optimizing overall network efficiency, and emergency deliveries that facilitate rapid transfers of critical items to prevent patient-level shortages. Emergency deliveries can also be triggered by irregular high-priority orders sent to central inventories or suppliers. While economically-driven transshipments are rarely implemented due to high coordination and transportation costs, emergency deliveries can help to mitigate the risk associated with demand estimation errors in geographically heterogeneous scenarios with high demand (Spieske et al., 2022; Wang et al., 2022). However, the success of emergency deliveries depends on robust coordination systems and standardized transfer protocols between hospitals that require investments. Thus, it is helpful to visualize the benefits in different scenarios to decision makers.

Result and Performance Indicators

HosNetSim provides a comprehensive set of result and performance indicators to evaluate and compare scenarios across multiple agent levels. These indicators address the fundamental trade-off between service level and costs for each item type, while accounting for the potential conflicts between individual hospital objectives and a network-wide perspective. The simulation tool implements a hierarchical visualization framework that allows stakeholders to analyze performance at distinct levels:

At the *inventory level*, service quality is measured through stockout rates, emergency order frequencies, order fulfillment rates, and lead times and delays for critical supplies. Cost efficiency is tracked via storage costs, ordering costs, transportation costs (both absolute and relative to hospital capacity), inventory turnover rates, and item expiration rates. These indicators help decision-makers assess the effectiveness of specific configurations at the individual hospital level. For example, they can examine whether a dynamic, forecast-based inventory strategy outperforms a static, target inventory level approach across different scenarios.

The *hospital level* adopts inventory-level metrics, as the current model assumes one central inventory per hospital. Additional hospital-specific indicators include capacity utilization rates and patient rejection rates, providing insights into the facility's patient load.

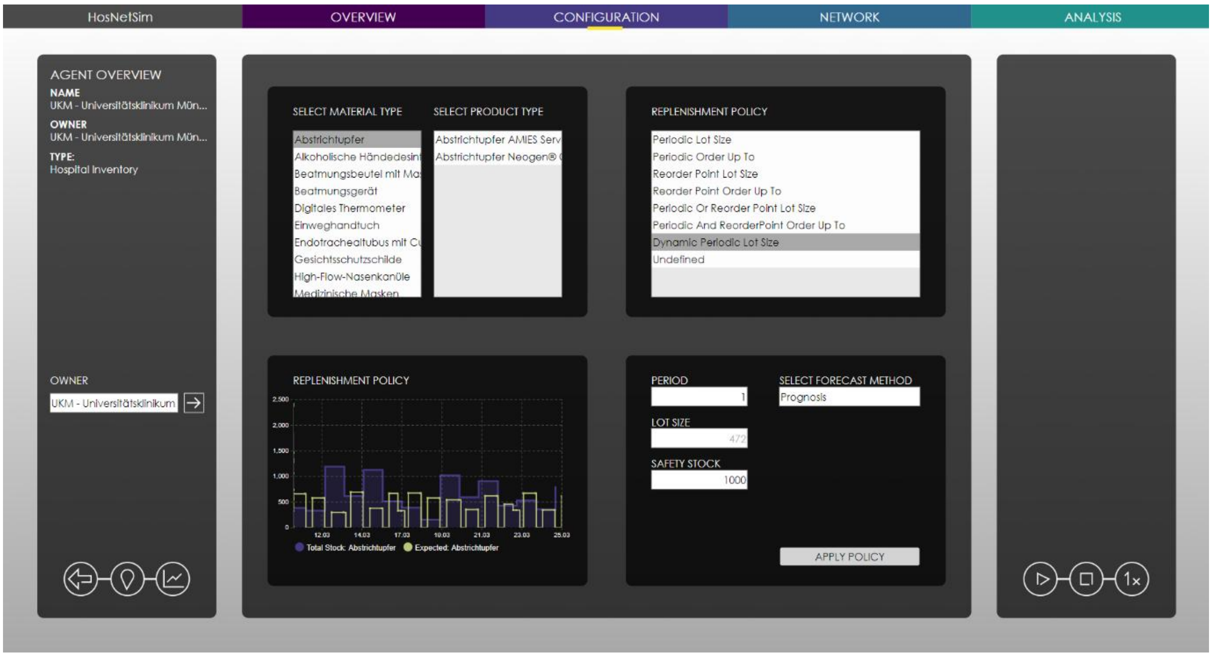
The *hospital group level* consolidates metrics across affiliated facilities and their respective inventories. A key performance indicator at this level is the inter-hospital reallocation rate, which reflects the effectiveness of resource sharing within the group.

Finally, the *network level* provides a public health perspective by aggregating data across all participating hospitals, enabling assessment of system-wide performance and resource allocation efficiency. This multi-level approach allows decision-makers to evaluate how local decisions impact both individual facilities and the broader healthcare network. For example, a hospital might overestimate demand and incur only minimal internal costs, yet simultaneously contribute to shortages at facilities facing high demand. By allowing reallocation within hospital groups or through transshipments, such inefficiencies can be mitigated and overall material usage can be improved.

Beyond the core hospital-centric hierarchy, *HosNetSim* incorporates supplementary analytical perspectives through supplier, geographical district, and item-specific views. While these perspectives currently offer a more limited set of indicators compared to the primary hierarchical levels, they provide valuable complementary insights and lay the foundation for future extensions of the tool's analytical capabilities.

