Quantitative Analysis of Demurrage Risk associated with a Rwandan Cement Producer's Virtual Warehousing

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ABSTRACT

CIMERWA's virtual warehouse (VW) in Kigali, Rwanda, supports the pre-emptive dispatch of product toward the epicentre of its demand for delivered cement. This practice yields many benefits. Expansion both in terms of the number of VWs and vehicles dispatched to VWs would increase these positive effects. However, this exercise is also fraught with uncertainty, as customer order behaviour is variable. If a truck arrives at a VW location, it must await an order, sometimes overnight, which may result in a demurrage charge being incurred. CIMERWA requires a stronger understanding of the risk of demurrage associated with each type and extent of expansion of its VW model prior to implementation.

A mathematical model was developed to provide this insight by both determining the optimal locations for VWs if more were to be added to the network, as well as test the designs under different degrees of aggression when numbering trucks to be dispatched. An optimization model was built using an Advanced Planning System to position VWs such that the market reach of the network was maximized. It was found that 50.94% of CIMERWA's demand could be satisfied via a single optimally placed VW, while 87.43% of its total demand could be reached pre-emptively via the network if five VWs were used.

An Excel Monte Carlo simulation model was subsequently used to test the five optimal networks using different planning methods. A planning method was defined as the combination of the strength grade of cement used to load VW-bound vehicles and two variables that accounted for how the moving average forecast might be used by the logistics office to decide on the number trucks to dispatch. Relationships between each of the planning method parameter and the number of demurrage charges incurred annually were determined for each network. Other system performance metrics, including the reduction of waiting days spent by customers, were also calculated for each scenario and used to analyse the dynamics governing the behaviour of the operation and the merits of each scenario.

Simulation data was then used to develop recommendations according to postulated minimum annual improvements in lead time days saved. It was found that a saving of 500 days per year would come at an average cost of nine demurrage charges if a single VW and forecast factor of safety of 0.2 was used. Using the same network, a factor of safety of 0.4 would satisfy a saving threshold of 1000 days while incurring 51 charges on average. The three-VW network would require a factor of safety of 0.6 to be used to reach the threshold performance of 2000 days saved with a mean of 220 demurrage charges. A factor of 0.8 would be needed in conjunction with four VWs to achieve the threshold of 3000 days, which would incur an average of 645 charges annually. Should management require more than 3810 days of waiting time to be saved, 32.5N strength cement would have to be substituted with 42.5N cement so that VW-bound trucks could deliver to customers who order either variant. The use of this stronger cement in conjunction with five VWs would achieve a saving of over 4000 days, with 1367 charges incurred.

NOMENCLATURE

- **APS**: Advanced Planning System
- **CPFR**: Collaborative Planning, Forecasting and Replenishment
- **EDI**: Electronic Data Interchange
- **EO**: Enterprise Optimizer
- **ERP**: Enterprise Resource Planning system
- **IBP**: Integration Business Planning
- **KPI**: Key Performance Indicator
- **LP**: Linear Programming
- **MTP**: Multi-Time Period
- **S&OP**: Sales and Operations Planning
- **SAP**: Service, Applications and Products
- **SLA**: Service Level Agreement
- **SO**: Sales Order
- **STO**: Stock Transfer Order
- **STP:** Single-Time Period
- **TMS**: Transportation Management System
- **VW**: Virtual Warehouse

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1. INTRODUCTION

1.1 Research Background/Context

CIMERWA is Rwanda's only cement producer. It competes aggressively with regional cement importers for its share in a growing market in a country experiencing rapid economic growth and urbanisation [1]. CIMERWA also exports cement to the Democratic Republic of Congo.

The Rwandan cement marketplace is highly sensitive to customer service levels, especially order-to-delivery time. Construction companies rarely employ forecasting methods or robust processes that ensure that materials were ordered before they are immediately required. A high proportion of these companies also do not have credit facilities with their cement suppliers. Order placement is therefore often delayed until the product is urgently needed and the cash for the purchase is available. This order behaviour, coupled with the fact that cement is viewed as a commodity, often results in a supplier being selected solely on its ability to deliver its product quickly.

Service delivery is particularly important to CIMERWA's value proposition. As the only cement supplier that manufactures its cement within Rwanda, it is uniquely limited to importing raw materials such as gypsum, which increases transport costs and hence makes it difficult to compete on the basis of price [2].

Physical positioning of the product close to centres of demand is critical to improving logistical performance cycle time when transportation methods are limited [3] and road transportation in Rwanda is slow[1]. CIMERWA elected to position its factory as close as possible to supply of its raw materials and chose the relatively remote town of Muganza near the south-western border of the country as the location for the plant. It therefore manufactures its product in an area of little demand. However, CIMERWA does not make use of warehouses to re-position its product closer to demand since its route-to-market strategy mitigated the effect of the large distances between its plant and centres of demand[2] on lead time. By selling to cement distributers operating within the Rwanda's major construction hubs, cement consumers could receive their cement from a local source without CIMERWA operating a secondary distribution network. Distributers also provided a buffer between supply and demand [4].

[1] Although water transport over Lake Kivu was used to supply Rwanda's western region and the DRC, most transport within Rwanda was done using trucks on the country's existing road infrastructure.

[2] The factory is 262 kilometres from Kigali, where approximately half of CIMERWA's demand resided. Hilly terrain and speeding limits resulted in an average incident-free driving time of 12 hours between these two locations.

This strategy achieved geographic specialisation of the product while transferring the inventory cost to the distributer, as well as the residual risk implicit with at-once orders when long delivery lead times are experienced [5]. Some pitfalls, however, were experienced.

Distributers represented an external intermediate link in the supply chain and thereby eroded the profit margin CIMERWA made on its products. Selling to distributers rather than end-users resulted in a consolidation of customers. A distributer had the ability to negotiate lower prices than an individual customer[3], which weakened CIMERWA's business position. Distributers ordered cement according to their cash flow and did not adhere to volume and exclusively agreements, which resulted in volatile demand. CIMERWA also did not own the relationship with the end-user of their product, which hindered customer relationship management and destabilised sales prices.

These disadvantages led CIMERWA to implement a direct delivery model to reduce its reliance on distributers. The use of outsourced transport to deliver truckloads of cement to customers directly from the production plant was added to CIMERWA's logistical service offering in 2016. Although the sales and operations planning benefits were felt by disintermediating the distributers, so too was the disadvantage of losing the geographic specialisation they provided. The delivery to the origin of the final transport leg to the customer was, in most cases, significantly further and the order-to-delivery time was therefore increased.

One operational mechanism used to combat this worsened delivery time involved the use of a virtual warehouse (VW). This warehouse exists only on CIMERWA's enterprise resource planning system (ERP) as a theoretical storage location in Kigali. Transactions for the actual transfer of cement to this warehouse can be initiated and managed even though the facility does not physically exist. This capability supports the IT and business processes for a pre-emptive dispatch of stock to Kigali as a stock transfer order (STO) before an order for the truckload of cement is received.

If a sales order (SO) is received and allocated to the truckload while it was in transit to the VW, the vehicle is diverted to the customer en-route. If not, the vehicle arrives in Kigali and the driver awaits further routing instructions. In either case, the order-to-delivery time experienced by a customer in Kigali is reduced, although the latter could incur demurrage charges or "standing costs" for the use of the vehicle to store the

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[3] This manifested in a rebate table that provided discounts for large-scale purchases. A consortium of distributers achieved significant savings by placing bulk purchases as single customers.

stock while waiting for demand to be secured. The stock is theoretically sold to the customer from the VW and reflects as such on the ERP (see Figure 1).

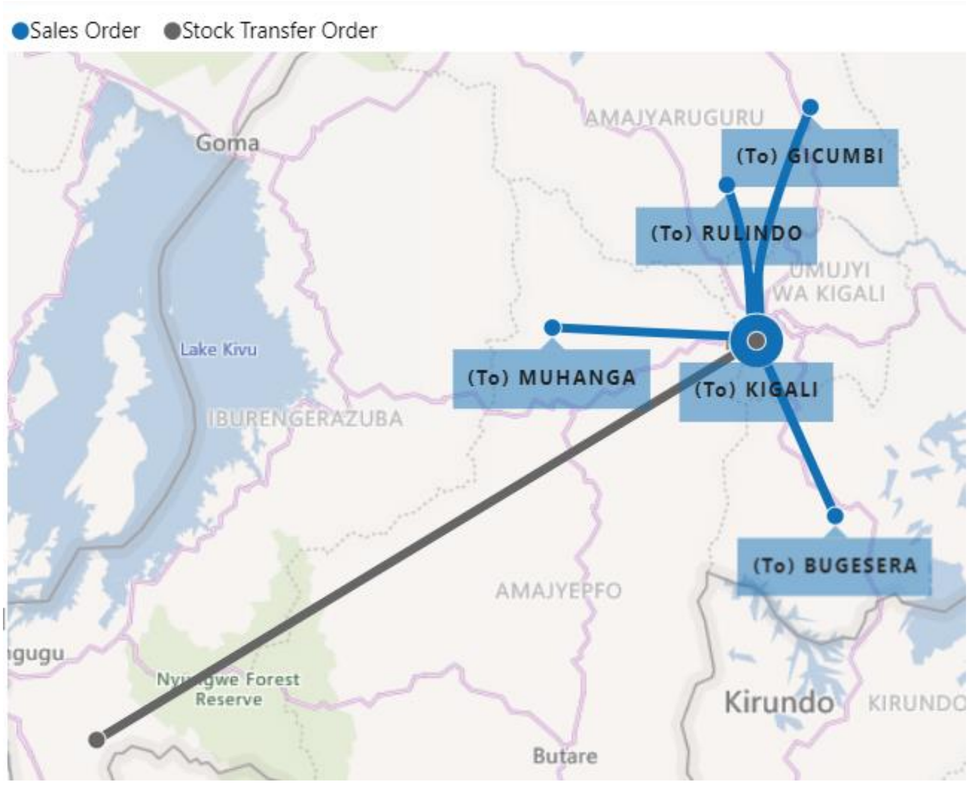

Figure 1: STO legs to the Kigali VW and SO legs to customer locations

This process therefore simulates the use of a warehouse to improve customer service levels, with the same vehicle used for the transport to and from the warehouse without arriving, offloading or loading at such a facility. Stock is thereby positioned closer to the predicted demand without incurring the material handling costs[4] associated with storing product in an actual warehouse. This offsets the increased inventory holding cost associated with the use of a truck for storage instead of a warehouse when demurrage charges are incurred [3] and the cost of inventory obsolesce incurred when cement hydrates in the vehicle. The reduced lead times achieved by this mechanism increases CIMERWA's market share as customers that urgently require cement and would have typically purchased a competitor's product from a distributer at a higher price can now receive their required material directly from the CIMERWA production plant without waiting longer to receive their stock.

[4] CIMERWA profit margin was especially sensitive to material handling costs. In addition to traditional handling costs, re-bagging damaged bagged cement was often required when multiple handling was performed.

The benefits of pre-emptively sending inventory to Kigali are not limited to those associated with reduced lead times. Greater urgency is placed on the CIMERWA sales team to secure demand for in-transit stock to prevent demurrage. This increases sales.

The VW buffers uncertainty regarding fleet sizing, which gives rise to logistical benefits. When available paid-for dedicated trucks exceed secured orders for delivery, directing the surplus trucks to the VW ensures utilization of the transport equipment. This reduces the risk associated with aggressive sizing and contracting of dedicated vehicles, which enables management to further leverage the lower cost associated with the use of such fleets.

This buffer also increases opportunity to use backhaul transport. The production plant became a preferred loading destination for vehicles in the area before returning to their domicile locations in Kigali. This transport is typically provided at reduced rates as it allows carriers to recover the cost of bringing vehicles back to their depots. The VW concept increases the likelihood of such a truck receiving a backhaul load from CIMERWA within the required timeframe, as an open order is not a pre-requisite to load and dispatch a vehicle.

Invoices for cement received via the VW are delivered to customers by the CIMERWA sales office. This is cited as the most operationally problematic aspect of the VW operation. The additional complexity in executing this function for export loads renders pre-emptive dispatching of cement to cross border customers impractical. The relative operational efficiency gained by delivering this documentation to CIMERWA's cross border customers in the DRC on the same vehicle as the product outweighs the strategic advantages associated with pre-emptively exporting cement using a VW.

1.2 Motivation and Problem Statement

The VW operation involves moving stock toward the market before demand or an exact final destination is finalized. It can therefore be said that this tactic involves decision-making under a fair degree of uncertainty. Uncertainty gives rise to opportunity and risk [6]. Predictive routing provides the opportunity to achieve a positive outcome (i.e. reduced delivery time, a sale that might have otherwise been given to a competitor or a transport cost saving), but also introduces the risk of a negative outcome (i.e. demurrage charges).

The opportunity and risk associated with this operating model depends on some strategic and operational parameters that are under CIMERWA's control. Strategic considerations include the number and locations of VWs used. Operational aspects include the truck planning method or "rules-of-thumb" that are used by the logistics office to determine the number of trucks to dispatch toward each VW daily. The supporting sales forecast method used, the strength grade of the cement loaded on VW-bound trucks and the degree of freedom assigned to the planner to deviate from the rule are also aspects of how the uncertainty is managed.

Defining the current CIMERWA model in terms of these parameters highlights the risk-averseness of its design, as well as the opportunity for its expansion. The model currently only supports pre-emptive routing to the densest and most consistent area of demand. The operation, however, is not limited to the use of one VW and can be upscaled to include pre-emptive routing to other centres of demand. Risk is also avoided by the high degree of discretion afforded to the planner to elect to not use the VW and thereby avoid a negative result.

Analysis of CIMERWA's transport data[5] reveals how tentatively the VW has been utilized (see Figure 2). A total of 207 loads (2.45% of all deliveries) were dispatched using the VW mechanism from March 2018 to March 2019 with a decreasing trend exhibited from June 2018. Fewer than three percent of such loads were executed in the final six months of the year analysed.

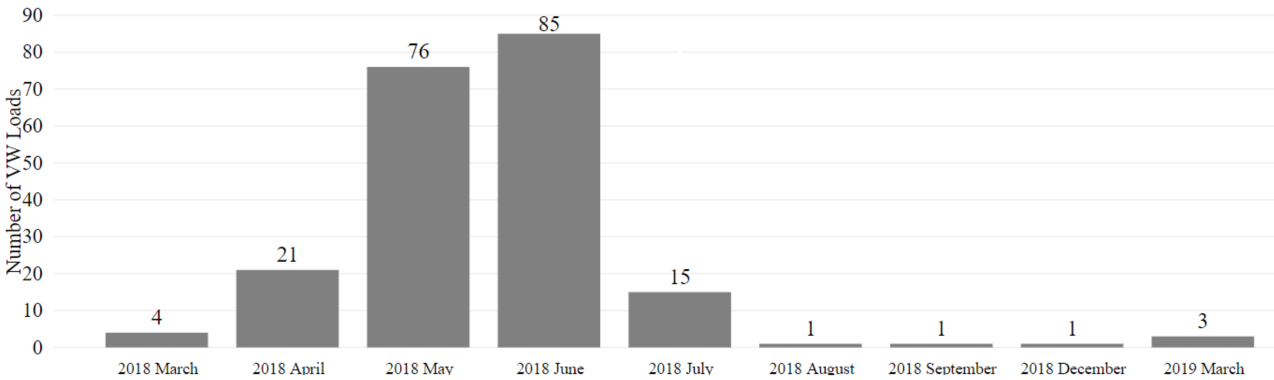

Figure 2: Number of trucks directed to CIMERWA's Kigali VW

Furthermore, 75% of these VW loads represented the use of the VW to support sales to confirmed customers that did not have a CIMERWA credit facility. In such a case, the truck was dispatched before the credit or receipt of cash payment had been approved, but the demand had been established within a reasonable degree of certainty when the VW load was planned. The described risks and benefits associated with pre-emptive routing therefore did not apply in these cases and, as such, it could be said that only approximately 50 loads had been executed according to the intended pre-emptive routing process during this period.

[5] Data was generated through use of CIMERWA's TMS. Analysis was limited to loads with actual pick-up dates between 25 March 2018 to 24 March 2019.

The infrequency of pre-emptive dispatching of vehicles using the Kigali VW resulted in a falling away of the practice of carriers invoicing CIMERWA for demurrage. The risk of additional utilization for standing time was implicitly included in the single transport rate quoted to CIMERWA.

Production shortages[6] due to Rwanda's "construction boom" and CIMERWA's expansion into the DRC and Burundi markets [2] did account for many periods when the VW was rightfully not used. If existing ordered stock exceeded on-hand stock, that product should be have been allocated to a processed order on the order book and pre-emptive routing should not have taken place. However, the low number of VW loads dispatched after the order backlog was cleared reflected the tentativeness that underpinned CIMERWA's use of pre-emptive routing.

Problem Statement

Expansion of CIMERWA's VW operation would leverage the concept to increase its positive effect on the business. Such expansion could be implemented along two dimensions.

Figure 3 shows expansion along the first dimension, which would involve an increase in the number of VWs used within the distribution network (i.e. increasing the static set target destinations for pre-emptively dispatched trucks). This would require the modification of the strategic design of the VW network on an ad hoc basis.

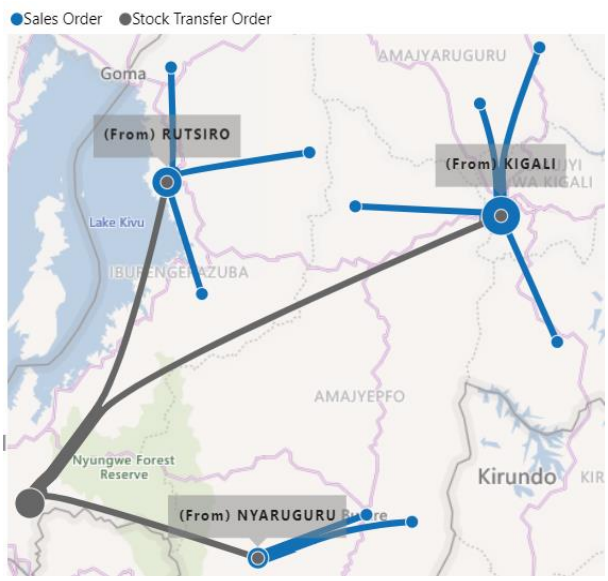

Figure 3: Map showing an expanded VW operation with an addition two virtual warehouses

[6] 278 loads (3.34% of all deliveries) were loaded late during the analysis period of 25 March 2018 to 24 March 2019 due to production shortfall. Carriers reported production shortfall as the reason for 1810 (20%) late deliveries.

The second dimension along which the VW operation could be expanded is the degree of speculation evident in the way the logistics office determines how many vehicles to dispatch to each VW daily. This applied logic is referred to as the planning method and adjusting these rules-of-thumb such that the number of trucks pre-emptively dispatched toward VWs was reliably increased would represent an expansion of CIMERWA's use of VWs.

A stronger quantitative understanding of the risk associated with pre-emptive routing of vehicles would have assisted in overcoming the risk aversion that hindered expansion along these dimensions. However, CIMERWA had no data or analytical tools to provide this insight.

1.3 Critical Research Question

What is the relationship between the strategic and operational parameters of CIMERWA's VW operation and the risk of incurring demurrage charges?

1.4 Research Objectives

The primary objective of the study is as follows:
To develop and demonstrate a quantitative method for generating alternative expanded VW network designs for CIMERWA and determining the risk of demurrage associated with each design. The method must incorporate the planning method as an input, including the type of cement dispatched, the forecasting method used and the level of appetite for risk evident in the manner in which the forecast is used to number the trucks dispatched to each VW.

The supporting objectives are to:

1. Develop and use an analytical model for determining the most desirable[7] VW positions (i.e. the network design) when different numbers of VWs are used.
2. Develop and use a predictive simulation model for determining the relationship between the number of VWs and the risk of incurring demurrage charges. Each network design must be simulated using different planning methods. Each method must prescribe which strength grade of cement is loaded on VW-bound vehicles and how the daily forecast is translated into the planned number of trucks sent to each VW such that different levels of appetite for risk are mimicked.

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[7]VWs should be positioned in such a way that the satisfiable demand in their collective catchment areas would be maximized while minimizing the travel distance required to meet this demand from the VW.

1.5 Limitations

The following limitations of this study were identified:

- Data collected and used for the modelling of the expanded VW operation were historical in nature. Future changes in demand patterns could not be reliably anticipated. Prediction of or accommodation for future modifications to CIMERWA's sales and operations strategy such as the closure of current or establishment of new production plants, changes to the output capacities of these plants, the establishment and subsequent redesign of owned or rented physical warehouse networks and introduction of new modes of transport therefore resided outside the scope of this study. The models were therefore developed and run under the assumption that these parameters would remain unchanged when any VW operation expansions would be implemented.
- The models that were central to this study represented logistical systems that had never existed. Learnings extracted through analysis of the current VW operation were used to model the expanded operations and care was taken to ensure that the modelling assumptions would be valid under the new conditions that were modelled. Nonetheless, the increased activity and expansion of the VW network into new geographic areas of Rwanda may introduce new constraints and rules that govern interactions between vehicles, customers, plants, logistical infrastructure, products, etc. that were not anticipated by the modeller.
- The logistical systems that were modelled involved human role-players and many aspects of the inherent unpredictability of their behaviour were not modelled. The model results and, by extension, the interpretation thereof therefore did not consider many aspects of human behaviour.
- The dynamics of the supply chain were modelled using transaction-level operational datasets that comprised of thousands of entries. Data validation techniques therefore focused on identifying outliers. Any verification of data points that were not identified as outliers had to be selected as a random sample, which meant that many transactions were not individually verified.

2. LITERATURE REVIEW

The literature review covered four topics which were used as inputs to the stated supporting objectives: (a) virtual warehousing and the extent to which CIMERWA's use of a VW incorporates general VW principles and (b) vehicle routing, (c) network design and (d) simulation modelling techniques and their applicability to the CIMERWA VW operation. Further reference is made to literature elsewhere in the document where the literature applies directly to the topic being discussed.

2.1 Virtual Warehousing

The VW is a concept developed by Global Concepts, Inc. to improve supply chain responsiveness [7]. It was presented as a hardware and software framework to support decision-making and operational processes by consolidating real-time data from several sources. These typically include stock inventory levels and geographic positioning of vehicles [8].

The most common use of a VW is to pool inventory from physical inventory locations into a single theoretical location. This aggregation facilitates the use of algorithms that link points of supply and consumption [9] (see Figure 4). As such, the VW serves to replace a network of physical warehouses with policies and processes that optimally respond to existing demand given the current positioning of inventory in the supply chain. A VW implementation thereby gives rise to a responsive "pull" of material to its demand point rather than an anticipatory "push" downstream the supply chain [8]. This results in lower levels of inventory and associated capital, insurance, obsolescence and storage costs [3].

