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Improving Blood Supply Chain Crisis Management by Simulation-based Optimization

Verbesserung des Krisenmanagements in Blutlieferketten durch den Einsatz von Simulationsbasierter Optimierung

Dennis Horstkemper, WWU Münster, Münster (Germany), horstkemper@ercis.org

Melanie Reuter-Oppermann, TU Darmstadt, Darmstadt (Germany), oppermann@is.tu-darmstadt.de

Michael Middelhoff, Adam Widera, Bernd Hellingrath, WWU Münster, Münster (Germany), middelhoff@ercis.org, widera@ercis.org, hellingrath@ercis.org

Abstract: Blood supply chains are a specialized type of supply chain dealing with several legally independent actors that cooperate to facilitate the demand of a resource with limited availability and shelf life. In this setting, adequate decision support tools are needed to ensure good design choi1ces are made, as any interruption in the blood supply chain endangers human lives. To handle the complexity of such a supply chain, we propose a simulation-based optimization framework that enables the depiction of strategic and operational decision-making throughout the overall BSC. We illustrate the toolkits capabilities by applying it on a use case with the aim of improving the utilization of mobile blood donation facilities during a crisis.

1 Introduction

Blood products are a very critical resource in healthcare systems, affecting several procedures, such as scheduled or unplanned surgeries. Providing timely, sufficient supply of blood products to match demand is a challenging task, reliant on volunteer blood donations. Often, it is already challenging to fulfil everyday demands. During a crisis, existing structures and resources might not be available anymore, while high demand and supply fluctuations require short-term contingency plans. The COVID-19 pandemic has not only led to a shortage of blood products worldwide, but the loss of crucial staff due to sickness or public health restrictions significantly affected the blood supply chains (BSC) (Stanworth et al., 2020). Although decision support systems or crisis management plans can support BSC management, several characteristics of BSCs might explain the rather low uptake of current practices and research from the areas of supply chain management and logistics. Firstly, the multi-stakeholder setting of BSCs hinders the application of integrated supply chain design and planning approaches. Secondly, the degree of uncertainty in demand and supply is significantly higher compared to other supply chains. Thirdly, it is not only the diverse shelf life of blood products making the application domain highly dynamic in terms of supply and demand: the need and stock of blood products is highly interrelated with disruptions in other areas, such as power outages, mass-casualty incidents, or large-scale disasters. Finally, a high degree of complexity and interdependency can be identified when considering the different variations of blood demands vs. supply as well as geographical and cultural contexts.

To handle the described challenges, we suggest the development and application of combined simulation-optimization approaches. The main rationale lies in the ability to vary and analyze assumptions that must be made for an optimization model, as for example input values, relevant scenarios, and functional areas, within the approach. Furthermore, stochastic influences can be tested within the simulation while keeping the optimization model deterministic, reducing the mathematical complexity. Finally, this approach combines rigorous methods with a continuous involvement of domain experts. Simulation-based optimization approaches have been applied to BSCs and production planning in disaster management before, yet existing approaches either assume a centralized decision problem, only focus on smaller excerpts of the BSC, or neglect the implications of disasters on the demand and supply of blood products (Osorio et al., 2015; Ramezanian and Behboodi, 2017; Ghasemi et al., 2020). Based on related works in the respective fields, a systematic simulation-optimization-human loop is designed, enabling decision makers to identify both weak points and improvement potentials. An exemplary application of the toolkit for design decisions in the South-African BSCs is described afterwards. The toolkit uses deterministic optimization to configure the network structure for the stochastic simulation, which in turn analyses constraints and changes to the target function in an iterative process while considering further operational decision-making activities. The aim is to find an improved supply chain design that performs well under stochastic influences. Thus, we propose a toolset enabling the depiction and evaluation of the dynamics between different actors and their decisions throughout a complete BSC. The remaining paper is structured as follows: The relevant foundations presented within Section 2. In Section 3, we describe the proposed simulation environment as well as the tools to consider decision support within the simulation and present an exemplary use case. The paper closes with a discussion and outlook in Section 4.

2 Foundations

2.1 BSC management

Blood products are not or only partly substitutable resources and people in critical conditions may depend on their availability (Heidari-Fathian and Pasandideh, 2017). In order to increase availability, an efficient BSC is required, comprising the minimization of costs and the avoidance of wastage while meeting the demand. The BSC process can be divided into four stages or echelons, being: (1) collection, (2) production (including testing and processing, i.e. separation into different blood products), (3) storage and inventory, as well as (4) distribution, each containing main decisions on a strategical, tactical and operational level (Osorio et al., 2015). Some of those decisions are interdependent, so an isolated approach could lead to a myopic perspective which makes a real-life application impractical (Osorio et al., 2015).