Implementation

HosNetSim is implemented in the simulation environment AnyLogic and Java. While AnyLogic offers several general simulation elements, e.g., the simulation clock or live visualization of a simulation run, most of the agents' process logic within *HosNetSim* is written in an external Java module. Configuration data can be added and stored via Excel, while analysis data is stored in an external MySQL database and can be accessed in a browser using the business intelligence tool Metabase.



AGENT OVERVIEW
NAME: UKM - Universitätsklinikum Mün...
OWNER: UKM - Universitätsklinikum Mün...
TYPE: Hospital Inventory

OWNER: UKM - Universitätsklinikum

SELECT MATERIAL TYPE: Abstrichtupfer
SELECT PRODUCT TYPE
REPLENISHMENT POLICY: Dynamic Periodic Lot Size

PERIOD: 1
SELECT FORECAST METHOD: Prognosis
LOT SIZE: 472
SAFETY STOCK: 1000

Figure 5. Configuration Tab of the Inventory Agent View

The simulation tool provides users with ready-to-use input data via the internal database. This database encompasses 1748 hospitals in Germany, including their bed capacities and operators, which represent hospital groups. The hospitals are matched to the 400 German districts in 16 federate states, allowing for easy selection of regions and configuration of scenarios. Additionally, the database includes predefined disease types, associated sample material types, product types, and suppliers offering these products, providing a foundation for simulation trials. Users can upload Excel files or directly modify the available data in the database through a configuration cockpit, which can be accessed before a simulation run. All configuration data can be stored to the hard drive to enable reproducibility. Besides agent configuration, users can input supply scenarios, adopt demand scenarios from prognostic input data and customize them, for example, to create worst-case scenarios or stochastic demands between the upper and lower bounds of the forecast data.

HosNetSim leverages AnyLogic's GIS map. This integration enables the simulation to visually display the hospital network and illustrate the transportation of items in real-time, as shown in **Figure 2**. Such live visualization in combination with the indicators is crucial for identifying bottlenecks in the supply chain and facilitates a better understanding of the overall system. The simulation can process multiple days per second at maximum speed, with settings adjustable to slower rates as needed. Furthermore, the GIS integration allows users to easily select individual agents on the map and access detailed analysis data for specific agents with a simple click. For instance, **Figure 5** illustrates the configuration tab of an individual inventory agent, where users can view the current inventory policies for each item type alongside the corresponding stock trajectory, and adjust these policies as needed. This immediate feedback on performed configurations significantly enhances system understanding. Users can observe the impact of their decisions instantaneously, enabling them to make informed adjustments and gain deeper insights into the dynamics of the hospital supply chain network. *HosNetSim* further regularly exports relevant data, e.g. the orders, deliveries, and stock levels, to a MySQL database. This allows for in-depth analysis and comparison of different simulation runs via Metabase or a different data analysis tool of choice. Not only are all result and performance indicators output, but all decisions are also logged to the database. This comprehensive logging allows users to retrace which decisions generated specific changes in output, providing valuable insights into cause-and-effect relationships within the system.

Limitations and Outlook

HosNetSim faces two key limitations: the scarcity of comprehensive supply chain data and the challenge of converting hospital burden metrics into material demand. To address these constraints, we designed a flexible simulation infrastructure that allows practitioner experts to input their specific data and context. Since no single decision maker has visibility across the entire supply network, future research opportunities exist to develop more complete datasets. The simulation tool has been developed with an iterative approach, laying the groundwork for several planned enhancements after a thorough validation and evaluation of the current implementation. The framework can be extended to incorporate advanced supply chain management mechanisms, including vendor-managed inventory and collaborative forecasting, planning, and replenishment systems. While the current model implements first-tier supplier inventory policies, expanding to include second-tier suppliers from various countries would enable the simulation of international supply chain disruptions, such as border closures. Additionally, the present version of patient allocation sends patients to hospitals of the same district, which neglects cross-border cases. The COVID-19 pandemic highlighted the importance of sophisticated allocation strategies, particularly for high-intensity care patients. The patient allocation mechanisms thus represent another crucial area for future development.

The current implementation of *HosNetSim* operates on a single thread, constrained by AnyLogic's single-threaded simulation engine, limiting computational efficiency. However, when simulations run without visualization, this architecture allows parallel execution of multiple independent instances on a single CPU, facilitating comparative analysis. AnyLogic's simulation chaining capability creates opportunities for reinforcement learning applications, allowing for systematic parameter optimization through iterative simulation runs. This feature enables *HosNetSim* to function as an optimization platform, where decision parameters are progressively refined based on previous simulation outcomes. Through this iterative approach, the system can identify increasingly effective hospital supply chain management strategies across diverse scenarios.

CONCLUSION

The COVID-19 pandemic exposed critical vulnerabilities in hospital supply chains and resource management systems. The *PROGNOSIS* project addresses these challenges through an integrated approach combining epidemiological forecasting with sophisticated hospital resource management tools. This paper has presented the interface between these components and demonstrated its application through *HosNetSim*, a novel hospital supply chain network simulation tool. *HosNetSim* enables decision-makers to evaluate different supply chain configurations and collaborative measures across multiple scenarios, from individual hospital operations to network-wide impact. While current limitations in data availability present challenges, the tool's configurability allows practitioners to apply the tool to their custom settings. Through this work, we contribute both a practical decision support tool and a framework for improving hospital supply chain resilience, helping bridge the gap between individual hospital interests and broader public health objectives.

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