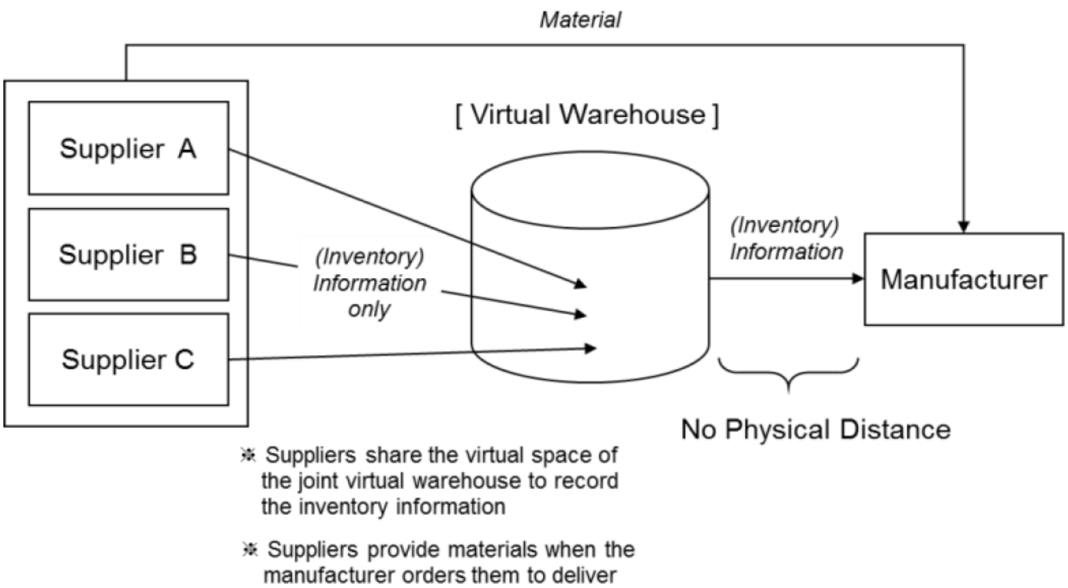

Figure 4: The virtual warehouse concept [9]

The CIMERWA model appeared at odds with the "pull" philosophy that underpins the VW concept. The VW in Kigali enabled a predictive push of material towards demand. The trigger for transport was not the customer's order, but the anticipation of an order, which is a practice more indicative of an anticipatory business model than that of a responsive model [3]. Analysing CIMERWA's process as two sub-processes, however, aided its reconciliation to the more general VW concept. The initial dispatch of cement to Kigali represented a "push", while the diversion of the truck en-route represented a "pull." The use of real-time transport and sales data to co-ordinate the linkage of supply (i.e. the truck) and demand (i.e. the customer) during the diversion represented the application of a key tenet of the VW concept [8].

The project's primary objective, however, focused on the anticipatory "push" process within the VW operating model used by CIMERWA. Sales and Operations Planning (S&OP) techniques (e.g. vehicle routing methods, network design, simulation etc.) were therefore more applicable than those usually associated with the use of a VW (e.g. real-time, cloud-based tracking and stock visibility systems).

2.2 Vehicle Routing Techniques

CIMERWA's anticipatory "push" of cement toward the VW could have been described as a Stochastic Vehicle Routing Problem (SVRP) as trucks were dispatched under a high degree of uncertainty. This is observed in any distribution system where deliveries must satisfy orders received in real-time, such as flower or fast food delivery, repair of electrical or transport infrastructure or retailer replenishment [10]. Since CIMERWA's customers may or may not have ordered any number of truckloads of cement each day, the problem could have been more specifically classified as a Vehicle Routing Problem with Stochastic Customers and Demands (VRPSCD) [11].

The VRPSCD is a specific example of a Capacitated Vehicle Routing Problem (CVRP). Solving these problems usually involves compiling a set of vehicle routes of minimum total cost, with each vehicle starting and ending at its domicile location [12]. The VRPSCD is considered a particularly difficult CVRP to solve with a variety of approaches that can be used [11].

Arguably the most well-known approach was proposed by Bertsimas (1992), in which the problem was solved as a standard SVRP using closed-form expressions and algorithms. The assumption was made that all possible customers would have had to be visited, but the solution allows for re-optimization in real-time once the demand was known [13]. This two-step process is also evident in the tabu search method developed by Gendreau *et al.* (1994) [12]. While the delayed confirmation of demand was a feature of the CIMERWA operation, this approach is more applicable to multi-drop routes [11]. CIMERWA only delivered full truckloads.

Ulmer *et al.* (2018) developed an approach to solving the VRPSCD using Markov decision processes to allow for anticipatory pre-emptive depot returns. These allow delivery vehicles to restock during the planning period [14]. This approach can be used to model the delivery of full truckloads, but it is of little use if the vehicle cannot return on the same day to reload. A return trip to a CIMERWA customer usually required more than one day to fulfil. Trucks also might not have returned to the CIMERWA production plant, as they could have been routed to provide transport for other companies. This revealed the implicit pitfall in applying CVRP concepts to the CIMERWA VW model. The solution to a CVRP is the optimal sequencing of vehicle stops, but a CIMERWA delivery route could only consist of one planned delivery stop per planning cycle.

Markov decision processes are an application of probabilistic dynamic programming, which is used to model situations in which the state of the environment changes from one stage to the next [15]. This transition depends on the action made by the decision maker and other probabilistic events. The multi-time period nature of the CIMERWA problem and the stochastic nature of its demand and vehicle performance made this technique attractive for modelling the operation.

A dynamic programming recursion is defined in terms of “stages” and “states” [16]. CIMWERWA’s operating days could be defined as stages, while the number of vehicles stationed at and en-route to each VW could be modelled as states. The probability distribution of the number of orders being planned for delivery to each of CIMERWA’s cities of demand could be incorporated into the transition of each state to the next, although some simplifying assumptions would have to be made and built into the model. This disadvantage is shared by most network design techniques that could be applied to meet the project’s primary objective.

2.3 Analytical Network Design Techniques

The CIMERWA VW operation simulated the use of a physical warehouse. Analytic methods that support physical warehouse network design can therefore be applied to the upscaling of its VW model. Good design of physical networks is underpinned by the systems concept, which emphasises the understanding and quantification of relationships between components in order to maximise performance of the entire system. Locational modification was recognized by Bowersox *et al.* (2013) as a key influencer of total logistics performance and the effect that positioning of facilities has on other network design elements was noted [3]. If this principle is applied to the CIMERWA operation, these facilities would be VWs, while the “other element” would be the number of trucks dispatched daily. Location analysis techniques were therefore applicable.

Location analysis has played a crucial role in the development of operational research and the problem of determining optimal locations has been well researched [17]. Several established analytic techniques are available for optimally numbering and positioning facilities. Simchi-Levi *et al.* (1997) presented an algorithm for the p-Median problem, in which a set of facilities are positioned optimally when customers are serviced by only one warehouse and the maximum distance of the customer from the warehouse is fixed [17]. These features are applicable to CIMERWA's positioning of VWs because trucks could only be feasibly diverted to delivery locations located within a certain area around the VW.

The p-Median algorithm was then expanded by Simchi-Levi *et al.* (1997) to address the Single-Source Capacitated Facility Location Problem (SSCFLP). This formulation allows the number of warehouses to be optimally determined while constrained by the capacity of each warehouse. An alternative distribution system design formulation was also presented to incorporate product variety and customer order volumes into the optimal network [17]. This allowed for modelling the uneven effect CIMERWA's customers had on the weighted geographic spread of demand for its product.

Sebbah *et al.* (2011) demonstrated how analytical network modelling can also provide insight into the relationship between network design parameters. Canadian Forces' distribution of supplies to their military bases was modelled and optimized repeatedly as the modellers adjusted the values of certain input variables, such as the demand for tactical supplies [18]. Such a method could be used to investigate the relationships between parameters of the CIMERWA VW operation, such as the number of VWs and the risk of demurrage.

These formulations provided insight into the nature of the algorithms utilized by algebraic modelling systems (e.g. LINGO) and Advanced Planning Systems (APS), such as River Logic's Enterprise Optimizer (EO). The former allows users to formulate and solve linear, integer, quadratic, general nonlinear or global optimization problems using an easy-to-use syntax and programming interface and pre-verified solvers that are automatically selected prior to optimization [19]. The ability to define systems by first principles provide the LINGO user with the flexibility to solve almost any simple problem.

An APS also provides a method of employing linear optimization techniques to optimization problems, but more specifically within sales and operation planning (S&OP) contexts. It simplifies the formulation of complex supply chains by allowing modellers to define a supply chain network using ready-to-use concepts such as plants, warehouses and customers. It thereby provides a quicker, less mathematically rigorous and pre-verified method for generating suggested answers to questions such as the optimal number, size and location of facilities [3].

EO is one such APS, although it is more commonly referred to as an Integrated Business Planning (IBP) software tool. EO provides a simple diagram style interface that can be used to model the business processes that create value within the organisation. Four basic object types, namely purchase, conversion, inventory and sales, are used to graphically model the supply chain. Once a minimum amount of information is specified for each model, the algorithm optimizes for profit on any unconstrained variable [32].

The use of APSs such as EO, however, requires the skilful aggregation of data and appropriate definition of warehousing and transport costs, service level requirements and future demand to obtain feasible results. This often proves problematic. Furthermore, difficulties arise when mathematically modelling real-world complexities such as variation in travel time and inventory shrinkage [17].

The shortcomings of such analytical modelling methods become more pertinent when considering that variation in demand is particularly key to any analysis of CIMERWA's VW model. Furthermore, the operation supported a relatively low transaction volume when compared to most modelled supply chains[8], making "smoothing" of natural variation through aggregation less effective. This exacerbates the stated difficulties of modelling stochastic relationships.

2.4 Simulation Modelling Techniques

Stochastic relationships are particularly prevalent in logistical systems [19]. The use of analytical methods to model environments governed by these types of relationships usually requires so many simplifying assumptions that generated answers cannot be implemented. It is therefore often more effective to improve logistical performance by imitating the behaviour of the operation by replicating the relationships and then analysing "what if" scenarios [15].

This replication can be achieved through pseudo-random number generation, an application of simulation modelling known as Monte Carlo simulation [20] that has been used to gain insight into the dynamics of many supply chains. Simchi-Levi *et al.* (1997) recognized that the assumption of known or constant demand necessary for analytical inventory modelling is often inappropriate and presented algorithms for single and multiple time-period stochastic inventory problems with an extension to multi-echelon supply chains [17].

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[8]An average of 23.55 truckloads of cement were dispatched per day from the CIMERWA production plant between 25 March 2018 and 24 March 2019.

Albright *et al.* (2005) presented methods for using Microsoft Excel as a tool for developing Monte Carlo simulation models, including an example of its use for determining the economic order quantity (EOQ) under conditions of uncertainty [21]. Excel was also used by Zabawa *et al.* (2007) to develop an "inventory management business game" that demonstrated the power of this software to test the effect of different inventory policies on logistical key performance indicators (KPIs) [22].

Monte Carlo simulation is particularly useful for a targeted study of the sensitivity of one logistical system parameter to another. Klug (2011) demonstrated the use of Monte Carlo methods to generate a graph depicting the relationship between the standard deviation of circulation time of returnable automotive containers and the standard deviation of their demand [23]. De Grotte *et al.* (2011) showed the use of stochastic modelling to investigate the effect of increasing product variety on product availability and replenishment lead times in an integrated production and distribution system [24]. The latter relationship was of particular interest to the CIMERWA VW operation, as the limited product variety associated with the cement market and the relatively low importance of product assortment to cement distribution performance were key positive contributing factors to the feasibility of pre-emptive vehicle routing.

These stochastic techniques do not carry the discussed disadvantages of analytical methods. They were therefore well-suited to modelling the CIMERWA VW operation and could have been applied to investigate the relationships between its strategic and operational parameters and the risk of demurrage. Winston (2004), however, noted that the use of simulation for produce specific output to enhance operations is slow [15]. The need for scenarios to be tested through simulation means it is better suited to investigating the effect of changes to systems than the generation of suggested answers to questions.

Simulation modelling could have been used to effectively test changes to the CIMERWA VW operation and operational parameters, but these changes had to be developed first. This requirement makes generating solutions using simulation a slow process if the modeller uses the simulation model to test the entire solution space. It is therefore preferable to first use some form of analytical technique with simplifying assumptions to produce a smaller set of feasible solutions that are later simulated using the Monte Carlo model. These techniques can be simple spreadsheet analyses and subsequent elimination of clearly infeasible or insensible alternatives, or more rigorous optimization techniques such as dynamic or linear programming [43]. This can be an iterative approach, with the findings of the simulation exercise informing the analytic techniques (see Figure 5).

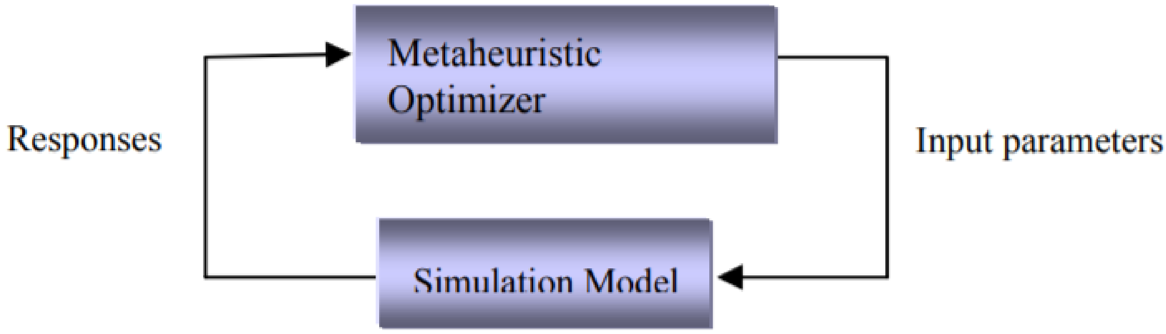

Figure 5: Iterative approach to the combined use of analytic and simulation techniques [43]

This method of simplification by first optimizing using analytical methods and then simulating binary options has a successfully track record in supply chain integration [3]. An example of a real application of this technique was presented by Wang (2012), who demonstrated the method while modelling perishable goods within a grocery retail chain in the United Kingdom in order to optimize pricing [29].

It is clear both that both analytic and simulation modelling techniques have their advantages and disadvantages that render each more applicable to some problems than others. The CIMERWA VW expansion exercise, being both solution-driven (i.e. supporting objective 1) and investigative (i.e. supporting objective 2) in nature, would be well served by the selective and iterative use of both techniques. An iterative process by which the output of one technique is fed into the other for an increasing improved VW expanded model would be beneficial.

3. RESEARCH METHOD

3.1 Technique Selection

The literature review served as a broad study of theory that had been applied in contexts of varying degrees of similarity to problem presented in section 1.1. While the applicability of each area of theory to the problem statement was discussed, it had to be processed further into a modelling approach that would achieve the primary objective.

3.1.1 Mathematical Modelling

The primary objective focused on the provision of quantitative insight into the risk associated with the expansion of a speculative operation. This insight could be gained by simply changing the real system and observing the operational data that was forthcoming. This approach, however, would introduce numerous costs and risks.

Although many of the systems and processes for pre-emptively dispatching trucks to VWs are already in place, actual expansion of the operation for investigative purposes would require significant rework on these systems and processes. An example of such rework would be the establishment of new VW locations on CIMERWA’s ERP, SAP, and the transportation management system (TMS), BluJay Transportation Management.

Significant change management would be required. This would include training of CIMERWA’s and carriers’ transportation planners, drivers and financial managers to manage the of pre-emptive dispatching of vehicles to multiple VW locations. Commercial terms with carriers would also be affected, as more stable volumes dispatched to various regions of Rwanda would provide CIMERWA the opportunity to renegotiate transport rates. The higher risk of demurrage introduced could also prompt renegotiation of standing charges. These would have resulted in new contractual terms.

The abovementioned implementation activities would incur significant cost in the form of monetary investment, implementation time and effort and disruption to the business. This cost would be repeated with every change to the parameters to test the various scenarios (i.e. combinations of VW networks and planning methods) and collect the necessary data.

However, the most significant disadvantage associated with the use of actual implementation of different scenarios to gain the required insight would be the actual introduction of the risk under investigation. If an experiment is conducted using many VWs and an aggressive planning method, this operating model would introduce a high risk of demurrage charges for which CIMERWA would be liable. This would add to the cost of the investigation. The repeated dispatch of vehicles in anticipation of demand that did not materialize and requiring vehicles to stand overnight without accurately explaining the risk to the carriers beforehand could also be interpreted as CIMERWA's lack of control over and understanding of its own supply chain. This would result in a loss of CIMERWA's reputation as an excellent logistics operator.

It follows that a virtual method of testing different expanded operations is a preferable means of investigating the risk of demurrage associated operational expansion, provided that this method could provide a sufficiently reliable set of results for each scenario. Mathematical modelling was identified as such a method. The literature review highlighted the advantages and disadvantages of two popular mathematical modelling methods, namely analytical and simulation modelling. However, the methods required some sharper review through the lens of the primary objective of the project before a technique, or hybrid of techniques, could be selected.

3.1.2 Simulation Modelling

Bowersox *et al.* (2013) recognized two criteria used to evaluate alternative modelling methods: generalizability and accuracy. These criteria often compete. Generalizability refers to the ease with which the model can be adapted and scaled to cater for special situations. Accuracy refers to the model's ability to closely replicate performance characteristics and the degree to which the results represent the true optimal solution [3]. Both criteria were considered when determining whether analytical or simulation modelling methods would be used to address the project's problem statement. Given the complexity of the CIMERWA virtual warehouse VW operation and the various ways in which its parameters could be changed to expand it, generalizability received more consideration as the modelling approach was developed.

The deliberate emphasis placed on generalizability favoured the selection of simulation as the technique for modelling the operation. The ease with which complex real-world heuristics and stochastic processes can be modelled using Monte Carlo simulation methods enhances the modeller's ability to adapt the model to cater for new scenarios or additional complexity. Monte Carlo methods are therefore well-suited to providing insight into the dynamics that govern predictive logistical operations within an environment as fraught with uncertainty as the Rwandan cement market. Simulation modelling was therefore deemed a better suited technique to address the project's primary objective and was thus chosen over analytical methods as the underpinning virtual method of testing the expansion of CIMERWA's VW operation.

A significant limitation of Monte Carlo methods, however, is the slow speed at which they can be used to find the optimal solution to a problem [15]. Examination of the project's primary objective, however, revealed that the essence of the investigation was not the determination of a best possible operation, but rather the understanding of the relationships between the system's performance and the two dimensions along which the existing operation could be expanded.

The manner in which the VW model would be expanded along these dimensions, however, was not defined in the project's primary objective. If different operations were to be simulated, these operations would first have to be formulated as part of the study. This requirement could be stated in more general terms: if the primary objective required insight into a future state that was not defined, the future state first had to be developed by giving answers to two important questions. Firstly, if CIMERWA decides to increase the number of its VWs, to what extent would it attempt to optimize the locations of these VWs? Secondly, if CIMERWA employed a more aggressive planning method, how would it define the planning method and how sophisticated would it be?

The techniques by which each of these questions were to be answered was subject to some discretion, as a trade-off existed between the optimality each solution and the feasibility of CIMERWA developing, implementing, operating and maintaining it. These questions are addressed separately in sections 3.1.3 and 3.1.4.

3.1.3 Optimization

As the number of VWs is to be increased, the placement of these VWs would have to be determined before any simulations could be run. CIMWERWA delivers cement to 57 Rwandan cities. The difference in historical annual demand for CIMERWA's products per city ranges from one truckload to 2496 truckloads, with a standard deviation of 348. Evidently, there are delivery cities that introduce significantly more risk of incurring demurrage charges than others. The number of orders placed in adjacent cities that could be fulfilled by a truck that was standing at its VW is another factor that affects the risk of demurrage. It could therefore be assumed that the simulation results would be significantly sensitive to the placement of the VWs.

The decision regarding where to place VWs is too complex to optimize intuitively. A network of five VWs provides 502 452 720 different possible combinations of VW network arrangements. The placement of VWs would be a strategic decision and would not be changed daily. The optimization of VW networks could therefore be conducted as *ad hoc* studies, the results of which computed by skilled modellers and implemented and reviewed periodically with no need for sophisticated operational systems and training.

These considerations suggest that CIMERWA would attempt to optimize the positioning of additional VWs should it expand the operation along this dimension. Furthermore, this problem lends itself to analytic optimization techniques as it can be reasonably solved as a deterministic model if the assumption was made that demand in each Rwandan city would remain constant [15]. This was evident in the literature review, as LP was the overarching analytical method of the various network design algorithms presented by Simchi-Levi *et al.* (1997). It enjoys an extensive record of successful application in the area of locational modification, especially when an APS is used to model the supply chain prior to optimization using an LP engine [3]. LP was therefore selected as the analytical technique for generating the VW locations for the future states to be simulated.

3.1.4 Simple Heuristics

Analytical optimization of the operation's expansion along the planning method dimension, however, would be less feasible. While the decision regarding the number of trucks to dispatch to each VW is also complex and the risk of demurrage could be highly sensitive to the quality of any rules-of-thumb that would guide such decisions, the feasibility of replacing these heuristics with optimization techniques that computed the number of VW trucks to dispatch daily is questionable.

The frequency with which these decisions have to be optimized would necessitate the implementation of an operational system that would require data feeds from SAP and the TMS to generate meaningful results, as well as a skilled operator to run the algorithm and validate the results. Furthermore, CIMERWA's somewhat low transactional volume would limit the benefit of developing and implementing sophisticated machine learning and/or optimization techniques, such as a probabilistic dynamic programming algorithm, rather than a simpler intuitive rule-of-thumb informed by a basic forecast.

As such, the chosen technique for simulating the planning method did not include any optimization techniques. Rather than utilize machine learning or advanced forecasting methods to simulate CIMERWA's prediction of the following day's orders for delivery to each VW's catchment area, the use of a moving average forecast was simulated. Instead of utilizing probabilistic algorithms to determine how to use the forecast values to determine the number of trucks to dispatch, basic rules-of-thumb were developed and their use simulated. The parameters of the rules-of-thumb were adjusted to reflect a greater degree of speculation used by the logistics office and thereby simulate the expansion of the VW operation along this particular dimension.

3.1.5 Modelling Approach

These three technique selections, namely simulation modelling for investigating expanded VW models, linear programming (LP) for determining the VW locations for these expanded VW models and rules-of-thumb for simulating the planning method, gave rise to two different modelling exercises that would be conducted sequentially as a hybrid modelling approach (see Figure 6). This pair of exercises served as the supporting objectives of the project (see section 1.4):

1. Network optimization modelling: An LP model of the CIMERWA distribution network was modelled. The optimization engine determined the optimal positions of the VWs. The key input to this exercise was CIMERWA's historical demand, both in terms of volumes by product type and customer geography. The key output of this exercise was the optimal cities in which VWs should be located for each number of VWs used (i.e. optimal VW networks).
2. Operation simulation modelling: The VW operation was simulated using Monte Carlo methods. The model was run to simulate the implementation of differing degrees of expansion of the operation, both in the number of VWs used and the planning method. The planning method was simulated within the Monte Carlo model, which entailed a moving average forecast calculation using the simulated sales volumes in each VW's catchment area and rules-of-thumb that governed how the forecast was converted into the number of trucks to dispatch to each VW daily. The key inputs to this exercise were CIMERWA's historical demand as well as the optimal VW networks (i.e. the output of the network optimization exercise). The key output of this exercise was the number of days' demurrage charged to CIMERWA by carriers per year for multiple simulated years of operation under different levels of expansion, which would be interpreted as risk of demurrage.