This work focuses the South African blood transfusion system. There are two blood establishments operating in South Africa: the Western Cape Blood Service (WCBS), responsible for the Western Cape province, and South Africa National Blood Service (SANBS) providing blood transfusion services in the remaining parts of South Africa (Wise et al., 2020). As nonprofit organizations, WCBS and SANBS must operate cost-effectively. Both blood establishments collect blood from 100% voluntary, non-renumerated donors and operate facilities on all relevant echelons of the BSC. SANBS operates 85 blood banks serving more than 600 hospitals. WCBS runs 7 blood banks providing blood products to approximately 190 hospitals.

2.2 Simulation-based optimization for blood logistics and mobile blood donation

While simulation-based systems have commonly been applied to evaluate and design BSCs, they usually only focus on single echelons and do not enable an integrated view of the whole BSC (e.g., Alfonso et al. (2012) and Lowalekar and Ravichandran (2010) focus on the collection stage). Only a few works that consider the whole BSC within their simulation models exist (e.g., Baesler et al. (2014)). Combining simulation and optimization approaches is an even rarer methodological approach. For example, Lang (2009) combine heuristics with a simulation to depict the impact of transshipments and substitutions in the BSC, while Osorio et al. (2017) describe a combination of linear programming and discrete-event simulation to improve production planning in BSCs. However, both approaches focus on specific problems and are not suited to evaluate a broad selection of practical tasks in BSC operations.

Several publications have addressed the concept of locating mobile facilities or routing collection vehicles in order to increase the number of blood donations. Sachdev et al. (2016) for example describe the concept of blood donation mobiles in India and analyze their use between 2012 and 2014. The authors list several advantages of using mobiles including the flexibility and the existing air-conditioning that is especially helpful during hot periods. Şahinyazan et al. (2015) study a mobile blood collection system in Turkey. Blood mobiles are routed through the area and stay at least one day at each chosen location, up to three days. Shuttles take the blood donations to the processing facilities. Gunpinar and Centeno (2016) present an IP model to simultaneously identify the daily number of blood mobiles to operate while minimizing the distance travelled. The authors allow the blood mobiles to relocate during the day and assume a service time of three to seven hours at each location. Two routing models for blood mobiles are analyzed by Rabbani et al.(2017), Heidari and Pasandideh (2018) as well as Karadağ et al. (2021) integrate mobile collection units into an Mixed-Integer Program (MIP) that optimizes the whole BSC. A two-stage stochastic selective-covering-inventory-routing model was proposed by Bashiri and Ghasemi (2018) with stochastic blood demand as well as blood donations.

3 Simulation

3.1 Simulation framework

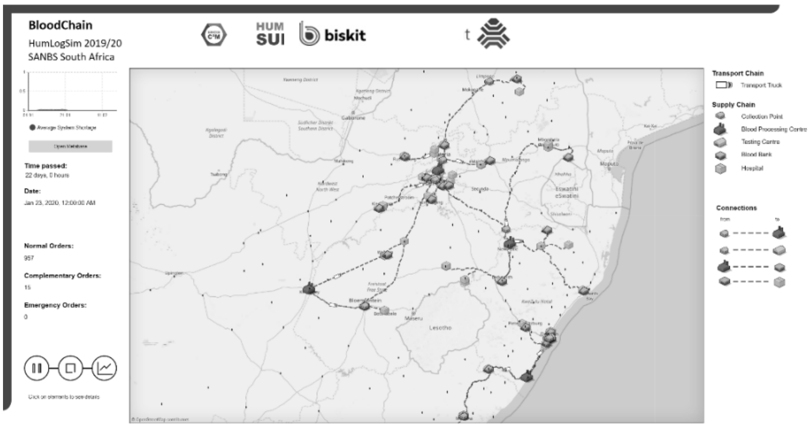
The South African BSC structure is modelled using the HumLog Suite, which was developed in previous works by the authors (Widera et al., 2017a; Widera et al., 2017b). HumLog Suite offers an environment for agent-based simulations of humanitarian logistics operations. It is based on the commercial simulation software AnyLogic and thereby extendable for specific use cases. In addition to AnyLogic, HumLog Suite offers a predefined set of common humanitarian actors and their basic decision logic, like beneficiaries representing needs, transport units for goods and people or medical and storage sites. These actors provide basic parameterization and state charts that can be specialized for the requirements of the modelled context. Furthermore, it offers a web-based dashboard to configure simulation scenarios and to view performance metrics derived through the simulations in a practitioner readable manner. In the past, HumLog Suite was applied in other contexts like flooding events and urban evacuation scenarios (Detzer et al., 2016).