River Logic's Enterprise Optimizer (EO) was selected as the advanced planning system (APS) for the network optimization exercise due to its extensive use for supply chain modelling and its powerful LP optimization engine. Microsoft Excel was selected as the Monte Carlo modelling tool. Excel was also used for data preparation, cleansing and validation, as well as model verification and analysis of the results of both individual modelling exercises and the hybrid model as a whole. Microsoft Power BI was also used for validation and analysis of input data to and output from the models.

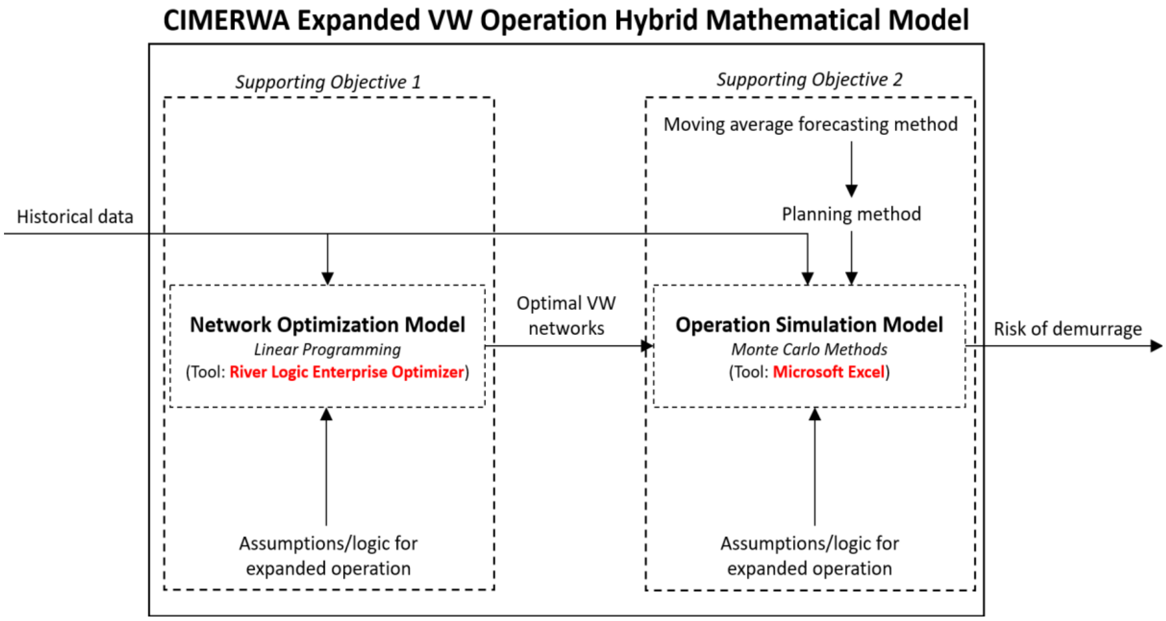

Figure 6: CIMERWA hybrid mathematical model concept

The primary objective stipulates that the optimal VW networks are a required output of the method. This data therefore represents both an input to the second component of the hybrid mathematical model and an output of the hybrid model as a whole. Some activities performed on this data can therefore be classified differently and are discussed in different sections of this document depending on the model in focus. For example, validation of this data could either be viewed as a data cleansing and preparation exercise and therefore be discussed in section 3.3.5 or a model verification activity and hence be discussed in section 5. It was decided to discuss this data as an output of the hybrid model.

3.2 Research Procedure

3.2.1 Research Phases

Albright *et al*. (2005) [21] presented a modelling framework that can be used to execute both analytical and simulation modelling exercises. It consists of seven-steps that, when followed correctly, guide the development of a mathematical model and implementation of the recommendations it generates to address the problem that initiated the exercise (see Figure 7). This process was selected as the modelling framework for developing the hybrid mathematical model that included both the LP model that produced the VW network designs and the Monte Carlo simulation model that tested the designs when different planning methods were used.

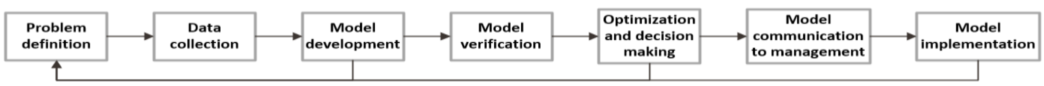

Figure 7: The seven-step modelling process [21]

While some aspects of the two modelling exercises overlapped and informed each other, the models were, for the most part, developed and run sequentially. It follows that many of the modelling steps were executed twice for this project at different times, once for the fulfilment of each supporting objective. However, the seven-step framework was used to describe the modelling of the execution of approach for the hybrid model holistically. As such, the sequence of steps is described once, but the explanation of each step includes detail regarding of how it was followed for each component of the hybrid model.

The sixth step of the Albright *et al*. (2005) modelling framework, "Model Communication to Management", was deemed to lie inside the scope of the project. However, a large component of this step typically involves the analysis and interpretation of data, which is addressed as part of the "Results and Analysis" and "Discussion" section of the document. These two sections can therefore be considered tantamount to the sixth step. The process also makes provision for solution actualization [21]. The scope of this project, however, excluded any operational implementation of recommendations that may have stemmed from the operational insights gained from the exercise. As such, a streamlined adaptation of that framework was used, which excluded the seventh and final step of the process.

Much of step one of the framework, "Problem Definition", was completed during the development of the research questions, problem statement and project objectives. The details related to the execution of this step of the process are included in the introduction of this document, resulting in this step of the modelling process being excluded from the "Research Methods" section.

Bowersox *et al.* (2013) [3] also provided a more granular framework for executing operations analysis exercises and made provision for the use of analytical and simulation methods as part of those exercises. There is a large degree of overlap between this methodology and that presented by Albright *et al*. (2005) and, as such, many of the concepts presented can be incorporated into the seven-step modelling process. These were included in the research procedure for the hybrid model where deemed appropriate. Examples of such inclusions were the business, management and analysis assumptions that were noted, documented and included in the "Data Collection" step of each modelling exercise.

3.2.2 Ethical Considerations

Only demand for delivered cement is relevant to the design of CIMERWA's VW structure. As such, data generated from CIMERWA's use of a Transportation Management System (TMS), developed by BluJay Solutions, could be used to model the operation. The TMS is cloud-based and access to the data was given by CIMERWA. Express consent to use the data was provided by the office of CIMERWA's Chief Executive Officer, Bhekizitha W. Mthembu.

Full ethical clearance was provided by the Ethics Committee of the University of the Witwatersrand's School of Mechanical, Industrial and Aeronautical Engineering. The ethics clearance number for this study is MIAEC 178/19.

3.3 Data Collection

Good quality, appropriate input data is essential to the success of a quantitative study [43]. The fulfilment of the primary objective of the project required a highly quantitative analysis of the CIMERWA VW operation using both an analytical and simulation model. It follows that reliable data had to be sourced, cleansed and prepared in such a way that the conceptual model could be run as intended.

3.3.1 Assumptions

The two models that were developed did not aim to fully represent the environment in which CIMERWA operates or the expanded operation. Rather, the distribution network and VW logistics operation were modelled intentionally to address the objective. This allowed for certain simplifying assumptions to be made, which mitigated the risk of introducing computational difficulties or modelling parameters that were not fully understood, or developing a model that would produce extraneous output that would only serve to pull the focus of the analysis from the aspects that were of relevance to the objective [25].

Simplifying assumptions were especially important to the development of the first component of the hybrid model. This component involved modelling the CIMERWA distribution network as a LP model using an APS, an analytical technique that presents significant difficulties when attempting to model complex systems without a set of simplifying assumptions that are strictly enforced [30].

This consideration, coupled with appreciation of the inherent complexity of the underlying dynamics and sources of variation within the Rwandan cement market and pre-emptive routing methods, resulted in the optimization component of the hybrid mathematical model being modelled as a "black box" [26]. Although the second component of the hybrid model was a Monte Carlo simulation model, an inherently easier method for modelling complexity, many simplifying assumptions were also deemed appropriate for inclusion in its underlying logic.

Assumptions were also necessary to construct a stronger experiment for investigating the relationship to which the project's primary objective referred. An exact depiction of the system and its underlying mechanisms could have impinged on the hybrid model's ability to produce insight into the relationship between the expansion of the VW operation and risk of demurrage. For example, the CIMERWA production plant often had established demand for its cement in the form of sales orders (SOs) well before the cement was produced and ready for dispatch. This would have often prevented the logistics office from speculatively dispatching cement toward VWs if an aggressive planning method were employed. If this limitation on the logistics team was modelled, the data would have understated the risk associated with highly speculative rules-of thumb for dispatching VW loads because their implementation would have seldom resulted in more VW trucks being dispatched than if more moderate heuristics had been used. Assumptions were therefore used to explore what-if scenarios that may not have been feasible, but would contribute to the achievement of the primary objective.

An additional benefit of simplifying assumptions is that they often reduce the model's data requirements. With each simplification, the extent to which the inner workings of the system must be modelled reduces. This results in a higher-level representation of the system and the modelled components being aggregations of the sub-components of which they are comprised. The data that describes the behaviour of these aggregated components is therefore also aggregated. Fewer datasets are then required to model the system and, as these datasets represent aggregations of others, the sample sizes increase [27], which increases the confidence associated with inferences made using the data. Outliers in larger datasets are also easier to detect and failure to detect them have less effect on the validity of the data [41].

For example, if CIMERWA's demand patterns were modelled in terms of delivery cities, rather than individual customers, the sales volumes per grouping would have been greater, showed less variation and provided more reliable representations of the demand in each node of consumption. Failure to identify an erroneous sales datum would also have had a lesser impact on a city's summary statistics than a customer's.

It follows that the modelling assumptions should inform the manner in which the data is collected and prepared for the modelling exercise and should therefore be established as an initial task of the data collection step of the modelling process.

Bowersox *et al.* (2013) described three types of assumptions that should be documented during the data collection step of an operations analysis exercise.

- Business assumptions define the business environment in which the modelled system operates, including opportunities and constraints introduced by external entities such as suppliers, customers and regulating bodies. Business environments are typically dynamic and complex and are therefore difficult to define in their entirety. It is therefore critical to use the business assumptions to define the elements of the system that are necessary to include in the model. This activity therefore serves the modeller by stripping complexity from the model without detracting from the usefulness of the model to answer questions about the environment [28].

- Management assumptions outline the characteristics of the system's operation that are under management's control, such as internal policies and procedures that support a strategic objective.
- Analysis assumptions state the constraints and limitations that must be adhered to in order to protect the feasibility of using the analysis technique to address the objective [3].

All three classes of assumptions improve the validity the model output by providing a base, agreed with management, upon which the modeller can develop the underlying logic of the model. They can also serve to simplify the model, the benefits of which are described above. Of the three classes, analysis assumptions typically have a greater simplifying effect on the model than the remaining two assumption classes.

The assumptions that informed the data collection and model development procedure are described in Appendix 1. Some justification is given where an assumption was made specifically to simplify the environment and operation that was to be modelled. The learnings that informed a justification may have been found after the data collection step of the seven-step process and then included with the other assumptions in this section. Assumptions that were found to be unjustified and thereby triggered rework on the data and model were omitted from the list below.

Some assumptions required some validation. This validation is included in Appendix 1 as it was performed at this point of the exercise for both components of the hybrid model, although the validation of the model as a whole is discussed in detail in section 5.

Many assumptions made regarding the expanded CIMERAW VW operation linked across these three assumption types. This can occur when an assumption of one type gives rise to an assumption of another type. Reference is made to these associations in Appendix 1.

3.3.2 Data Sources

The analysis techniques were intentionally defined before the formal data collection process began according to the recommendation given by Bowersox *et al.* (2013) so that the data could be matched to the technique (see section 3.1). The documented business, management and analysis assumptions similarly informed the choice of data sources [3]. However, the converse can also be said to be true, as the availability and quality of data sources also justified and thereby gave rise to simplifying assumptions.

The developed hybrid modelling technique and the documented assumptions gave rise to the following data requirements:

1. Historic number of orders placed, including each order's:
    1.1. Ship-to address city[9] (i.e. demand city or node)
    1.2. Product type (i.e. 32.5N or 42.5N)
    1.3. Package type (in order to exclude bulk cement orders from the dataset as per analysis assumption 2)
2. Straight-line distances from the production plant to each ship-to address city and between each ship-to address city (as per analysis assumption 17).
3. Agreed lead times as per CIMERWA/carrier service level agreements (SLAs) (as per analysis assumption 4).

The following were notable exclusions from the data requirements that were allowed by the documented analysis assumptions:

- The customer of each order (as per analysis assumption 13)
- The creation date of each order (as per analysis assumption 9)
- The planned and actual loading and offloading dates of each order (as per analysis assumptions 3 and 9)
- Actual road network distances between cities (as per analysis assumption 10)

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[9] Attempts to define the concept of a "city" can be problematic, especially in developing countries such as Rwanda where the boundaries of metropolitan, rural settlements and general regions are often misunderstood and not correctly considered when geographic information is entered on systems. Furthermore, the levels of granularity of address data (i.e. differentiation between street number and name, suburb, city, district, province and country) are often not correctly used when data is captured. The data available and consideration of the primary objective of the project provided the basis for only modelling the demand for delivered cement at a city level of granularity.

The cities were defined according to how they existed on the TMS dataset. This resulted in some defined areas of demand being suburbs of others. This was especially evident with respect to city of Kigali. "Kigali" was the value entered as the delivery city for most orders dispatched to the capital city, but many of Kigali's suburbs' names also existed on the TMS as drop-off location city values.

It was assumed that this additional granularity would only serve to increase the validity of the model, as it allowed more accurate distances between the demand points to be calculated. However, it was also assumed that the absence of this granularity would not invalidate the results and no exercise was undertaken to translate city values of "Kigali" to the names of the suburbs in which the delivery points were positioned.

3.3.2.1 BluJay TMS

Data generated from CIMERWA's use of a TMS, developed by BluJay Solutions, was the primary dataset used to model the operation. This cloud-based system is integrated with CIMERWA's ERP, SAP, on which sales orders for customers and stock transfer orders for VW loads are entered. The entry of an order for delivered cement on SAP triggers the upload of a transport order to the TMS via electronic data interchange (EDI) in real-time. Cancellation of an order on SAP also triggers an order deletion message to the TMS, which voids the TMS order. Orders for collection were excluded from integration to the TMS as the logistics office is not responsible for arranging transport for these orders.

These three features of the integrated solution used by CIMERWA's logistics office support the claim that TMS data represented demand for delivered cement to a high degree of accuracy. As delivery is the only order shipping type relevant to the CIMERWA VW operation (see business assumption 5) and was the only shipping type in scope for the modelling exercise (see management assumption 6), it follows that this integration ensured that the TMS was a viable data source for the hybrid mathematical model.

The TMS is not the source system for customer or order data. As per standard business practice, CIMERWA's ERP is the primary system for order management. It could therefore be argued that SAP, not the TMS, should have been selected as the primary data source for this modelling project. However, the TMS's focused use as a transport planning, execution management and settlement platform produced data that was, in some respects, a better representation of the reality of CIMERWA's logistical activity than SAP.

While some data, such as carrier payment amounts, was transmitted back to SAP via EDI, much of the operational data that is captured on the TMS and provides the view of CIMERWA's outbound logistics was not reflected on SAP. The most pertinent example of such data is the ship-to addresses, both on the customer master data (see data requirement 2) and historical transactional data (see data requirement 1.1).

First, a CIMERWA sales agent could insert an order's or new customer's ship-to address to SAP incorrectly, either by entering the incorrect city for the ship-to address, capturing the incorrect province for the city, misspelling the city or failing to capture the address at the required level of detail (e.g. entering the geographic region as the city). This information is validated by the TMS upon order entry via EDI and by the logistics planners as part of their order management process. Any corrections made at this point of the order-to-delivery process are made directly on the TMS and might not have be replicated on SAP, which resulted in the TMS containing the most accurate set of CIMERWA's customer ship-to address data.

Second, the destination of an order can be changed through direct communication with the logistics office after order transmission from SAP to the TMS. The delivery location is subsequently changed on the TMS to ensure that the carrier was paid according to the actual, not planned, destination and the driver was informed of the new address. Again, this information may not be updated on SAP. This results in the TMS being a more accurate record of the actual geographic locations to which CIMERWA delivered cement. The TMS was therefore preferred to SAP as the primary source of data for modelling the CIMERWA distribution network.

The quality of the TMS data was ensured by its central role in the transportation settlement process. The TMS is used as the master record of CIMERWA's agreed contract transport rates and the primary system of record of rates for planned, in-execution and completed deliveries. Carrier payment values are derived from the TMS to support the creation of purchase orders (POs) by CIMERWA's finance team and invoices by the carriers. Inaccurate data therefore has a financial impact for CIMERWA and supplier alike and TMS transactional data is subject to a high degree of continued scrutiny and control by operators representing both parties.

3.3.2.2 Google Maps

CIMERWA's full truckload sales model (see management assumption 5) precludes the planning of loads that involve drop-offs at more than one destination. This greatly reduces the opportunity for route optimization, and, by extension, the level of sophistication required of the logistics office in terms of load planning. This, in turn, shaped the data that has been accumulated through use of the TMS.

Rates for full truckloads transported over large distances are typically defined as flat values per lane (i.e. combination of origin and destination city). CIMERWA follow this rating model. Optimization of outbound transport therefore consists of selection of the best carrier to execute a load according to the carriers' transport rates for the lane of the load. As such, only a load's origin and destination cities need to be defined in order to optimize transportation cost and the longitudes and latitudes of the delivery locations are not required. CIMERWA's TMS master data therefore excludes detail that is often included in the master data of other deployed TMSs[10], that being the GPS coordinates of stop locations (see data requirement 2).

[10] Logistics operations that support less-than-truckload deliveries over short distances typically require exact positions of delivery points in order to optimize order consolidation and stop sequencing.

It follows that an alternative data source was required for delivery location longitude and latitudes. Such a dataset did not exist at the time of collecting data for the hybrid modelling exercise. As such, a geocoding exercise had to be undertaken. Due to the small number of ship-to cities and the inhibitive cost of bulk geocoding software, this exercise was performed manually using the Google Maps web application.

3.3.3 Data Time Range

Integration of the BluJay TMS with CIMERWA's production SAP environment went live on 5 March 2018. This deployment was subject to a three-week post go-live stabilization period. This entailed detailed daily validation of transmitted SAP orders and modification of the SAP and the TMS configurations, as well as the code that controlled the interface between these two systems. Changes were also made to the designed workflow during this period to better align the business process to the integration rhythm. These activities resulted in some manual intervention on the systems. While the risk that this intervention compromised the validity of the data was considered to be low, especially considering that carrier payment for loads, a process dependent on good quality SAP and TMS data, was successfully completed after this period, it was recognized that the quality of TMS data generated after stabilization would be higher than that generated during stabilization.

Furthermore, one of the two cement mills at the production plant was under scheduled maintenance during this system stabilization period, which resulted in *ad hoc* underproduction and a severe backlog of orders awaiting stock allocation and delivery. Inclusion of data for this period would have therefore introduced an outlier that would have to be managed, which would have been problematic considering the modelling decision to exclude periodic fluctuations in demand for transport from the hybrid mathematical model (see analysis assumption 9).

Consideration of the unusual business conditions that existed during this time, coupled with the described concern regarding the effect of stabilization activities on the validity of TMS data generated during this period, meant that historic data for this period was excluded from any analysis. As the time period of the simulation was chosen to be one year, TMS data generated over a period of one year was utilized. As such, the historic TMS data used for developing the hybrid model represented CIMERWA's cement distribution from 1 April 2018 to 31 March 2019. This was retrieved directly from the online TMS platform by means of an *ad hoc* Excel spreadsheet report.

3.3.4 Data Retrieval

TMS data for CIMERWA's logistics operation during the selected time period was extracted as an *ad hoc* Excel spreadsheet report. The TMS provides a reporting portal on which such reports can be built by the user. This process involves selection of a system data mart, selection of fields to be included in the report, reordering and renaming columns, configuration of filters and advanced sorting of the data. These steps were followed to produce a load performance[11] report that included the following columns:

- TMS load ID
- Order number for the original SAP order on the load
- Order number for the SAP order to which the load was diverted
- Package type
- Carrier name
- Load group
- Load status
- Order origination date
- Last drop[12] location reference
- Last drop location name
- Last drop location city

This consolidated report was not only used as a direct input to the two individual models, but to also generated the list of cities for which longitudes and latitudes were sourced using Google Maps.

3.3.5 Data Preparation and Cleansing

The modelling technique developed for the simulation of the expanded operation included two separate models linked by the output of one (i.e. the optimal VW locations generated by the network optimization model) that was used as the input to another (i.e. the Monte Carlo simulation model of the VW operation). It follows that the output of the optimization model required preparation for input to the Monte Carlo model. This data was validated as a verification activity of the optimization modelling exercise and required little transformation to fit it to the purposes of the second modelling exercise. This activity is addressed in section 5. The interpretation and transformation of this data such that it could be used by the operation simulation model is discussed as an optimization activity as it constitutes an output of the model as a whole. Cleansing and preparation of this data as an input to the simulation model is therefore discussed in section 6.

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[11] An order is built into a load on the TMS when stock is confirmed as available and the transportation planning process initiates. It follows that analysis of load data only encompasses fulfilled demand. Demand patterns were derived from TMS load data, not order data, which addressed the production capacity constraint (see analysis assumption 14). While the variation in the plant's production rate and order backlogs were not modelled, characterising the placement of orders using load data ensured that the number VW warehouse loads dispatched over the year did not reflect a volume of cement that could not be feasibly produced.

[12] The last drop location could be assumed to be the only customer delivery location of the load, as analysis assumption 11 states that only full truckloads are delivered by CIMERWA. If follows that only one drop stop would exist for each load.

Externally sourced input data (i.e. TMS data and city longitudes and latitudes) was required for both components of the hybrid model (see section 3.3.2). The bulk of this data was generated by the use of an operational system (i.e. the TMS) for a specific purpose. The condition of TMS data, while being appropriate for the purposes of managing CIMERWA's transport, was not immediately suitable for the developed mathematical modelling technique. Some preparation (i.e. filtering transactions that are out of scope for the exercise, etc.) and cleansing (i.e. removal or correction of outliers) of this dataset was therefore required.

The TMS *ad hoc* report, including the product per order looked up from an order extract, was prepared as the primary input data set for the hybrid mathematical model. The data preparation and scrubbing actions taken were sequential and differed for each data requirement. These sequences of steps are therefore presented separately in Appendix 2.