In our case, the South African BSC is represented by a set of actors within the agent-based simulation. Stationery facilities are the collection points, at which blood is donated by the population, the testing centers, at which the infectious disease testing is performed, the blood processing center, which transform the collected blood into the various blood products, the blood banks, which store the blood or blood products for a period of time, and the hospitals, which administer the blood to patients and hence create the demand in the system. Each of the facilities is defined by its location in latitude and longitude, its processing capacities and resource requirements. The blood banks provide an additional storage capacity and hospitals create the demand for blood products. Individual facilities can also be situated at the same location, which eliminates transports between them and affects their cost structure. This is for example the case, if a hospital runs an own blood bank. The logistics operations between these facilities are taken care of by a logistics service provider, who offers services via drones and trucks. These transport units must fulfil specific requirements for the transportation of blood products, like for example a guaranteed steady cooling. They are defined by their overall availability at a certain facility, their transport capacities, costs factors and further parameters on their mode of transportation, like for example speed. Finally, the potential supply of blood to be donated is modelled in the population. The supply chain can be distinguished between a supply-driven "push" and a demand-driven "pull" segment. Starting from collection points via test and processing centers to the storage in the blank banks, the supply chain is supply-driven and provides as much blood and blood products as possible according to the configured donation and processing plan. The amount of blood donations of the various blood types at each collection point follows a normal distribution with a configured mean, standard deviation and size for each of the local donor populations. The hospitals have a demand-driven order policy with the blood banks. The demand for blood products is derived from a safety stock at the hospitals and the local population in size and blood type division.

To properly account for the influence of transports in humanitarian operations under potential crisis events, HumLog Suite utilizes a geographical information systems (GIS) map based on the real-world road, water and air infrastructure. This functionality is provided by the AnyLogic software and was customized to be manipulated according to disaster events, to block parts of the network as consequence of a flooding, for example. According to the mode of transportation, each transport unit needs to route within the GIS space, which results in realistic transport conditions.

A specific simulation scenario is defined through a set of input parameters, which affect the blood product demand, the blood donations, the facility placement, and their allocation to each other. The location and capacities of hospitals is seen as a longterm. Yet, disaster events might affect the availability of a hospital due to for example power outages. Still, within a simulation study, is it typically not changing. The demand for blood products can be varied to compare best to worst case scenarios and can be subject to stochastic influences. Also, the blood testing facilities in South Africa are fixed to two major locations as described before. The amount, location, capacity, safety stocks and allocation of blood banks to hospitals can the varied to test different network configurations toward the objectives, e.g., the minimization of transport costs. The blood processing is defined alike. A set of stationary and mobile donation sites is provided to collect as much blood as needed to fulfil the demand. Given these input parameters, the simulation will assess the BSC performance under potential additional constraints like affected infrastructures or demand fluctuations. The simulation user interface is displayed in Figure 1.

HumLog Suite tracks each individual transport and the amounts of donated, tested, produced, stored and administered blood at the locations as well as the resource utilization over time. This data is used to conclude on key performance indicators for the BSC, which are defined in line with the objectives. Among others these are the utilization of blood and blood products, the amount of discarded blood products due to exceeded shelf life, the transport and overall supply chain costs and the utilization rates of the facilities and transport units. The analysis outcomes are aggregated and displayed via the web-interface, which can point practitioners towards current bottlenecks and improvement potentials to be tested in further simulation scenarios.



BloodChain

HumLogSim 2019/20
SANBS South Africa

Time passed:
22 days, 0 hours

Date:
Jan 23, 2020, 12:00:00 AM

Normal Orders:
957

Complementary Orders:
15

Emergency Orders:
0

Figure 1: *Simulation Run*

3.2 Simulation and optimization

Following the VDI3633 Part 12 (Simulation and optimisation), two different ways to connect the simulation of the BSC with optimization-based decision support were implemented (c.f. Rabe and Clausen, 2015). To perform an optimization of strategic decisions, the simulation sequentially follows after an optimization of said decisions. Thus, strategic decisions, e-g. the location of facilities within the BSC, are first determined by a deterministic optimization, in this case using MIP models and the commercial CPLEX optimization software. They are then used as an input for the start of the simulation, which in turn can be used to evaluate the results of the optimization considering stochastic influences such as demand variations and disruptions caused by external influences such as crises.