3.3.6 Data Validation

Data that is inputted to a model to define the characteristics of the system should be validated prior to the development of a mathematical model. The technique developed for investigating CIMERWA's expanded VW network consisted of two separate mathematical models linked by the results of the first being used as an input to the second. It follows that the second component of the hybrid model, namely the Monte Carlo simulation model, required data that was generated within the hybrid model (i.e. the optimal VW networks). This data could therefore be classified as both output and input data for the mathematical model and the verification and validation of the optimization model simultaneously validated the VW networks fed to the Monte Carlo model. It was decided to address the validation of this data as a set of results, not as an input dataset. This section therefore only addresses the validation of datasets external to the hybrid model.

Bowersox *et al.* (2013) recommended that sensitivity analysis be conducted once the analysis technique is complete to evaluate the impact of data accuracy on the results. This is a powerful method of validating the data quality relative to the requirements of the technique. If the analysis shows the technique to be highly sensitive to a certain set of the input data, additional focused effort can be expended on improving that input data [3]. This validation activity, however, was not undertaken due to a high degree of confidence in the inherent quality of the TMS data used and the other validation checks that were followed.

3.3.6.1 Validating Transactional Volumes

As discussed, the transactional data of TMS was pre-existing and considered pre-verified by the transportation planning and, more importantly, settlement process. Nonetheless, checks were conducted on the cleansed consolidated *ad hoc* TMS report to validate this data. These involved a comparison of the number of tons reflected on the spreadsheet per month to those reported by the business using data drawn directly from CIMERWA's ERP.

While differences did occur between the TMS and ERP volumes per month, this was due to the movement of orders' loading dates performed on the TMS that were not reciprocated on the ERP (see section 3.3.2.1). This resulted in the same orders reflecting for different months on each system. The systems' respective values for the total volume of delivered cement over the seven months analysed, however, showed only differed by 0.56%[13]. The small degree of variation was deemed insignificant enough to validate the transactional volumes.

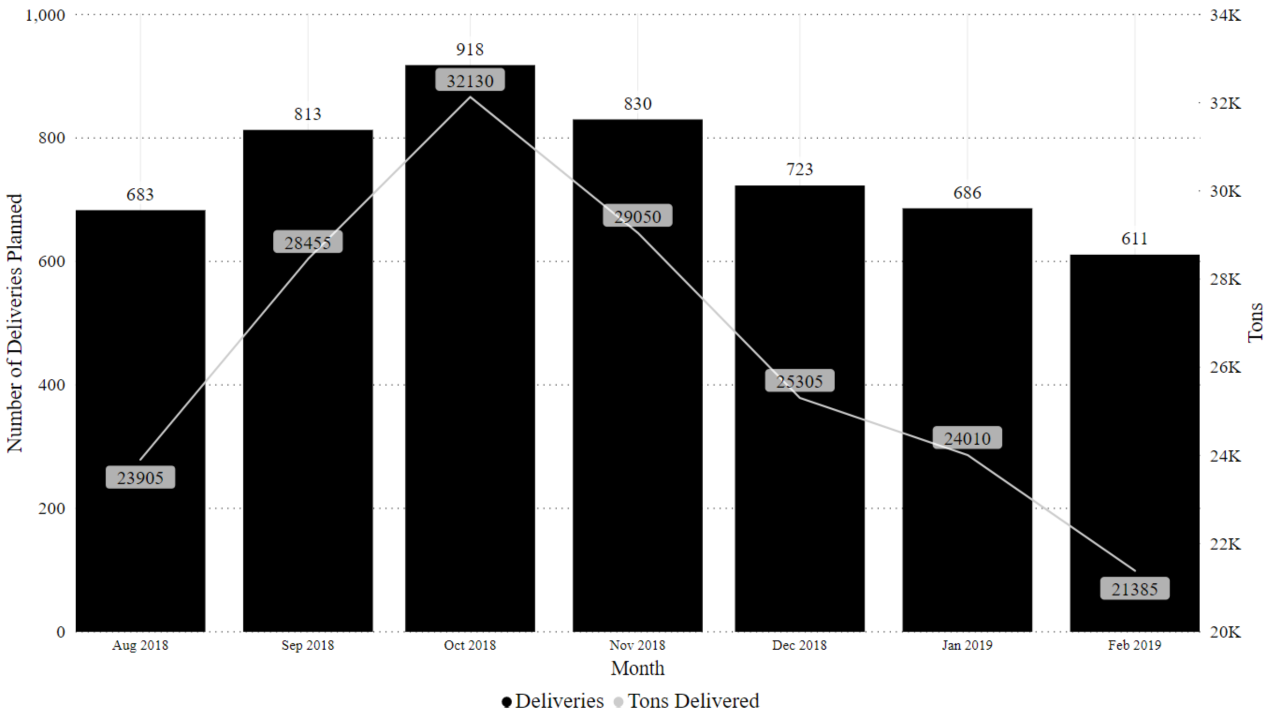
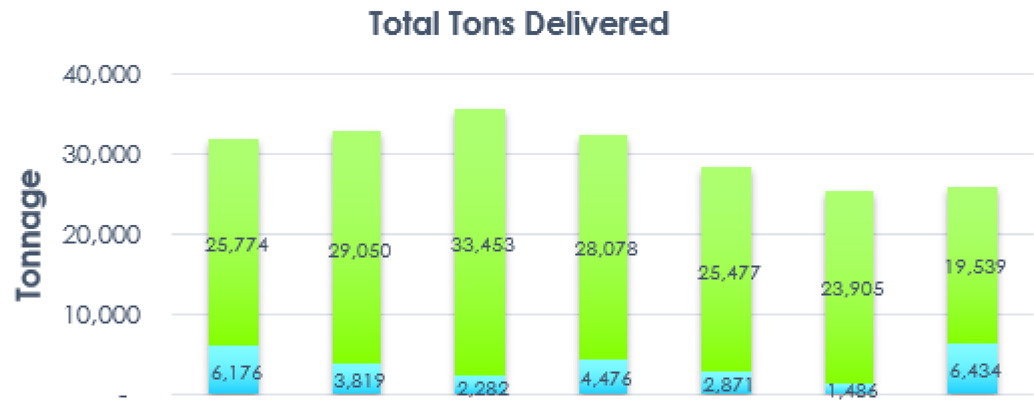


Figure 8: Deliveries and tonnages planned from August 2018 to February 2019

[13] A total of 185 276 tons of cement were delivered from 1 August 2018 to 28 February 2019 according to SAP. The TMS showed a total of 184 240 tons delivered during this same period.



	Aug-18	Sep-18	Oct-18	Nov-18	Dec-18	Jan-19	Feb-19
Delivered Tons	25,774	29,050	33,453	28,078	25,477	23,905	19,539
Own Collect Tons	6,176	3,819	2,282	4,476	2,871	1,486	6,434

Figure 9: Excerpt from a CIMERWA SAP report showing ERP generated delivery volumes from August 2018 to February 2019

3.3.6.2 Validating City Co-ordinates

The ship-to address city values were extracted from the TMS and verified during the city master data preparation steps. The longitude and latitude values per city, however, had been collected manually as part of the data collection process. This dataset was therefore more susceptible to errors than the transactional data and required a more intensive validation process.

The following checks were executed on the city co-ordinates:

1. The province values for existing stop locations on TMS with each city value were retrieved.
2. The province for each stop location city value was determined[14] .
3. The city locations were then visualized using the captured longitudes and latitudes on a Microsoft Power BI map, on which the boundaries of the Rwandan provinces are visible. Each city was isolated to verify that the position specified by the city's co-ordinates specified a location in the correct province (see Figure 10a).
4. The city locations were visualized on a different Power BI map using Power BI's in-built geocoding function that retrieves the location of cities based on their names (see Figure 10b).
5. Each city's positions on each visual were compared.

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[14] There were cases in which there were TMS stop locations with the same city value but different province values. These were investigated further and corrected as needed.

6. The cities for which the positions on the two Power BI maps differed significantly were investigated further and errors were corrected on the ship-to address city master data.

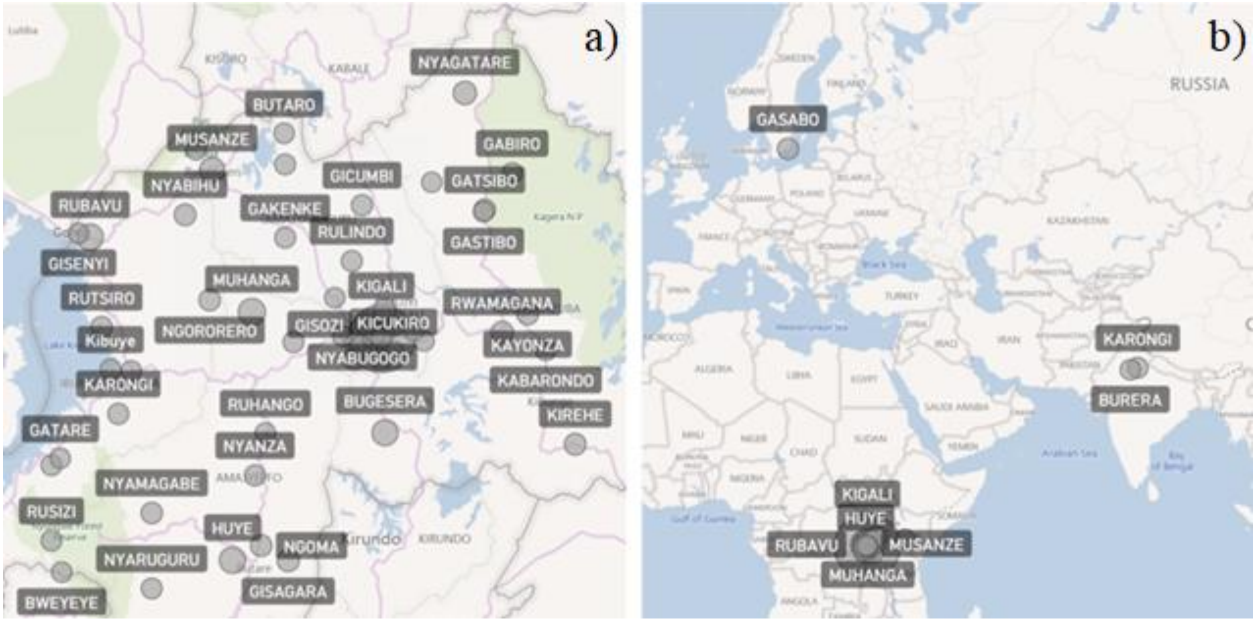

Figure 10: CIMERWA's delivery cities visualized with a) the manual Google Maps method and b) the automatic Power BI method for obtaining longitudes and latitudes

Any corrections made to the city coordinates would invalid the distances calculated and fed to the city master data and the transactional data. The linkage between these datasets using Excel lookup formulae ensured that these datasets were automatically updated when city names and coordinates and were modified.

3.3.6.3 Validating Distances

Visual inspection using Power BI was also used to validate the distance calculations for the linkages between each delivery city. The distances were calculated as straight-line distances (see Equation 1) as a simplifying assumption (see analysis assumption 10). A flow map visualisation was used to graphically depict vehicle movements from the CIMERWA production plant to every delivery city as well as linkages between the cities.

The data validation exercises were intentionally sequenced such that the distances were checked after these recalculations were performed. This type of Power BI visualization accommodates the representation of an additional variable as the thickness of the line connection between two geographic points. This was used to incorporate the straight-line distance value calculated for the distance matrix to every corresponding link on the flow map. A random sample of links were selected for analysis. The relative width and length of each link was considered. If a short link was represented with an unduly thick line, this represented a possible miscalculation that resulted in an overstated distance. Conversely, if a long link was relatively thin, the distance may have been understated on the distance matrix.

Consider Figure 11. The flow map for a random sample of cities shows no obvious candidates for investigation as the thickness of the lines correspond to their lengths. For example, the short line between Butaro and Burera is thin, indicating that the calculated straight-line distance on the distance matrix is relatively small. The link between Muganza and Gabiro, however, is represented by a much longer line. This line is also thicker, indicating a larger calculated distance on the matrix. This is the expected result and neither of these distances nor the records on the distance matrix were investigated.

A view of the distance matrix data further validated the conclusion that these two distances are valid. The straight-line distance value for Butaro to Burera is 9.60 kilometres, while the value for Muganza to Gabiro is 206.16 kilometres.

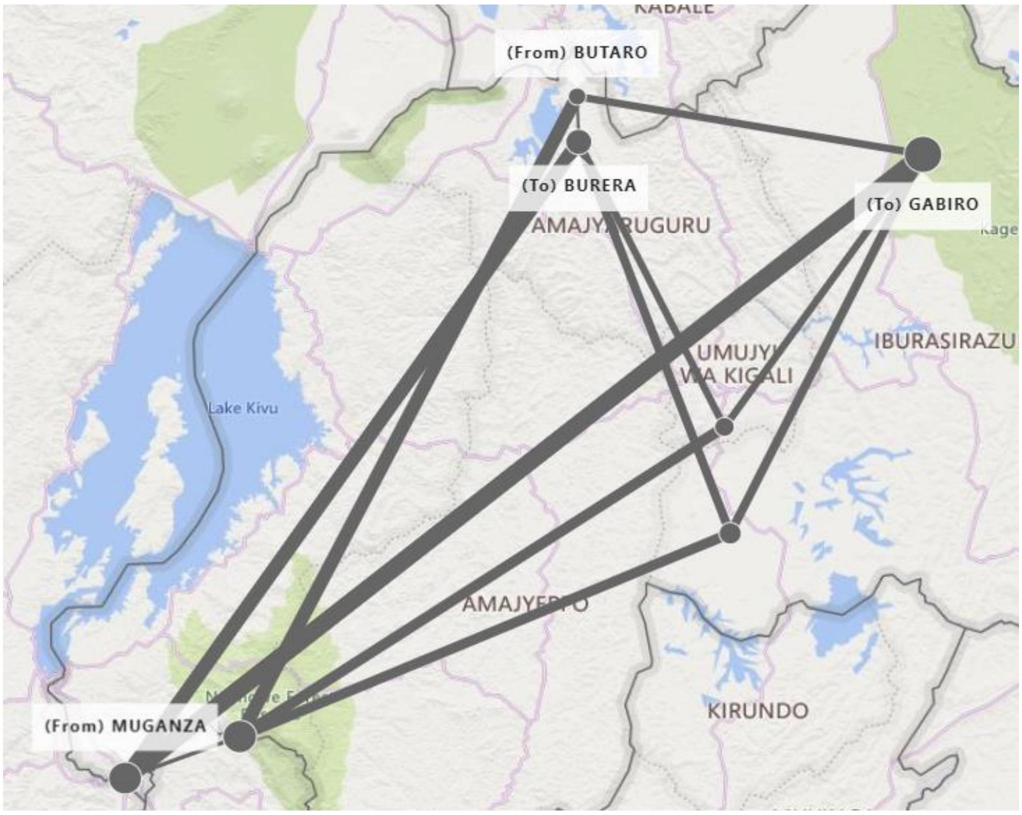

Figure 11: Flow map of a sample of CIMERWA's delivery cities showing linkages with widths proportional to the calculated distance

4. Model Development

The technique developed to address the primary objective included the separate development of two mathematical models, linked by the optimal VW networks that would be generated by the first model and used as an input to the second (see section 3.1). The development of each of the models are addressed separately in this section.

4.1 Network Optimization Model

The first component of the hybrid mathematical model was an optimization model. The placement of VWs within CIMERWA delivered cement distribution network was optimized for increasing degrees of expansion of the VW network.

The model was executed multiple times to determine the optimal network for different numbers of VWs introduced to CIMERWA's VW operation. Modification of the design of the optimization model was not needed to incorporate a change in the number VWs to be optimally positioned by the model. The number of network VWs was defined as a single constraint parameter that could be changed before each run of the optimization algorithm. The rules that governed the behaviour of the algorithm therefore remained consistent and the following descriptions thereof were equally applicable to each run of the model, despite the difference in the positions and number of VWs observable in the results for each run.

LP was the technique used to achieve the optimization. The LP calculations were performed by the optimization engine of an APS. The APS front-end was used to model the relevant segment of the supply chain in which CIMERWA operates and thereby define the parameters of the problem solved by the engine.

4.1.1 Linear Programming Formulation

Winston (2004) described three components that are common to all optimization models, namely the objective function, decision variables and constraints [15]. If fully and correctly defined, these three components provide the necessary model parameters for an optimization algorithm to determine the optimal values required. Each component is typically represented as a set of mathematical equations. These equations can be used manually in conjunction with the simplex algorithm to solve the optimization problem[15] or translated into a modelling system's syntax, such as LINGO, such that the system's algorithm can solve the problem.

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[15] Manual use of the simplex method is a slow process and is only feasible for exceptionally small optimization problems.

An APS does not require a user to define the optimization model using such mathematical expressions. It leverages off the commonality of certain concepts present in many supply chain integration problems and provides the user with a more intuitive method of defining the three components of an optimization model using concepts such as shipment costs, production rates and sales prices. As the modeller graphically constructs the enterprise on the user interface and describes each supply chain echelon with data, the objective function, decision variables and constraints are automatically and invisibly defined for the optimization engine as a set of equations that can be interpreted by the APS' algorithm. A powerful optimization problem can thereby be modelled and solved without the user being aware that these three model components were defined or, indeed, that the concepts of decision variables, objective functions or constraints exist.

The CIMERWA distribution system was modelled directly using an APS and mathematical equations were therefore not required of the modeller to define the objective function, decision variables and constraints of the optimization model components. However, these three concepts provided a framework for analysing the problem to be solved. The three components were defined in words, not equations, such that the method for incorporating the assumptions defined for the hybrid model into the network optimization model were established. This formulation clearly stated the principles by which the model would be governed and thereby informed the construction of the APS model and the configuration of its various objects (i.e. EO's purchase, conversion, inventory and sales objects). The formulation of the three components of the model are described in Appendix 3.

4.1.2 Supply Chain Model

The objective function, decision variables and constraints were developed as a conceptual model to clarify the basic principle of the network optimization model. They were not programmed as an optimization problem as described in Appendix 3. An APS was used to model the distribution network as a supply chain such that the abovementioned three model components were specified using the APS's concepts. The solution space and objective were thusly defined for the APS optimization engine, which was used to generate the optimal business model for the modelled supply chain.

River Logic EO was selected as the APS for developing the network optimization model. Appendix 4 discusses the use of EO supply chain modelling framework to model the CIMERWA VW operation and define the objective function, decision variables and constraints.

4.2 Operation Simulation Model

The output of the CIMERWA VW network optimization model described above constituted an important input to the Monte Carlo model used to simulate the expanded VW operation. It follows that the network optimization model was first verified, and its results analysed and prepared as collected data before the simulation model was run.

However, the sequence of this document follows the seven-step process as prescribed by Winston (2004) (see Figure 7), as opposed to the order that describes chronological performance of the modelling activities. The network optimization model and the operations simulation model both formed components of the hybrid mathematical model and, as such, the development of both these models are addressed in this section even though their development was separated by a substantial amount of model verification and data analysis and preparation.

Nonetheless, the VW networks generated by the optimization model did directly inform some simulation modelling decisions. As such, although effort was made to describe the development of the operations simulation in terms of a framework that was independent of the results of the EO model, some reference is made to the candidate VWs and their catchment areas recommended by the optimization model for each increment of the number of VWs utilized.

The Monte Carlo simulation method is predicated on the generation of pseudo random numbers and random variates that replicate the stochastic parameters that affect system performance [20]. These numbers are first generated according to probabilistic distributions and then used by the model as self-generated input. This data, combined with other static input quantities, some of which represent the independent variables of the simulation model experiment, defines the temporary state of the system for the following stage of the optimized time period. The logic built into the model then interprets this state and simulates a course of action taken by decision makers, either people or systems. The decision affects the state of the system for the next stage, which when combined with a newly generated set of random variates and static input data, describes the state of the stage that is again interpreted by the model logic. As this cycle repeats, output quantities are collected per time period and metrics of interest calculated such that repetition of the model using different values for the independent variables reveals the values for the changeable parameter that optimize system performance.

A simplified graphic representation of this principle is given by Cordero *et al.* (2012), which divides a Monte Carlo simulation model into three distinct components, namely input quantities, the model (i.e.

decision logic) and the output quantity. The development of the VW operation simulation model is described in terms of these three concepts in Appendices 5, 6 and 7.

The CIMERWA VW operation was simulated as a multiple time period (MTP) model. The output quantities of this model comprised of the running totals calculated values that were updated after each time period (i.e. simulated day of operation). The output quantities produced for each time period had an influence on the state to which the system transitioned for the subsequent time period. The output of time period t can therefore be said to be an input quantity of period $t + 1$. There was therefore a feedback loop from the output quantity to the logic that was not shown in the schematic presented by Cordero *et al.*, but was added to give Figure 12.

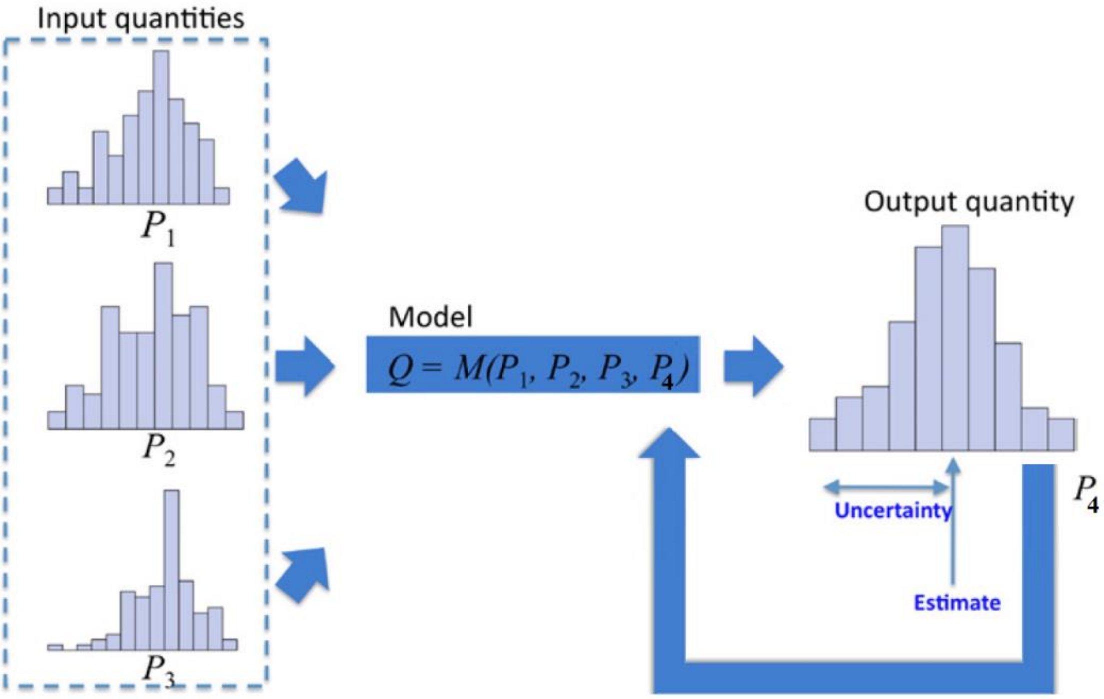

Figure 12: Monte Carlo-based technique adapted to show feedback of output quantities into the model

5. Model Verification and Validation

The hybrid mathematical model that was developed to support the primary objective of the project was verified[16] prior to the collection of results. As the hybrid model was comprised of two separate models, with the output of the first providing an input to the second, the verification of each model took place at different stages of entire modelling process. It follows that the model was verified by two different activities, one for the verification of the network optimization model and one for the operation simulation model, separated by a substantial amount of model development. These activities are jointly presented in this section, however, as the document is structured to replicate the seven-step process presented by Albright *et al.* (2005) [21] for the mathematical model as a whole (see section 3.2).

Sargent (2013) identified four distinct types of verification that can be performed during the simulation modelling process (see Figure 13), namely theory validation, conceptual model validation, computerized model verification (i.e. specification and implementation verification) and operational validation [37]. These classifications provide the framework for the discussion of the verification of the hybrid CIMERWA mathematical model. Some of the verification to which Sargent (2013) referred was discussed in Appendices 5, 6 and 7.

[16] While the terms *verification* and *validation* have distinct meanings, these modelling activities are often performed in unison to prove the model to be valid. The term verification is used in this document when referring to both verification and validation in order to align to the terminology used by the seven-step modelling process [21].

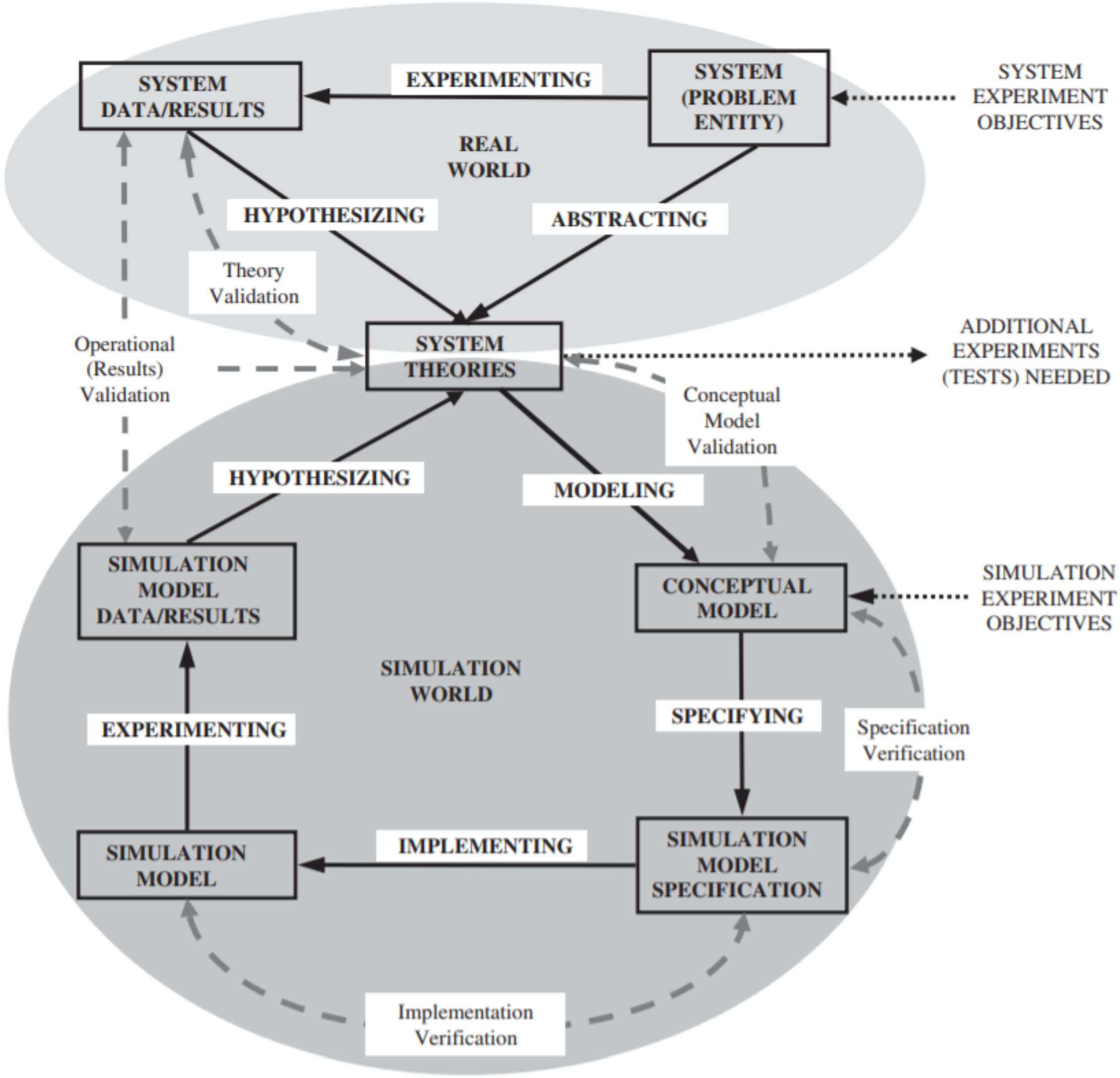

Figure 13: Real world and simulation world relationships with verification and validation [37]

5.1 Theory Validation

System theories "describe the characteristics and the causal relationships of the system (or problem entity) and possibly its behaviour (including data)" [37]. Manipulation of the real system and observation of the effects of these modifications is required to validate the theories on which the conceptual model is based [37]. However, such manipulation was beyond the control of the modeller for the modelling of the CIMERWA VW operation.

Sargent (2013) specified that if system theories cannot be validated due to the existing system's inability to be modified for experimentation due to the nature of the system or the cost associated with such changes, then the theories remain as proposed system theories [37]. The assumptions, modelling decisions and coded logic of the hybrid mathematical model were therefore classified as such. The set of system theories used for the VW operation conceptual model, however, corresponded closely to the concepts that were validated as part of the conceptual model validation using the described techniques. The closeness of the association between the theories and concepts for this project meant that the validity of the results was not endangered by the use of proposed system theories.

5.2 Conceptual Model Validation

Conceptual model validity refers to the correctness and reasonableness of 'the theories and assumptions underlying the conceptual model and the model's representation of the problem entity and the model's structure, logic, and mathematical and causal relationships' (Sargent 2013, p17). With respect to the CIMERWA VW modelling exercise, this refers to the validity of the business, management and analysis assumptions documented for the project and by extension the modelling decisions made based on the real-world operation being simulated and the model's input quantity, decision and output quantity logic.

Each of these concepts was validated before being modelled. This type of validation was therefore performed during the model development step of the seven-step process and each instance of such validation is discussed in the section in which the concept itself is discussed. Validation techniques included historical data validation (see business assumptions 3, 10 and 15 and analysis assumptions 18 and 19) and data plotting (see business assumptions 6 and 11). The modelled transit time per VW was validated using both these techniques.

Face validation with CIMERWA logistics experts was used as the primary method of validating these concepts if they did not lend themselves to numerical analysis. Each expert was presented with the documented assumptions, which were confirmed as valid. Face validation of each assumption, modelling decision and coded logic can therefore be assumed and is not explicitly mentioned for each concept.

5.2.1 Computerized Model Verification

The CIMERWA VW operation was modelled using two software packages, namely River Logic EO for the network optimization components and Microsoft Excel for the operation simulation component. The manner in which the conceptual model was built into the EO and Excel model had to be verified.

Sargent (2013) classified computerized model verification approaches as either static or dynamic [37]. Static approaches such as correctness proofs and review of the structure of each model were exercised for each modelled facet of the two components of the hybrid mathematical model. Static verification of each computerized calculation described in Appendices 5, 6 and 7 should therefore be assumed. The selected dynamic approaches used for each model, however, are discussed below.

5.2.2 Network Optimization Model Verification

The software used for modelling the network optimization model (i.e. EO) is pre-verified by the software provider (i.e. River Logic) and the user interface used by the modeller does not provide access to the back-end code used for calculating the optimal solutions for the various scenarios (i.e. number of VWs) that were run. Nonetheless, a dynamic approach, namely checking for data relationship correctness, was used to verify the network optimization model's output to the highest level of detail allowed by the granularity of the accessible model-generated data.

The EO objects (i.e. purchase, inventory, conversion and sales objects) used to build the supply chain optimization model are associated with data tables. Data is entered on these tables to define the input parameters of the object and drive the desired behaviour of the model (see Appendix 4). These tables, however, also include columns that are not populated by the modeller but rather by the optimization algorithm after each run. These constitute the decision variable values selected by the algorithm that influenced the value of the objective function.

While the set of output columns differs between tables, there are two such columns which are common to all tables:

- The "Total Solution Units" column, which indicates the number of units of material purchased, moved, converted, stored or sold as chosen by the optimization engine.
- The "Total Cost" or "Total Gross Sales" column, which is populated with the product of the "Total Solution Units" and the cost or price per unit value set by the modeller prior to the run.

The multiplication of the "Total Solution Units" value with the cost or price per unit value was inspected using Excel. The purchase activity table on the purchase object, the sort yield table on the purchase-to-inventory link, the inventory activity table on the inventory object, the distribution yield table on the inventory-to-sales link and the sales activity table on the sales object were exported to Excel after two test scenarios were optimized by the optimization engine. An Excel formula was used to multiply the two columns and a subtraction formula was used to detect errors made by EO when calculating the costs and revenues associated its generated solution. No errors were found.

5.2.3 Operation Simulation Model Verification

Like EO, Excel is a pre-verified software package. It differs, however, in the closeness it provides the modeller to the model logic. While EO executed calculations in a back end, the Excel formulae that perform the calculations that represent the model logic are written by the modeller. This both necessitated and facilitated more extensive verification of the operation simulation model than the network optimization model.

5.2.3.1 Logic Verification (Trace Testing)

While the interpretation of formulae and processing of data using user-defined formulae is pre-verified, the way in which the formulae are written by the modeller is original and unique to the concept being modelled, unlike the formulae used by EO. The high degree of control enjoyed by the modeller when utilizing Excel for simulation modelling meant that the output of each intermediate step and each time period was available for verification purposes. This allowed for the use of trace testing to verify the operation simulation model.

Trace testing was described by Sargent (2013) as a verification process during which 'behaviour of a specific type of entity in a model is traced (followed) through the model to determine whether the model's logic is correct and if the necessary accuracy is obtained' (Sargent 2013, p17). For the purposes of verifying the operation simulation model, the VW was chosen as the entity. The activity associated with randomly selected VWs for randomly selected time periods[17] was tracked from the generation of random variates for the sales per city within the VWs catchment through to the calculation of the number orders fulfilled by the VW's trucks and the number of un-diverted trucks remaining at the VW.

Table 1 includes data from two trace tests, which were intentionally selected for inclusion as they represent relatively complex scenarios that had to be simulated by the Excel model:

1. The Kicukiro VW when only 32.5N strength grade cement was dispatched with a factor of safety of 0.9. Note that trucks standing overnight for each period *t* was added to the trucks arriving at the VW at period $t + 1$. Note also the lag in the arrival of the vehicles post-dispatch to account for transit time.
2. The Burera VW when 42.5N strength grade cement was dispatched with a downward adjustment value of 2, but only the forecast or 32.5N strength grade cement is used to determine the estimated number of trucked required to dispatch. Note that the solitary vehicle present at the VW on 2 May was diverted to fulfil the 42.5N order. The five orders for 32.5N cement remained unfulfilled and were satisfied using sales order loads of 32.5N dispatched from the factory. This ensured that the loss in margin resulting from using higher strength cement than necessary to meet demand was avoided.

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[17] The lag between the dispatch and arrival of vehicles to and at a traced VW meant that an analysed time period had to be defined as the number of days required for dispatched vehicles to arrive at the VW.

Table 1: Trace test data

	Trace Test 1			Trace Test 2			
Date	**1 May 2017**	**2 May 2017**	**3 May 2017**	**1 May 2017**	**2 May 2017**	**3 May 2017**	**4 May 2017**
Un-Diverted Trucks at VW	0	0	3	0	0	0	1
32.5N Orders Forecasted	9.5	9.77	9.63	1.73	1.71	1.81	1.76
42.5N Orders Forecasted	-	-	-	0.33	0.32	0.34	0.33
Est. Req. Trucks to Dispatch	8.55	8.78	8.66	2.07	2.03	2.16	2.09
Trucks Dispatched	8	8	5	1	1	1	0
Trucks Arrived	8	8	8	1	1	1	1
Trucks Present	8	8	11	1	1	1	2
32.5N Orders Placed	18	5	7	1	5	0	0
42.5N Orders Placed	-	-	-	0	1	0	0
32.5N Orders Not Fulfilled	10	3	0	0	5	0	0
42.5N Orders Not Fulfilled	-	-	-	0	0	0	0
Orders Fulfilled from Other VWs	0	0	0	-	-	-	-
Trucks Diverted to Overlapping Demand	1	0	0	-	-	-	-
Trucks Diverted for Alternate Strength Orders	-	-	-	1	0	0	0
Trucks Standing Overnight	0	3	4	0	0	1	2

5.2.3.2 Random Variate Verification (Historical Data Validation)

As arguably the most important input data to either component of the hybrid mathematical model, the output of the random variates had to be verified. While trace validation provided an effective method by which the model logic could be tested, analysis of randomly selected time periods did not provide the modeller with the required view of the statistical distribution of the random variate values generated by the model. Aggregations of these values for multiple runs of the model were therefore collected and compared to the historical data that provided the probability distributions that were coded for the generation of the random variates[18].

If a high degree of correlation between the model and historical data per combination of delivery city or VW and cement strength grade (i.e. category), the random variate generation for the category was deemed verified. Due the high number of categories by which the random variate values could be aggregated, random samples of categories were selected for analysis. 10 sample values were collected per category and compared to the value observed for the category in the historical data. Table 2 includes such verification data for three example categories that were used to verify the model's random variate generation.

Table 2: Random variate verification

Category	**Historical Deliveries per Annum**	**Random Variate Deliveries per Annum (10 Sample Values)**		
		Minimum	**Maximum**	**Average**
Demand node: Bugesera City Strength grade: 32N	318	278	350	312
Demand node: All Strength grade: 42N	987	801	1048	955
Demand node: Huye VW Strength grade: All	704	620	732	681

[18] Although analysis of large quantities of output data is more commonly considered a validation technique, exercise was focussed on checking the code responsible for generating variable values. As a pseudo random number generator or random variate generator produces different values for each iteration of the model, this type of high-level analysis was the only dynamic method by which the random variates could be verified.

5.3 Operational Validity

The verification of the computations involved a both low-level inspection of the modelled parameters, rules and formulae defined for the two components of the hybrid mathematical model themselves as well as the data they produced. Analysis at this level of granularity thusly tested that the proposed system theories and conceptual model in code was specified and implemented correctly in code by checking if each individual calculation produced the correct results[19].

Due to the high number of time periods simulated and hence the large number of calculations performed as each model was run, a random sample of calculations often had to be selected for analysis, which meant a full picture of the behaviour of the model was difficult for the modeller to construct during verification. As such, higher-level analyses were required after the computerized models were verified to validate the models.

Winston (2004) described validation as the process of checking that the model is 'an accurate representation of reality' (Winston 2004, p5). Sargent (2013) recognized that most of the model's evaluation takes place during this step and that is generally used to detect errors made in previous steps of the modelling and verification process. Validation was therefore conducted as the last step before each component of the hybrid mathematical model was run and results collected for analysis. The nature of each component of the hybrid model and the questions they were intended to answer were considered when each validation technique was selected.

Sargent (2013) classified operational validation approaches as either objective or subjective and provides guidance in terms of the set of techniques to be used for each of these approaches for both observable and non-observable systems. Kalman (1960) described an observable system as one for which the input variable values can be determined from a 'limited set of measured variables in finite time' (Aguirre 2018, p2). The modelled CIMERWA VW system can therefore be described as an observable system. For such systems, Sargent (2013) recommended comparison using graphic displays and exploring model behaviour as subjective approaches and comparison using statistical tests and procedures as the objective approach.

Sargent (2013) recognized that the use of objective approaches is often not possible due to the statistical assumptions required for hypothesis testing that sometimes cannot be satisfied [37]. The assumption of

[19] The only verification activity that did not involve the checking of individual calculations was the random variate verification, which, due to the stochastic nature of the output, could only be checked by comparing large samples of the model's output to the historical data that the model was intended to replicate.

normality is given as an example of such a statistical assumption which could not be satisfied for the CIMERWA VW system. Daily delivery volumes were known to not follow a normal distribution.

Due to the abovementioned and other cited difficulties in conducting objective validation techniques, Sargent (2013) identified graphical analysis, a subjective method, as the most widely utilized method of validating operational results. As such, historical data comparisons and parameter variability–sensitivity analysis was used to explore both the network optimization and operation simulation models' output behaviours. Visual inspection of graphic displays that visualized the models' sensitivities to their input parameters was used to subjectively assess the validity of each of these components of the hybrid model.

5.3.1 Network Optimization Model Validation

The optimization of the VW placement was deterministic in nature. The absence of any stochastic variables defined for the linear programming model meant that results of the validation runs of the optimization engine did not significantly differ from those performed to collect the data that would constitute the final results of the project unless input parameters were deliberately modified for parameter variability–sensitivity analysis or the scenario that was optimized for the validation run did not form part of the scenarios used to generate the final results. Some of the results that were generated for validation and discussed below were therefore identical to the final results discussed in section 4.

5.3.1.1 Catchment Area Validation (Historical Data Validation)

Before any of the network optimization model's input parameters were adjusted for variability–sensitivity analysis, the optimization algorithm was run using the final input parameters for the optimal position of one, two, three, four and five VWs. The geographic positioning of the VWs was graphically represented on Power BI map visualizations alongside a heat map showing the geographic distribution of historical demand. The modeller's discretion was used to determine if the selection of VW positions by the optimization algorithm was sensible for each scenario.

Figure 14 shows two examples of the graphical comparisons made of the optimization model's outputs to the historical data. shows the cities located within the catchment area of the solitary VW activated by the optimization algorithm when the model was constrained to activating only one VW, shown as blue circles on the plot map. It also shows these cities overlap the geographic area of Rwanda with the highest density of demand for delivered CIMERWA cement, shown as dark blue on the heat map. The output of the model for that scenario was therefore deemed valid.

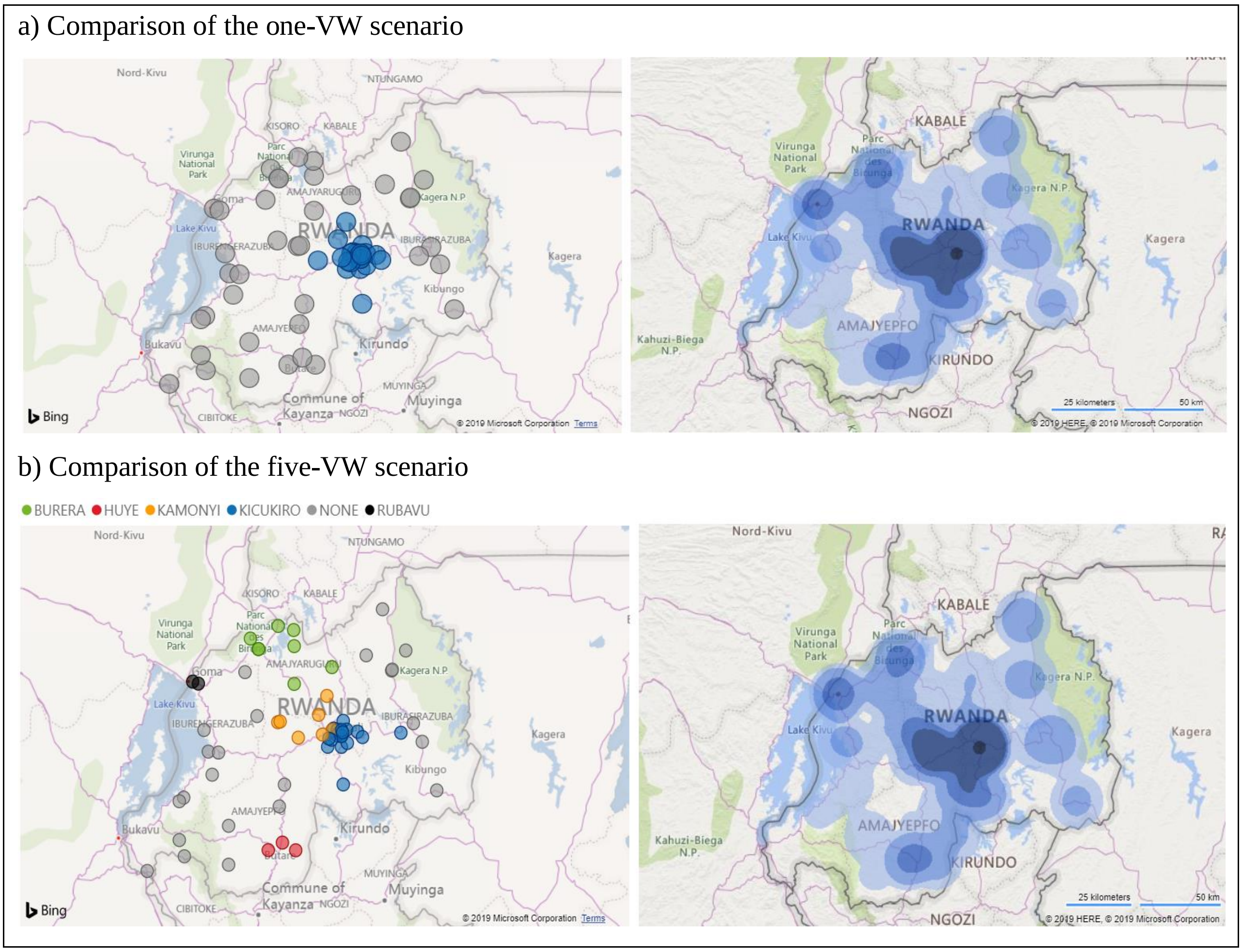


Figure 14: Comparison of the selected VW's catchment areas (left) for different scenarios to CIMERWA's historical demand density (right)

EO's placement of the solitary VW aligns with and validates the current practice of the CIMERWA logistics office. The currently used VW is located in Kigali due the high density of demand for delivered cement in Rwanda's capital city (see Figure 15).