In contrast, operational decisions are supported through an optimization integrated into the simulation. At predefined points in time, the simulation model is paused and calls the execution of an optimization as a hierarchically subordinate element. This optimization considers the current state of the simulation, e.g., to perform operational planning tasks such as route planning or the allocation planning of the blood products to the different facilities within the BSC. These optimizations can either be performed using MIP models and the external CPLEX solver again, or by performing manually implemented heuristics for the respective problems. Depending on the analyzed timeframes and decision problems, tactical planning problems can be implemented as either of these optimization types. Figure 2 depicts a sequence diagram visualizing the two different optimization approaches.

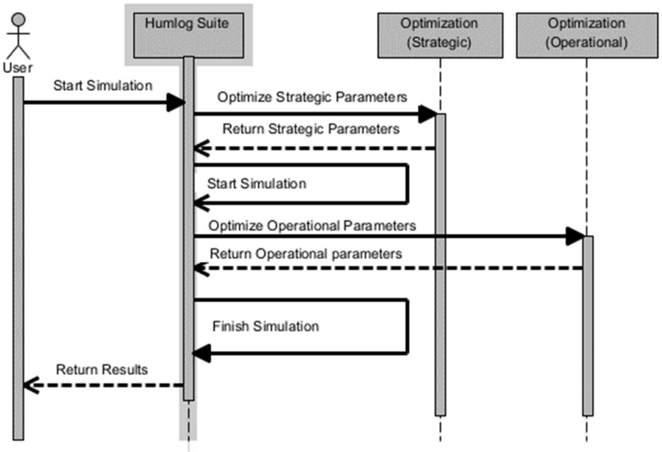


***Figure 2:** Simulation and Optimization*

3.3 Application case: demand-dependent assignment of mobile blood donation facilities

In addition to stationary blood donation sites, mobile blood donation facilities (MBDF) are used to make it easier for potential blood donors to reach the donation sites and thus to increase their willingness to donate. In the South African BSC, MBDFs operate in a single allocation Hub-and-Spoke system. Therefore, operating locations for MBDFs are always assigned to only one hub and each MBDF returns to the hub after operations. Hubs are usually located at blood banks or blood processing centers, where the collected blood can be processed and/or forwarded. Due to their decentral nature, usually only whole blood components are collected by MBDF. The MBDFs visit their operating locations mostly within a fixed pre-planned sequence.

Considering the corona epidemic, two contrasting developments influenced the south African BSCs. On the one hand, the government's action to forbid the sales of tobacco and alcohol severely reduced the need for a number of blood products in the hospitals (e.g., through the reduction of violent behavior under the influence of alcohol). On the other hand, the limited availability of public transport, sicknesses and quarantine measures led to an understaffing of several facilities in the BSC, limiting the blood supply even further. Thus, the existing sequence for operating the MBDFs is not aligned to the specific demand for blood products anymore. Furthermore, as not all MBDFs can be staffed, the efficiency of their utilization gains even more importance. Hence, one suggestion by domain experts of WCBS was to allocate the MBDFs considering the current stock and demand situation, taking the distribution of possible donors and their blood donation characteristics into account as well. Thus, a MBDF can be placed at a location that offers a concentration of blood donors that can provide a specific blood product (extracted from anonymized data from past donations), which is currently out of stock. The simulation-based optimization framework shall hereby be used to evaluate, this suggestions potential to reduce shortages within the BSC.

Keeping current staff availability in mind, the optimization preceding the simulation is used to determine the maximum number of available MBDFs, as well determining the hub locations. Therefore, a capacitated facility allocation problem is used (Melkote and Daskin, 2001). Depending on the operating radius of a MBDF, the possible operating locations near the hub location are enumerated and exclusively allocated to the MBDF. The maximum amount of MBDFs, their hub locations and their operating locations are then considered as an input for the simulation study itself.

During the simulation, aside from performing the usual transportation, transformation and storage processes within the BSC, it needs to be decided which operating locations are visited by the MBDFs on a daily basis. Therefore, the subordinate operational hierarchic optimization is called at the beginning of each day within the simulation. As an input for the optimization, the current demands and storage amounts of the different blood products weighted across all facilities in the BSC are used to determine which blood products are needed the most. Furthermore, the MBDFs, their possible operating locations and the expected blood donations per location are considered. The optimization model is then formulated as an MIP. Within the target function the demand fulfillment rate is being maximized. Calculating the expected donations using a specific combination of placements of the MBDFs and matching it to the existing demands, the fulfillment rates can be determined. To retain cost optimality, the operating costs of the MBDF are then subtracted from the demand fulfillment rate using respective weights. This modeling approach was chosen in contrast to the modeling using penalty costs, as the penalty cost factors itself are difficult to determine, i.e., cost factors for missing blood products that put patients at risk. The chosen locations for the operation of the MBDF are then returned to the simulation and used for the calculation of the blood donations and succeeding processes throughout the day. This is repeated until the simulations time horizon concludes.