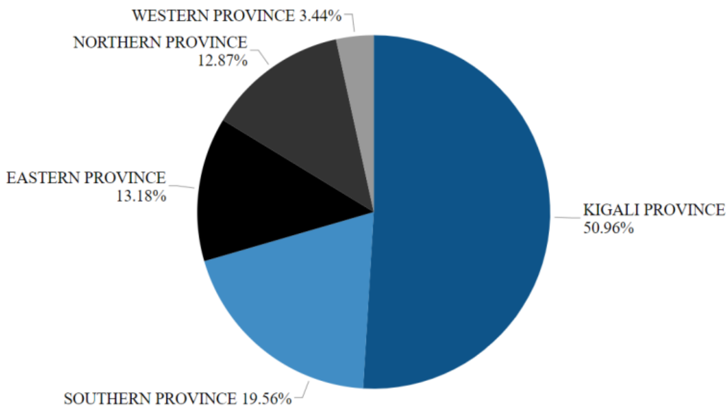


Figure 15: Percentage of deliveries per province

A similar comparison is demonstrated in Figure 14 for the five-VW scenario. However, the plot map represents the catchment areas of the VWs activated for when the model was run to optimize the placement of five VWs. Each colour on the plot map represents a different VWs catchment. Each VW was positioned such that the its catchment overlapped a demand hotspot. The optimal placement of VWs by the model for this scenario was therefore deemed valid.

5.3.1.2 Arbitrary Value Validation (Extreme Condition Testing)

The LP framework provided by the River Logic EO necessitates the selection of values for certain mandatory fields on the tables associated with the supply chain modelling objects used to build a model. Arbitrarily large or small values must therefore often be chosen when a model is not intended to be sensitive to the parameter. The selection of such values for the VW network optimization model is discussed in Appendix 4.

The boundaries of the EO model excluded the actual purchase of raw materials and business assumption 17 meant that the supply chain could be modelled such that the model would always attempt to fulfil an order via a VW as long as it was within the reach of the candidate VW. The purchase price was therefore selected as an arbitrarily small number and the sales price was chosen to be arbitrarily high to ensure the profitability of the delivery and drive the optimization algorithm towards fulfilling as much demand as possible. However, the sales price could not be larger than the arbitrarily high transport cost assigned to legs that represented movement of VW vehicles to outside their VWs catchment areas, lest the algorithm be incentivized to elect to fulfil demand from a VW that is out of reach of the VW and thereby maximize the objective function value.

These values were subjected to extreme condition testing, which not only validated the selection of the values themselves, but also the behaviour of the model as a whole. The model's optimization algorithm was run using various configurations of "low", "high" and "very high" arbitrary values for the purchase price, transport cost for legs beyond VW catchment areas and sales price and the results collected. The results were compared to those that would be logically expected. The actual results were found to correspond with the expected results and the model's arbitrary values and overall behaviour were therefore deemed valid (see

Table 3). All validation runs were performed for the five-VW scenario.

Table 3: Extreme condition testing sample data

Scenario	Purchase Price (RWF per truckload)	Beyond Catchment Cost (RWF per truckload)	Selling Price (RWF per truckload)	Units Purchased	Units Sold	Expected Result (Y/N)
Actual Model Values	1 (Low)	10^{11} (Very High)	10^{10} (High)	4907	4907	Y
Validation 1	10^{11} (Very High)	10^{10} (High)	1 (Low)	0	0	Y
Validation 2	1 (Low)	10^{10} (High)	10^{11} (Very High)	8544	8544	Y
Validation 3	1 (Low)	10^{11} (Very High)	1 (Low)	0	0	Y
Validation 4	10^{9} (High)	10^{10} (High)	10^{11} (Very High)	4907	4907	Y

5.3.2 Operation Simulation Model Validation

The operation simulation model component of the hybrid mathematical model was validated by graphical representation of the simulated activity at each VW and examination of the sensitivity of output values to modifications made to input values. The stochastic nature of the operation simulation model meant that increasing the number of runs of the model for each test would always further validate the model. The modeller’s discretion was therefore applied to determine the point at which the model was considered valid.

Due to the wide range of combinations of entities and scenarios that could be tested, the use of a broad set of combinations for the validation activity was preferred to repeated runs of the model using a single combination. An extensive number of runs of the model was therefore performed, although the parameters were often unique for each run. As such, much of the validation of this component of the hybrid model did not involve analysis of the statistical distribution of the results, even though the results were subject to variation.

5.3.2.1 Logic Validation (Operational Graphics)

The interpretation of the trace testing data in the manner described was onerous and therefore had to be performed selectively. The trace testing could therefore be said to be a verification of the logic, but not a validation of the output of the logic. As such, a streamlined method of reviewing bulk logic output was required to validate the logic.

The graphics of the operational activity at each VW provided for a more intuitive manual checking method and thereby allowed for the logic to be checked for all time periods for a run of the model for a VW. An example of logic that was checked using this method was the modelled lag of the arrival of vehicles at VWs after being dispatched.

Figure 16 represents a sample of simulation data that was validated using an operational graphic. The graph shows the number of trucks dispatched to the Butamwa VW per day as well as the number of trucks arriving at the VW daily for the month of July 2018. The number of trucks dispatched visibly corresponds to the number that arrived two days later. This corresponds to the modelled transit time for the leg from the CIMERWA production plant in Muganza to Butamwa (see Table 4). The application of transit time for that VW for that month was therefore deemed valid.

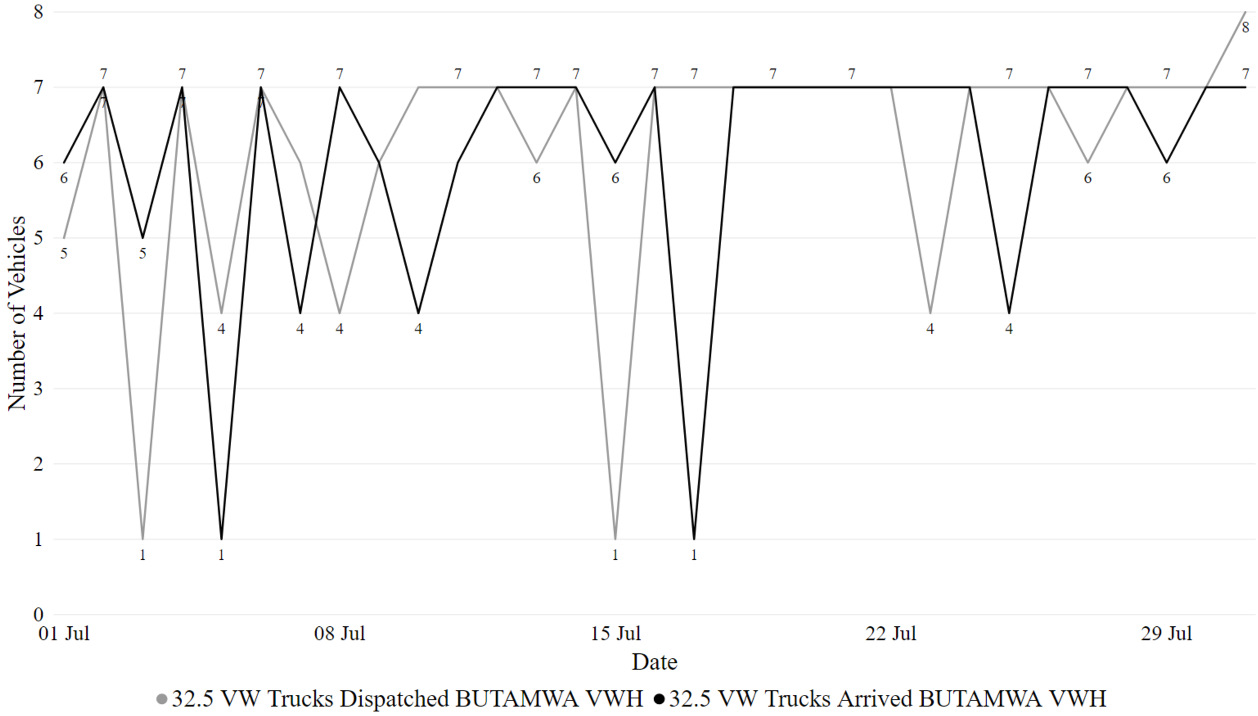


Figure 16: Validation of transit time

Figure 17 demonstrates an additional aspect of the simulation model that was validated using operational graphics. The number of trucks present at the Butamwa VW was a function of the number of trucks arriving from the production plant and number of trucks that parked overnight in the city. This graphic provided an efficient method of simultaneously checking the application of this logic for many periods.

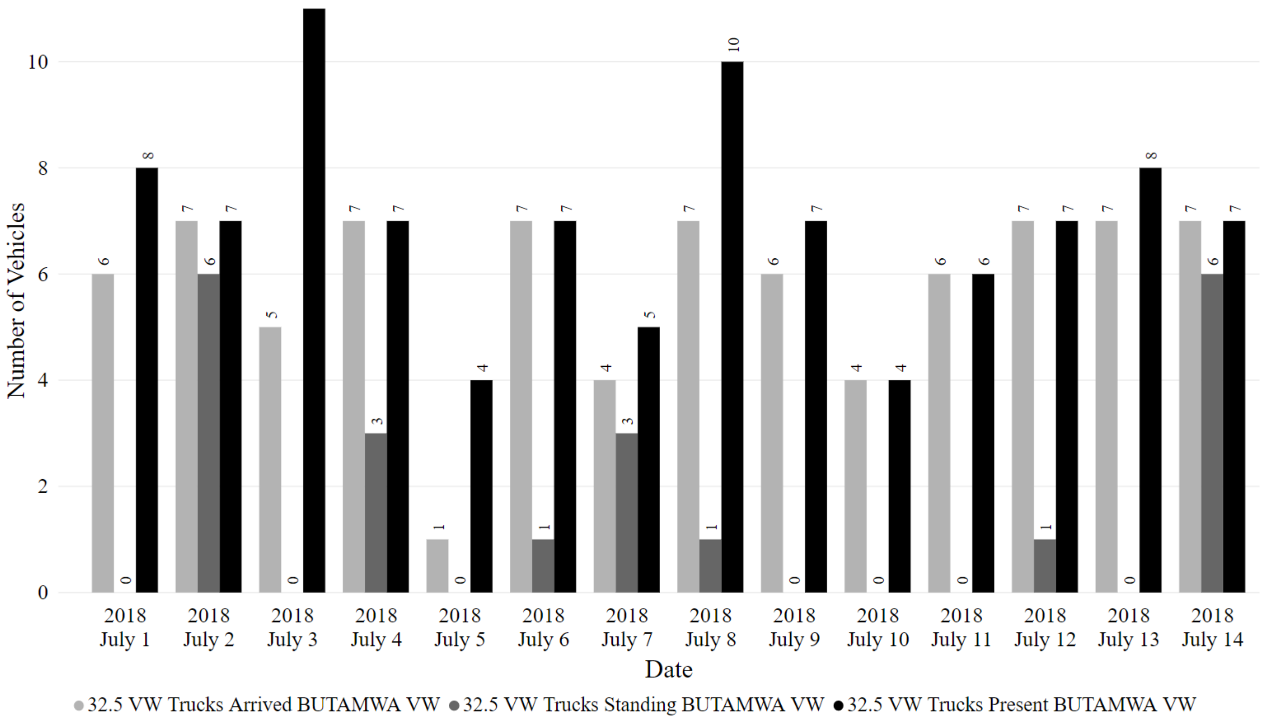


Figure 17: Validation of trucks present

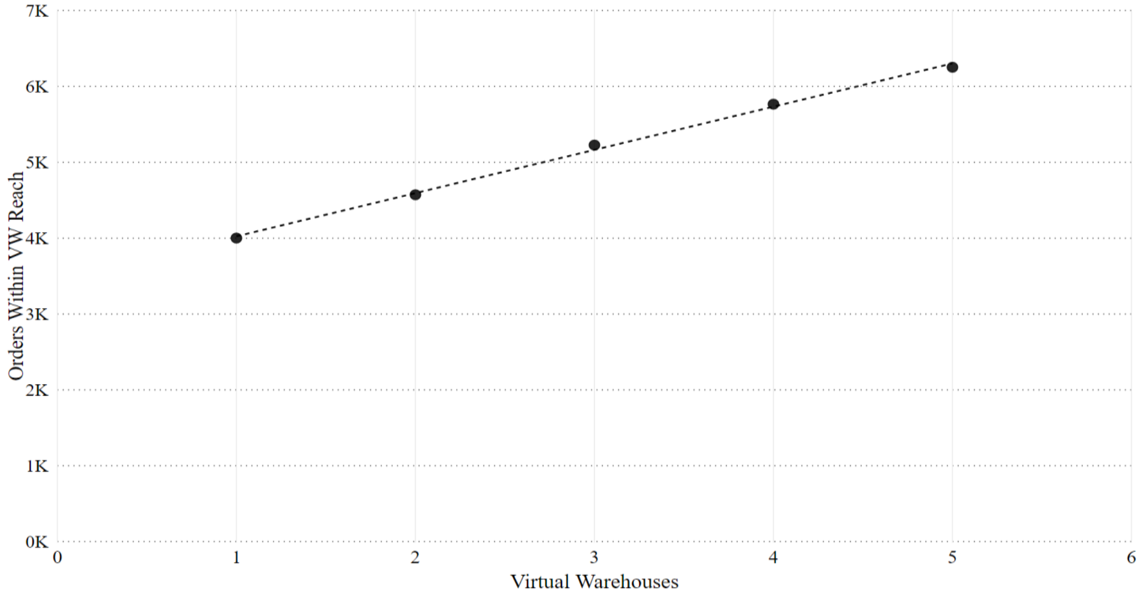
5.3.2.2 Expansion Effects Validation (Parameter Variability–Sensitivity Analysis)

The intention of the operation simulation model was to adjust the strategic and operational parameters of the CIMERWA VW operation such that the expansion of this operation was simulated and then observe the effect of these adjustments on the performance of the system. Prior to running the model repeatedly for selected scenarios for the collection of this data such that conclusions regarding the relationships of interest could be reliably made, the model's outputs' sensitivities to the input values were investigated using individual test runs of the model such that these relationships were validated.

The unavailability of real system values that would precisely describe the tested relationships meant that only the direction of the relationships could be examined to validate the modelled effects of the expansion of the VW operation on the risk of demurrage and auxiliary system metrics. The parameter variability-sensitivity analysis performed on the simulation model could therefore be described as qualitative [37].

An example of a relationship validated using this technique was that between the number VWs used, optimally positioned by the network optimization model, and the total number of simulated orders placed for delivery to locations within the catchment areas of the VWs during the simulated year of operation. Point samples were collected for the numbers of each strength grade of cement ordered for delivery within reach of each VW network. The graphic representations of these samples showed increasing relationships between these variables (see Figure 18). This was the expected trend.

a) 32.5N cement strength deliveries



b) 42.5N cement strength deliveries

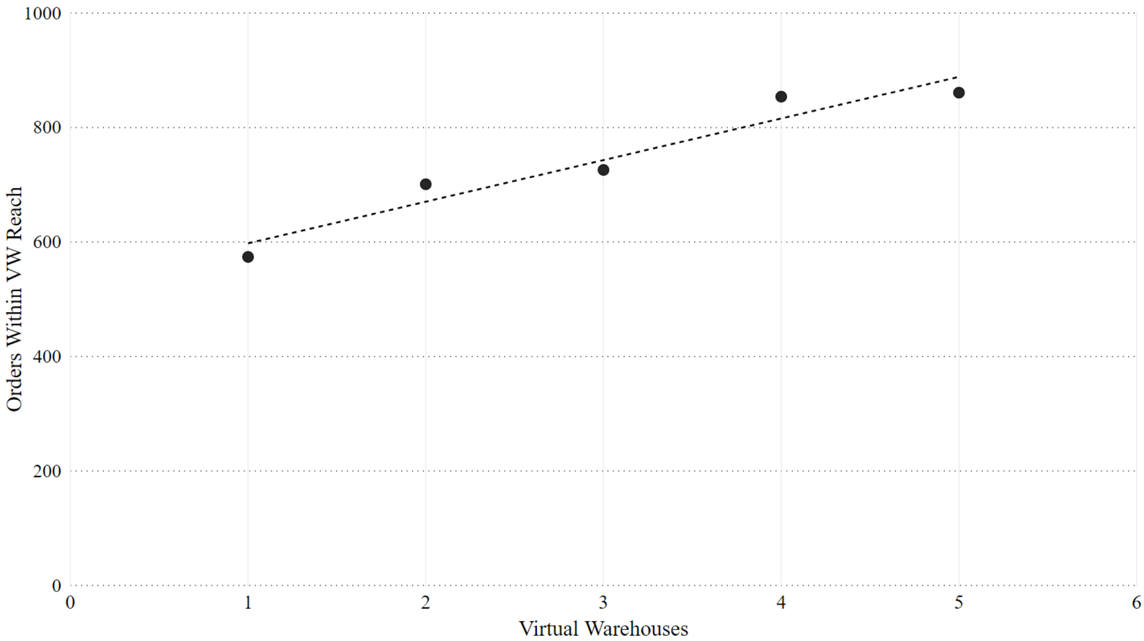


Figure 18: Relationship between number of VWs and deliveries for different cement strength deliveries

This combination of parameter variability-sensitivity analysis and graphical comparison of outputs was also used to validate the modelled effect of the expansion of the VW operation along the planning method dimension. Figure 19 shows the effect of a simulated increase of the factor of safety applied by the logistics office to the estimated number of required trucks while determining the actual number of trucks to dispatch to an example VW. The measured effects were the number of trucks carrying 32.5N dispatched to the Butamwa VW during the simulated year of operation and the total number of days spent by these trucks at the VW throughout the year. Again, only point samples were used so that that as many different combinations of input parameters could be tested as feasibly possible.

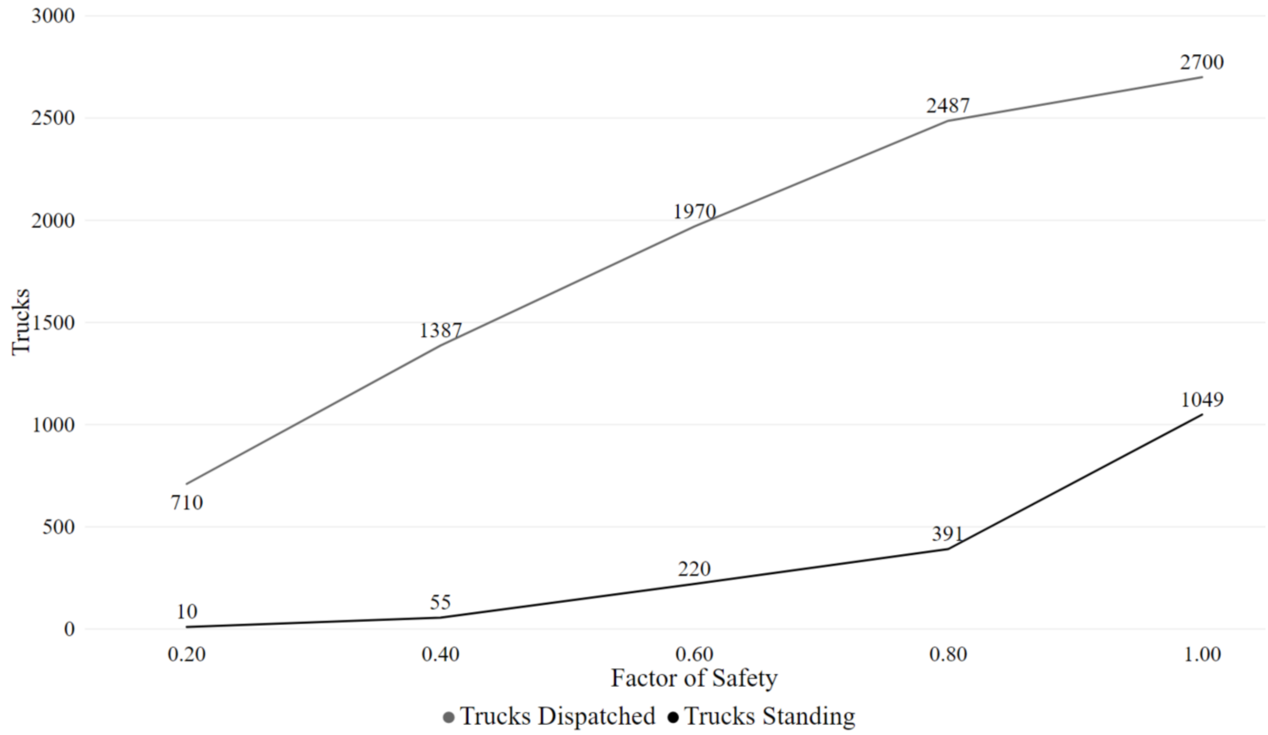


Figure 19: Relationship between the factor of safety inverse and the number of trucks carrying 32.5N cement dispatched to and standing overnight at the Butamwa VW

6. Optimization and Decision-Making

Step five of the seven-step modelling process (see Figure 7) typically involves the actual running of the mathematical model such that the data required to formulate recommendations for management is generated. This usually requires the collection and analysis of a substantial amount the output data. Such analysis aligned well with the Results section of a research report and was therefore included in section 4 and is not discussed in this section. The methodology followed when each component of the CIMERWA VW hybrid mathematical model was run, however, is discussed below.

6.1 Network Optimization Model Runs

For an analytical model, step five involves running the model's optimization algorithm and interpreting the results for management. The VW network optimization component of the hybrid mathematical model was an example of such a model. The algorithm was therefore run, but instead of only preparing the output data for human interpretation, the results were also processed for input to the second component of the hybrid model.

The optimal VW network was extracted from the inventory activity table of the EO inventory object after each run of the optimization algorithm. Due to the transport cost associated with the flow of material from the purchase object to the inventory object, such flow would be detrimental to the objective function of the model unless the material was subsequently directed from the inventory object to the sales object, where revenue to offset the cost would be registered. A record on this table would therefore only show a non-zero value for the "Total Volume In" column if it was used as a channel through which demand would be satisfied. As each record represented a candidate VW city, a record with a non-zero value for this column therefore represented a VW activated by the algorithm as part of the optimal network.

The EO model was run a total of five times, once for each number of allowable activated VWs[20]. This set of scenarios constituted a full analysis of the VW operation expansion along this dimension. The activated VWs for manually extracted from the inventory activity table and inputted to the operation simulation model. They were also listed, visualized and discussed as results of the project (see section 7.1).

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[20] The modeller's discretion was used to determine the maximum number of VWs tested. Analysis of the historical data visualized on a heat map (see Figure 48 and Figure 49) suggested that the geographic spread of demand would not justify networks of six or more VWs. If the operation simulation model later showed that the risk of demurrage was acceptable for a network of five VWs, the network optimization model could be revisited and run for a scenario of six VWs.

6.2 Operation Simulation Model Runs

In the case of a simulation model, step five requires systematic adjustment of input variable values and the collection of output data, which must then be analysed such that the optimal solution (i.e. the set of input variable values that maximize the simulated system's performance) is ascertained. However, the primary objective of the project did not require the optimization of the system modelled, as the benefits associated with each expanded VW model (e.g. lead time days saved) could not be quantified in the same terms as the disadvantages (e.g. demurrage charges). The output data was therefore collected only in such a way that it could be effectively presented to management to inform decisions regarding the extent of VW operation expansion along each dimension simulated.

Detail regarding the manner in which the different runs of the simulation model were executed is included in Appendix 8.

7. RESULTS AND ANALYSIS

The primary objective called for a demonstration of the full analysis method outlined in Section 3.6. Such a demonstration required the generation and interpretation of two different sets of results that could inform CIMERWA management's decision regarding the nature and extent of possible VW operation expansion, namely optimal VW network designs for different numbers of VWs introduced to the operation and the risk of demurrage associated with each network when used with different degrees of speculation.

These two sets of output data were generated by the two different components of the hybrid mathematical model and are presented and analysed separately in this section.

7.1 Network Optimization Results

Due to the deterministic nature of the VW placement problem, the network optimization model's optimization algorithm was run once for each number of VWs (see section 6.1). The optimal solution found by the Enterprise Optimizer's optimization engine for each of the five scenarios are discussed separately below in order of increasing number of VW. Although each run of the model's algorithm was independent of other runs (e.g. the results of the one-VW optimization had no effect on the results when the two-VW network was optimized), the discussion refers to the algorithm adding or removing warehouses between runs such that the expansion of the VW operation along the number of VWs dimension is described as a progression.

The utility of each network is discussed in terms of the percentage of CIMERWA's historical annual demand for delivered demand, both bagged and bulk (see analysis assumption 18), that would reside within the combined catchment areas of the activated candidate VW cities.

7.1.1 One Virtual Warehouse

The network optimization model's algorithm selected Butamwa as the best candidate city for establishment of a VW if only one VW would be used by the CIMERWA logistics office (see Figure 20). A vehicle en route to or parked at Butamwa could be diverted to any city within Kigali province, which would result in the 50.94% of the total national demand that resides within this province being satisfiable using VW trucks pre-emptively dispatched to this city. This selection therefore corresponds closely to the logistics offices' current practice of using a solitary Kigali VW.

Four cities that lie outside Kigali province would also lie within Butamwa's catchment, which would contribute significantly to the reach of this VW. Kamonyi in the southern province, Bugesera in the eastern province, and Rulindo and Shyorongi in the northern province represent a further 527 annual deliveries according to the historical data analysed. This would expand the Butamwa VW's reach into the CIMERWA market by an additional 6.12%.

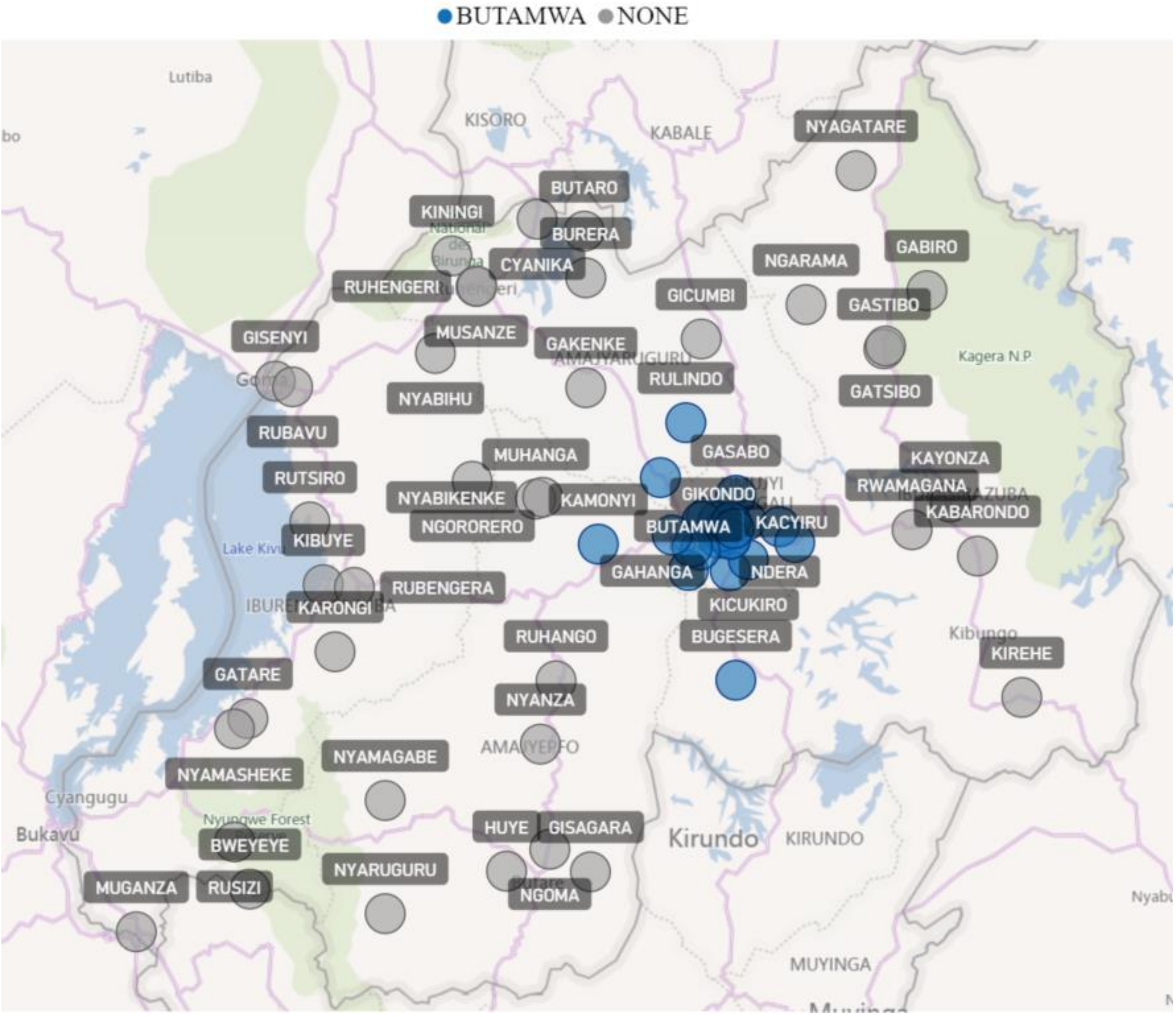

Figure 20: VW catchment area for the optimized one-VW network

7.1.2 Two Virtual Warehouses

The results of one-VW scenario show that Butamwa would be the optimal position of a VW for reaching the demand residing in the central region of Rwanda. This VW was retained by the network optimizer algorithm for the two-VW scenario. The second VW available to the algorithm was utilized to draw as much of the demand that resides in the southern province of the country into the VW network's collective reach as possible.

The southern province of Rwanda is significantly larger than Kigali province and less densely populated with delivery cities. Many of the candidate VW cities represented the only demand node that would be reachable by a VW truck en route to or parked there. The three cities Huye, Gisagaro and Ngoma, however, all reside within each other's catchment area and collectively received 704 deliveries during the analysed year. This cluster of delivery cities therefore represented 8.23% of the CIMERWA's total demand for delivered cement, which was added to the 57.10% of the demand that could be reached by the Butamwa VW when the algorithm selected Huye as the second VW location (see Figure 21). This resulted in a two-VW network having an optimized reach of 65.33% of the annual demand.

Although the activation of any of the three cities within the Huye VW's catchment would have contributed the equal demand to the VW network's collective reach, Huye was selected due to transport cost considerations. Huye's position relative to the production plant in Muganza and the other two cities would result in the lowest modelled transport cost to service the demand in this region via a VW, making it the selection that maximized the value objective function of the EO model.

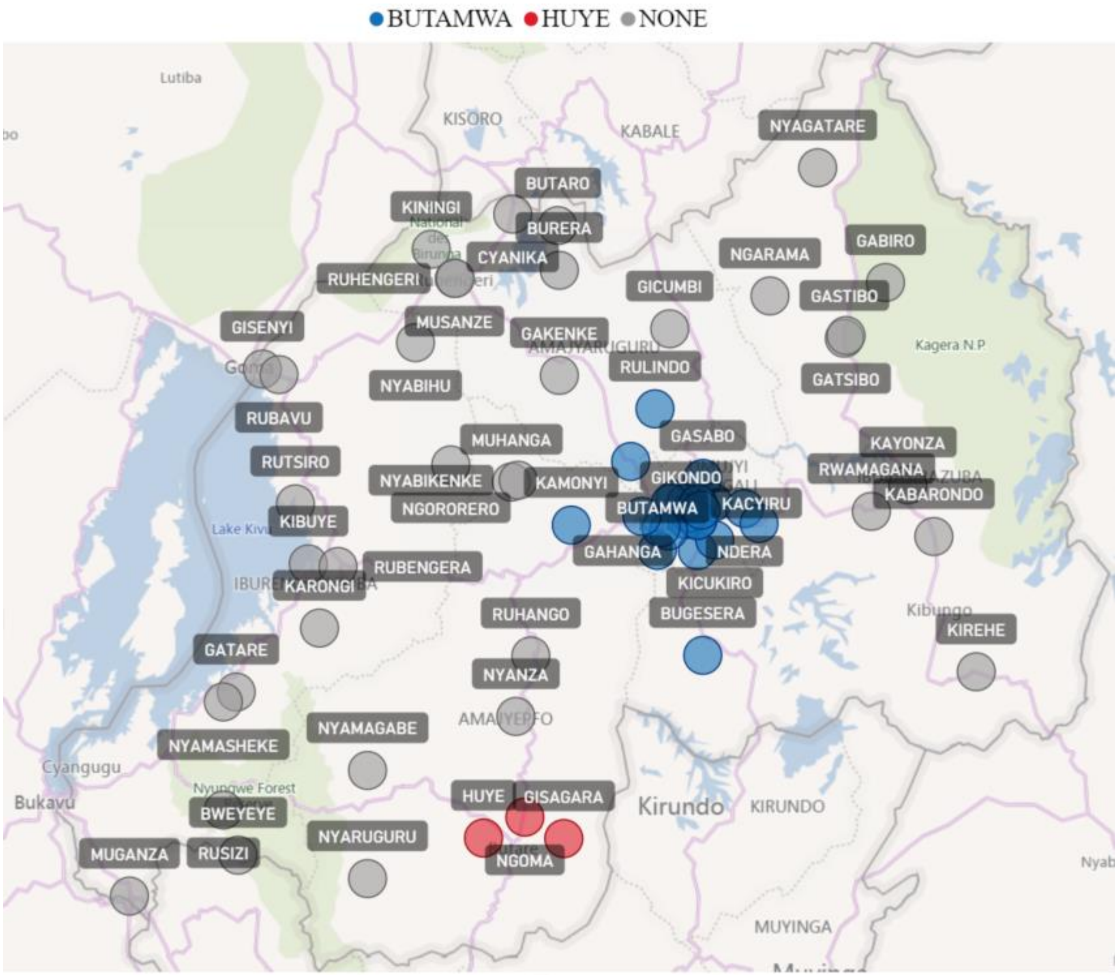

Figure 21: VW catchment areas for the optimized two-VW network

7.1.3 Three Virtual Warehouses

The provision for a third VW to be added to the CIMERWA VW network by the network optimization model represented the only instance in which the algorithm elected to remove a previously activated VW such that more demand could be absorbed into the VW network. Although the Huye VW was retained, the algorithm elected to service the Kigali province via two different VWs, each less centrally located than the previously used Butamwa VW (see Figure 22). In so doing, these two VWs, placed in Kamonyi and Kicukiro, would cover a larger geographic area and expand the VW network's collective reach in the central region of Rwanda while sharing the demand previously covered by the Butamwa VW.

Kamonyi, which represented the western boundary of the Butwamwa VW's catchment area, would now be used to deliver pre-emptively dispatched cement to customers in Muhanga and Ngororero, which had been out of reach of the Butamwa VW. This would add 607 historical orders to the VW network's collective catchment area and thereby extend its reach by 7.10%.

Similarly, trucks en route to or parked at a VW at Kicukiro would be able to service demand in Rwamagana, which lay outside the eastern boundary of Butamwa's catchment area. The historical data showed that 155 truckloads had been delivered to Rwamagana during the year analysed. Inclusion of these orders to the VW network's reach by establishing a Kicukiro VW would therefore increase the percentage of total demand serviceable by the VW network by a further 1.81%. The total reach of the three-VW network would therefore be 74.48%.

Transport costs were used by EO to determine which VW would service each of cities that that were would be overlapped by the Kamonyi or Kicukiro catchment areas. Although this assignment did not affect the calculated utility of the three-VW network, it was required by the operation simulation model component of the hybrid mathematical model as an input to the model output quantity logic (see Appendix 6). As Kicukiro is positioned closer to the locus of the Kigali province demand, most of the cities within this province were assigned to this VW to reduce transport costs associated with diversions from the VW to the delivery city.

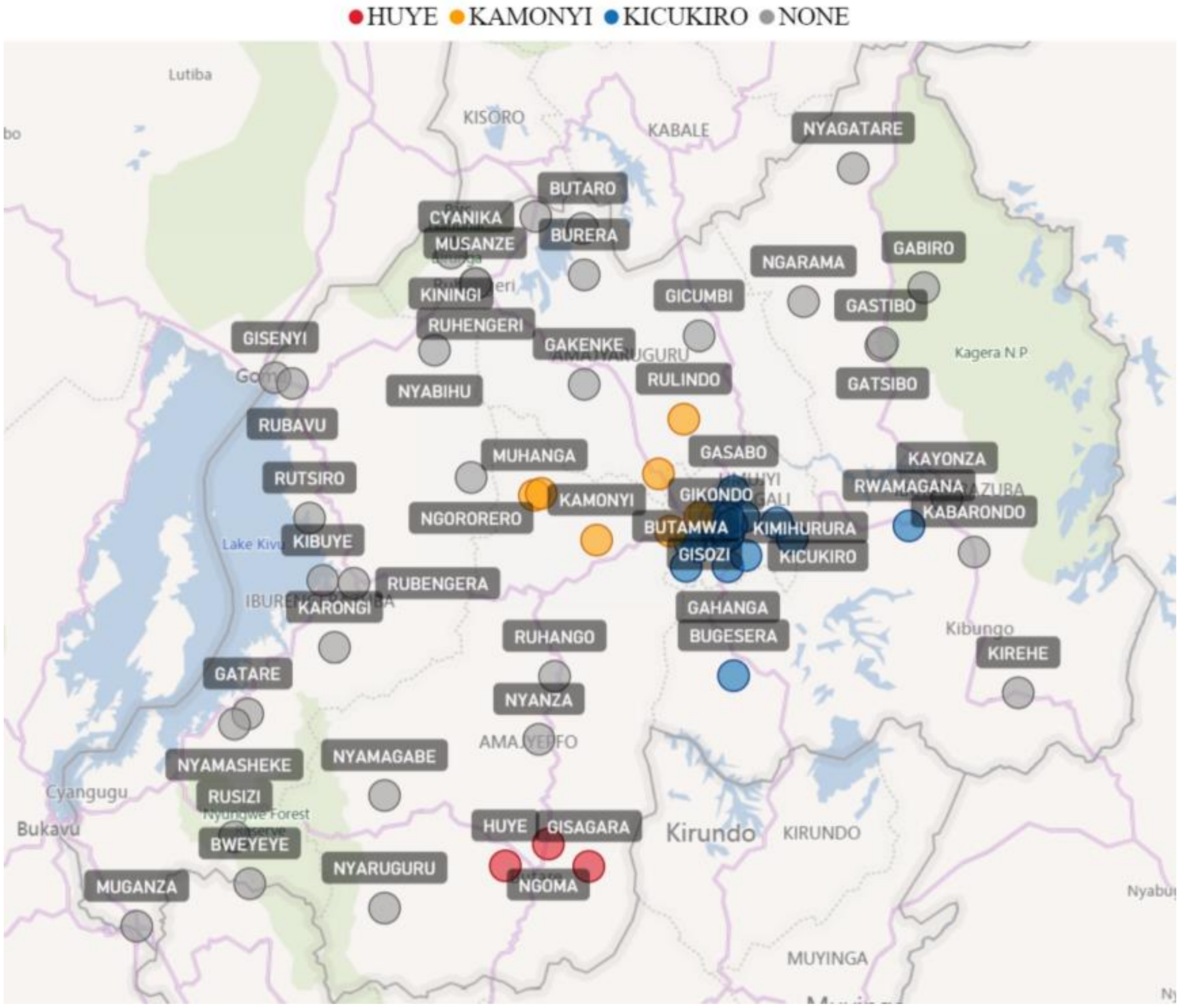

Figure 22: VW catchment areas for the optimized three-VW network

7.1.4 Four Virtual Warehouses

The VW positions selected by the network optimisation model's algorithm for the three-VW scenario, namely Huye, Kamonyi and Kicukiro, were also selected for the remainder of the scenarios optimized. The algorithm selected the northern province city of Burera as the fourth VW position for the four-VW scenario (see Figure 23).

The introduction of the Burera VW would draw an additional eight delivery cities into the VW network's collective reach. This set of cities would represent the largest geographic area covered by the VW network due to the presence of a single VW, which was partially due to Berera's relatively large catchment area radius[21]. These cities represented a further 650 annual orders and their inclusion to the VW network would represent an additional 7.60% of the total demand for CIMERWA's delivered cement serviceable by VW vehicles. The total demand coverage of the optimal four-VW network would therefore be 82.08%.

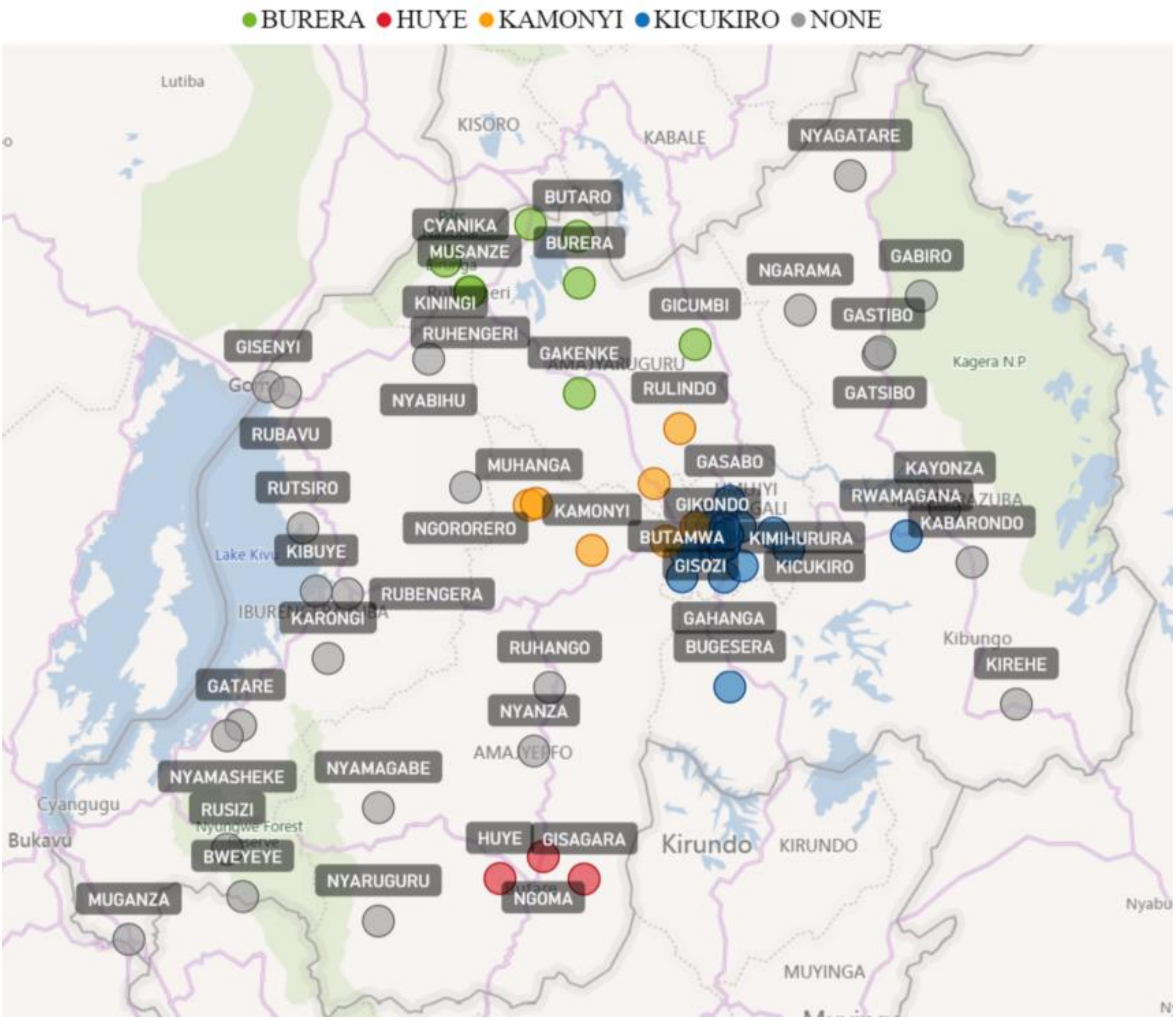

Figure 23: VW catchment areas for the optimized four-VW network

[21] Of the six different selected VW cities for all scenarios optimized, the Burera VW was the furthest from the CIMERWA production plant in Muganza. The catchment radius for each candidate VW city was a function of this distance (see 3.4.1.1), which resulted in Burera having the largest geographic catchment area of the six VWs.

7.1.5 Five Virtual Warehouses

The final scenario that was optimized by the network optimisation model involved the placement of five VWs. Four of these VWs were positioned as per the optimized four-VW scenario. The optimization algorithm selected Rubavu as the city in which the fifth VW should be established (Figure 24).

The Rubavu VW, like that in Huye, would be fairly isolated, with only one other delivery city (i.e. Gisenyi) that would be visited by trucks initially directed to the VW. Again, the model selected Rubavu rather than Gisenyi as the VW city based on the effect their positions relative to the CIMERWA production plant and each other would have on transport costs.

Inclusion of these two cities to the VW network introduced an additional 458 orders to the set of historical additional deliveries that would be executable using VW trucks. The Rubavu VW thereby expanded the demand coverage of the VW network by 5.35% to 87.43%.