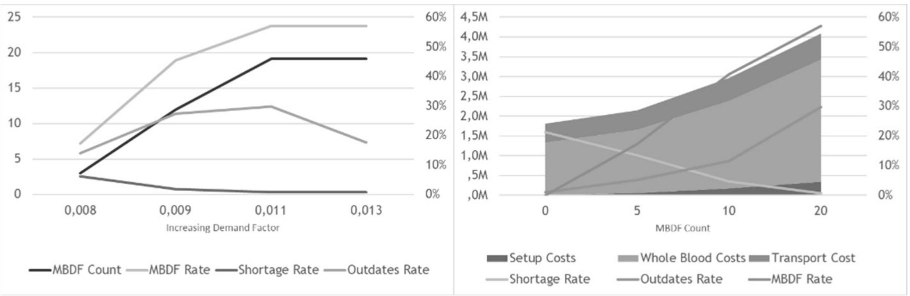


Figure 3: *Simulation Results*

First simulation studies were performed on the South African BSC based on the recorded data and statistics on blood type characteristics in the South African population. The objective of these first assessments was to validate the behavior of the combined simulation and optimization models and to identify first insights on the current performance of the BSC on highly aggregated values. The left-hand side of Figure 3 plots the BSC performance over an increasing demand factor across several simulation runs. With increasing demand, one can assume that in total more MBDFs are used, which was also observed. It has to be pointed out that the total of MBDFs at a given point in time was limited to 20 units, which peaked at 18.8 units used in average. The MBDF Rate depicts the rate of donations in relation to the total amount, which has a decreasing gradient, meaning that the next MBDF will add less donations due to the higher costs. While the increasing demand naturally decreases the shortages, the outages increased until no additional blood donations are produced and from then on, they decrease as well. This is reasoned by the overproduction of blood products of common blood types, which cannot be avoided, even when trying to optimize for donations matching blood type specific demands. With further increasing demand, shortages are expected to increase again, which was not recorded to this point. The right-hand side of Figure 3 plots additional performance indicators over an increasing MBDF count considering a fixed demand rate. Setup costs grow linearly as expected. Likewise, the linear transport costs are explained by the Hub-and-Spoke system. As MBDFs only collect whole blood, the whole blood costs of the network have an increasing gradient when more units are deployed. The MBDF Rate has a decreasing gradient again, yet not as significant, suggesting further analysis on that observation is needed in future research. Shortages and Outdates behave quite similar due to the increased production quantities. Yet, with a fixed demand, the outages are not expected to decrease as before as overproduction of blood types without demand will occur. 20 MBDFs seems to be the suggested limit for this demand scenario with close to zero shortages remaining. Both graphs illustrate a reliable and expectable behavior of the model supporting the validation of the combined simulation and optimization. Overall, the current analysis suggests, that a suchlike dynamic allocation of MBDFs is suitable to reduce shortages in the BSC especially under changing environmental influences. Limitations are the yet limited extend of simulation studies and the mixed use of WCBS and SANBS data with general population data, which can deviate from the individual organization’s reality, necessitating further research.

4 Discussion and conclusion

BSCs are complex networks encompassing many legally independent actors, transporting a critical good with a very limited availability and shelf life. Nevertheless, decision support tools known in the general logistics domain are often not being applied or transferred to this domain. As such, commonly used tools such as simulation and optimization are not employed often, which is particularly detrimental in times of crises, were established action plans do not consider the changed environmental influences onto the BSC. We have proposed a simulation framework enabling an integration of optimization algorithms for strategic, tactical, and operational decision support, displaying their interactions and the influence of an actor’s decision making onto the overall BSC. A suchlike system enables the BSC operators to adapt and prepare the BSC processes to the dynamically changing environmental influence, e.g., during a crisis. Furthermore, we gave the example case of the dynamic operating location choice of MBDFs to illustrate the interactions between the different optimization types and the simulation. The simulation-based optimization enables the evaluation of the process to dynamically choose the operating locations of the MBDFS based on the current stocks of blood products across the BSC. Nevertheless, the lack of detailed case data does limit the possibilities to evaluate the overall system at the current point in time. Future work therefore needs to include studies containing more detailed case data from the individual BSC operators and facilities to enhance the evaluation of the system. Additionally, extended workshops and interviews with the stakeholders of the BSC operators need to be performed to define other relevant evaluation cases, which then can be implemented and tested also. Finally, performance analysis and improvements need to be done to ensure the applicability of the approach to support operations in practice.

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