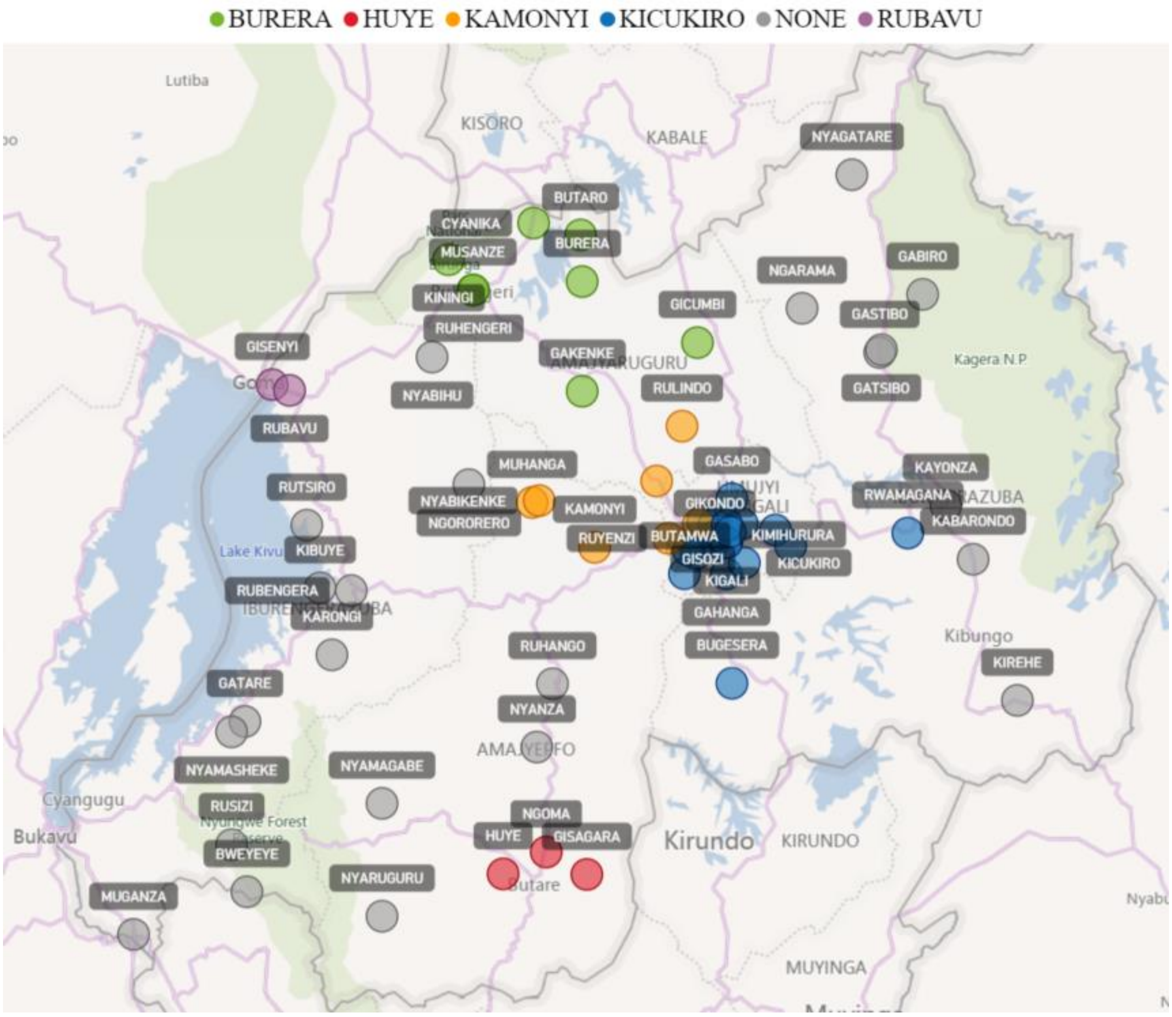

Figure 24: VW catchment areas for the optimized five-VW network

The optimized VW network demand coverage was represented as a function of number of VWs and is shown on Figure 25. It can be seen that there is a trend of diminishing return when VWs are added to the distribution network[22].

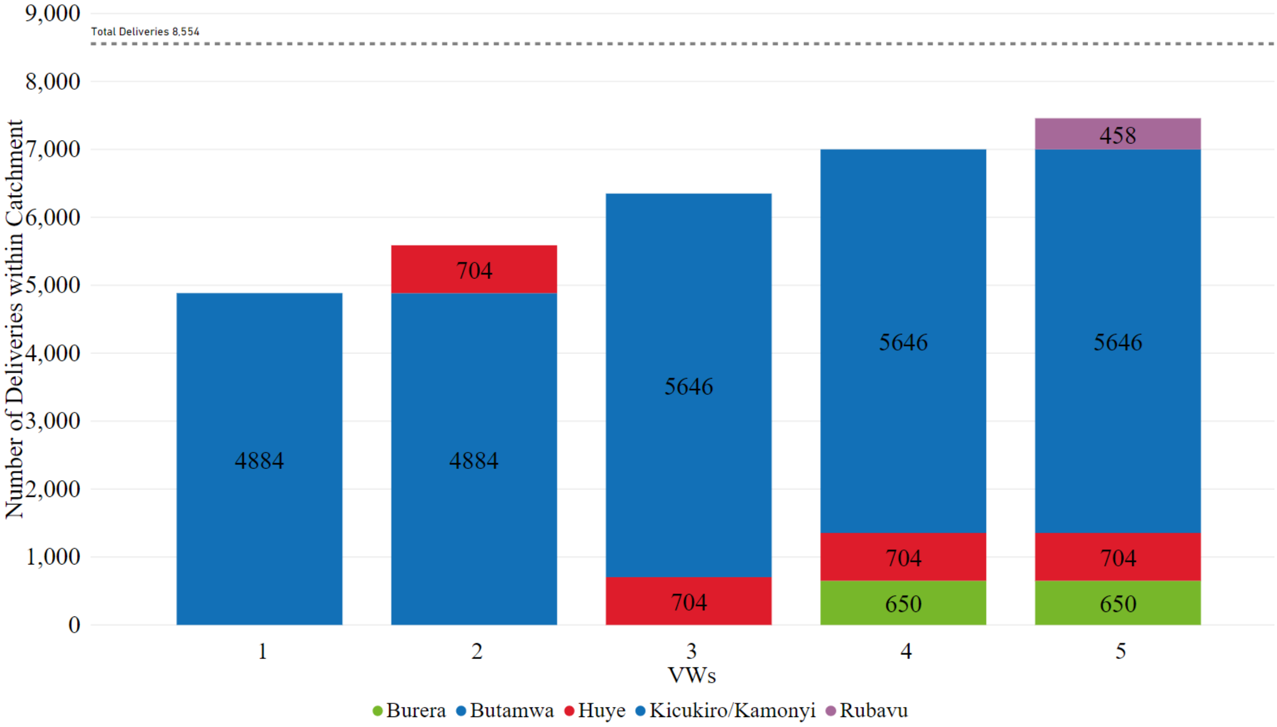

Figure 25: Number of deliveries within reach of each optimal VW network

7.2 Operation Simulation Results

The VW operation simulation component of the hybrid mathematical model was run with a focus on investigating relationships between planning method parameter values (i.e. the forecast factor of safety, the downward adjustment value and cement strength dispatched) and system performance for each optimal VW network. System performance could have been analysed from a variety of perspectives. For example, a simulated expanded VW model could have shown a relatively large saving in customer waiting time (i.e. lead time saving), but also reflect many days spent by vehicles at VWs waiting for orders (i.e. number of demurrage charges).

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[22] There is a larger improvement to the VW network's demand coverage when a third VW was introduced than when the second VW is added. The model's behaviour in this

These two KPIs of the simulated system represent the primary benefit and disadvantage of VW operation expansion and investigations into the effect of each planning parameter on both these metrics were conducted. The sensitivity of the ratio of these KPIs, namely the number of lead time days saved per demurrage charge, to changes to each planning method parameter was also performed. The relationships between these parameters and other auxiliary metrics, such as the number of vehicles dispatched to each VW, were also have investigated when any of the three abovementioned investigations prompted deeper analysis of the system's simulated behaviour.

7.2.1 Forecast Factor of Safety Relationships

The performance of the VW operation was simulated and analysed for the use of different factor of safety values by the CIMERWA logistics office.

7.2.1.1 Relationship with Number of Demurrage Charges

The increase of the simulated factor of safety value applied to the delivery forecast for each VW network had an increasing effect on the risk of demurrage. As the factor of safety value was increased by increments of 0.2, thereby simulating an increasingly aggressive planning method, the number of demurrage charges incurred during a year of operation increased exponentially (see Figure 26).

The average number of demurrage charges aggregated across all simulated VW networks increased from 10.33 to 55.29 for the first increment, representing an increase in demurrage risk by a factor of 5.35 when the factor of safety value was doubled from 0.2 to 0.4. This showed that the risk of demurrage was highly sensitive to the factor of safety value, although this sensitivity was less pronounced when higher factors of safety were used. The final 0.2 increment increased the average number of demurrage charges from 673.73 to 1325.07, representing an increase by a factor of 1.97.

The five-VW network experienced the greatest sensitivity to the factor of safety value. It also exhibited a high degree of variation between for the 100 simulated years of operation simulated. The inter-quartile range of the demurrage charges for this network was 227 and 208.25 when factors of safety of 0.8 and one were used respectively. The third largest inter-quartile range was significantly lower (i.e. 156 for the two-VW network when used with a factor of safety of one). This variability would be difficult to manage and therefore rendered the five-VW network particularly undesirable for high factor of safety values.

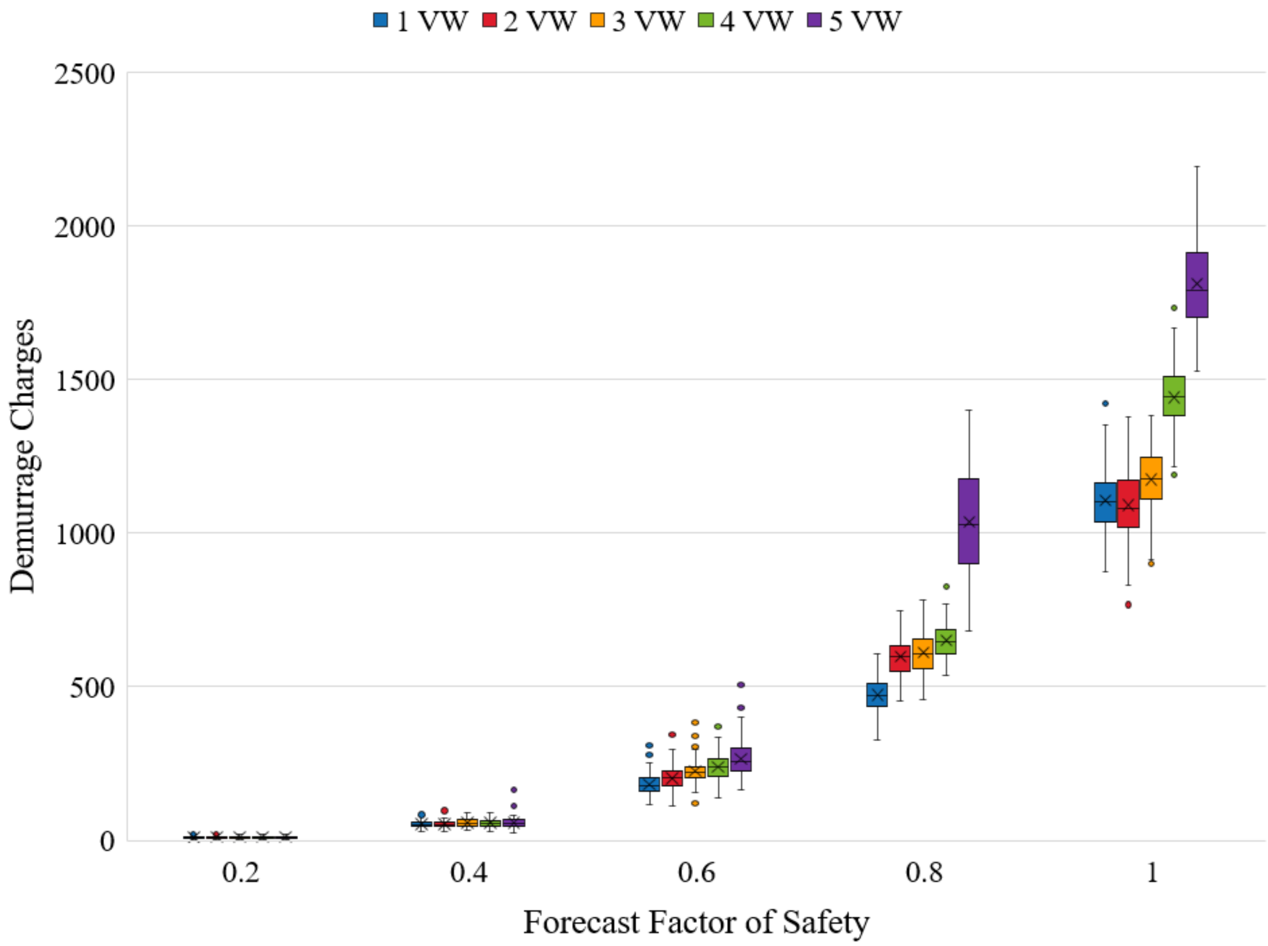

Figure 26: Demurrage charges per VW network as a function of factor of safety

The risk of demurrage also showed an increasing trend along the number of VWs used, but only when the simulated factor of safety value exceeded 0.2. This was due to the extremely low number of vehicles dispatched to the VWs that were added to the network for each increment (see Figure 27). When a factor of safety value of 0.2 was used, no trucks were dispatch to the Huye, Kamonyi, Burera or Rubavu VWs. In the real and simulated system, demurrage charges could only have been incurred if vehicles were, in fact, dispatched pre-emptively. Simulating the addition of these VWs to the network for this factor of safety value therefore could not have increased risk of demurrage.

Simulated vehicles were dispatched to the abovementioned four VWs when a factor of safety of 0.4 was used. However, this translated into relatively little additional risk of demurrage, with use of the five-VW network only resulting, on average, 9.80% more cases of demurrage than the use of the one-VW network. This is partly due to the 62% of the 350 simulated trucks being dispatched to these VWs being directed toward the Kamonyi VW. The catchment area of the Kamonyi VW overlapped that of the Kicukiro VW, which provided the opportunity to divert trucks that stood in Kamonyi to another non-assigned VW and thereby reduced the risk of demurrage significantly (see Appendix 6).

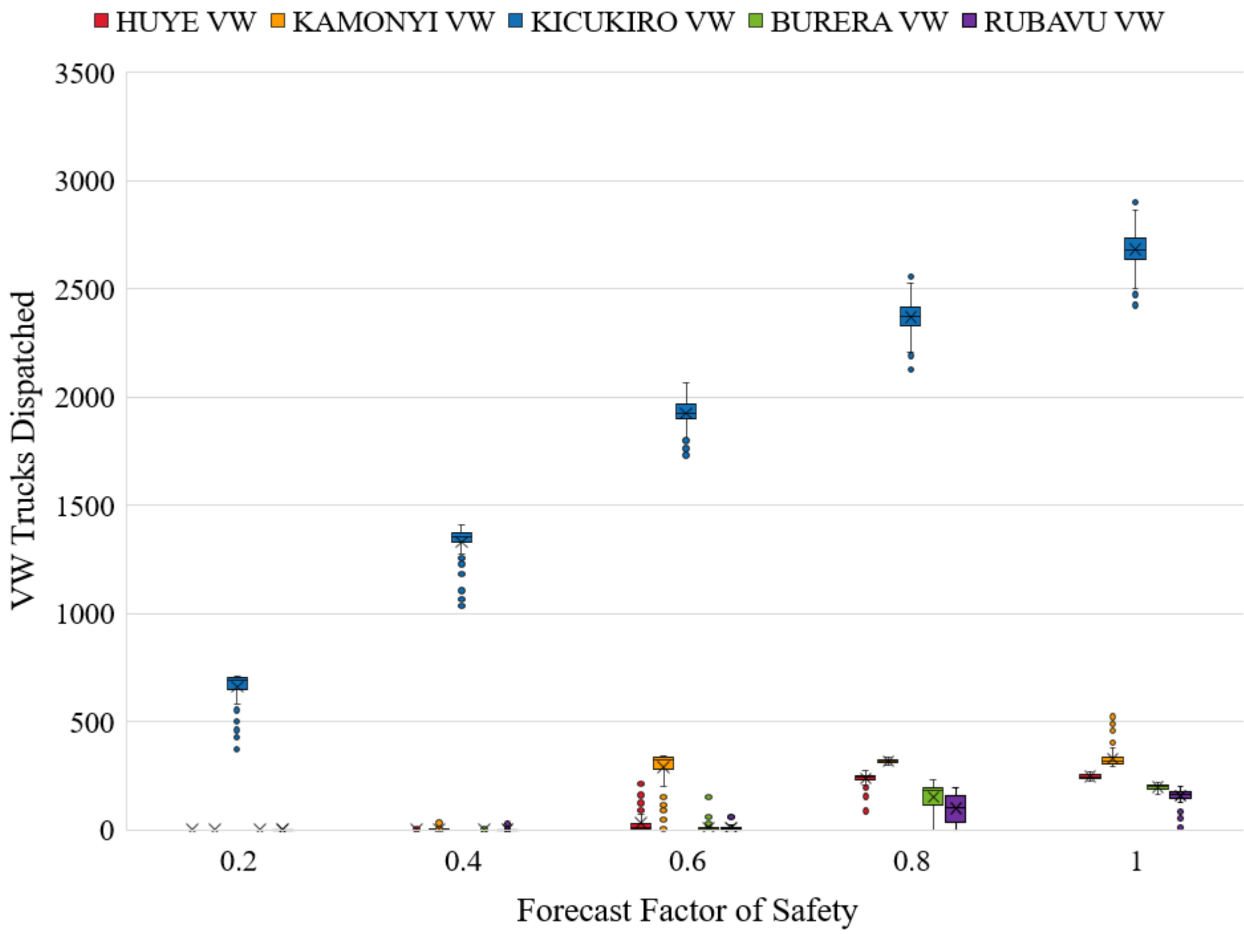

Figure 27: Vehicles dispatched to each VW in the five-VW network as a function of factor of safety

The low simulated usage of the Huye, Kamonyi, Burera or Rubavu VWs when low factor of safety values were used was due to the low values to which the moving average delivery forecasts converged for these VW catchments. For example, if the forecasted number of deliveries for a VW catchment for a specific date was 4.9, the application of a factor of safety value of 0.2 would have reduced this value to 0.98. This value would have been rounded down to zero and no trucks would be dispatched to that VW on that day. Convergence of the moving average forecast to this value therefore ensured that no trucks would be dispatched to this VW.

Figure 28 shows the moving average forecast values of an example actual run of the simulation model for the number of 32.5N cement strength deliveries to the Butamwa and Huye VW catchments. The “actual” values present the forecasted values before they were multiplied by any factor of safety value. The “adjusted” values represent the values after a factor of safety of 0.2 was applied. The adjusted value for the Butamwa VW forecast converged to a value above one, which meant the model could have dispatched trucks to this VW when this factor of safety was used. The adjusted value for the Huye VW forecast converged to a value below one, which was always rounded down by the model to zero, resulting in the VW not being used.

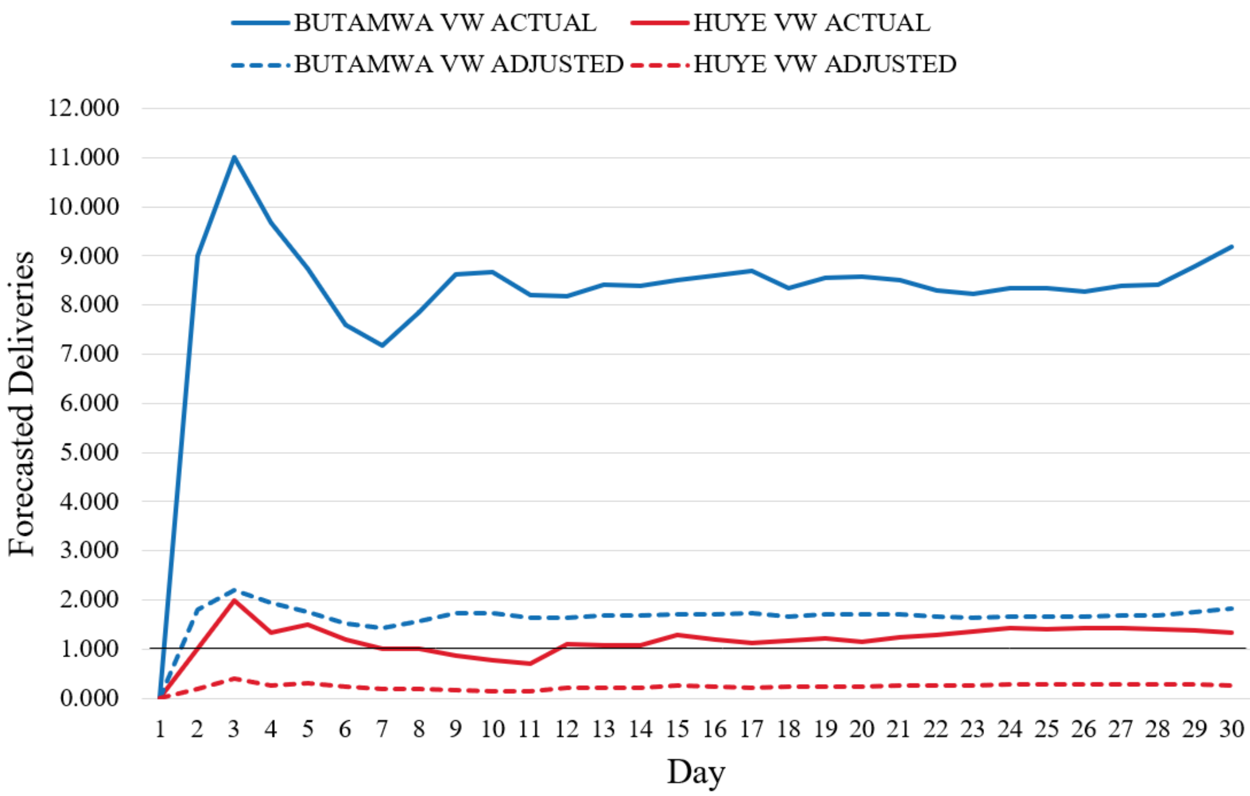

Figure 28: Actual and adjusted moving average forecast values per VW as a function of day of year using a forecast factor of safety value of 0.2 was used

7.2.1.2 Relationship with Lead Time Days Saved

The lack of simulated vehicles dispatched to the additional four VWs for 0.2 and 0.4 factor of safety values also resulted in no significant difference in the lead time days experienced by CIMERWA’s customers when different VW networks were used. However, when factors of safety of 0.6 or greater were used, the introduction of the third, fourth and fifth VWs to the operation produced significant system performance improvements with respect to this KPI. This was partially due to the absorption of geographically distant demand into the VW network. The transition from the one-VW network to a two-VW network involved the introduction of the Huye VW, which would have been close to the CIMERWA production plant in Muganza and only contributed one lead time day saved per delivery executed by a VW truck (see Appendix 7). All subsequent transitions along this dimension, however, involved simulated inclusion of delivery cities two or more days' travel time away from the plant into the VW network. Diversions of VW trucks to these cities therefore had a more significant effect on this KPI.

The simulated effect of the number of VWs was most evident when a factor of safety value of one was used. The mean number of lead time days saved increased from 2707.86 to 3881.71 when the one-VW network was replaced with the five-VW network (see Figure 29) Lead time days saved per demurrage charge as a function of downward adjustment value. The introduction of the four additional VWs therefore represented a 43.35% increase in the positive effect the VW operation had on customer waiting time.

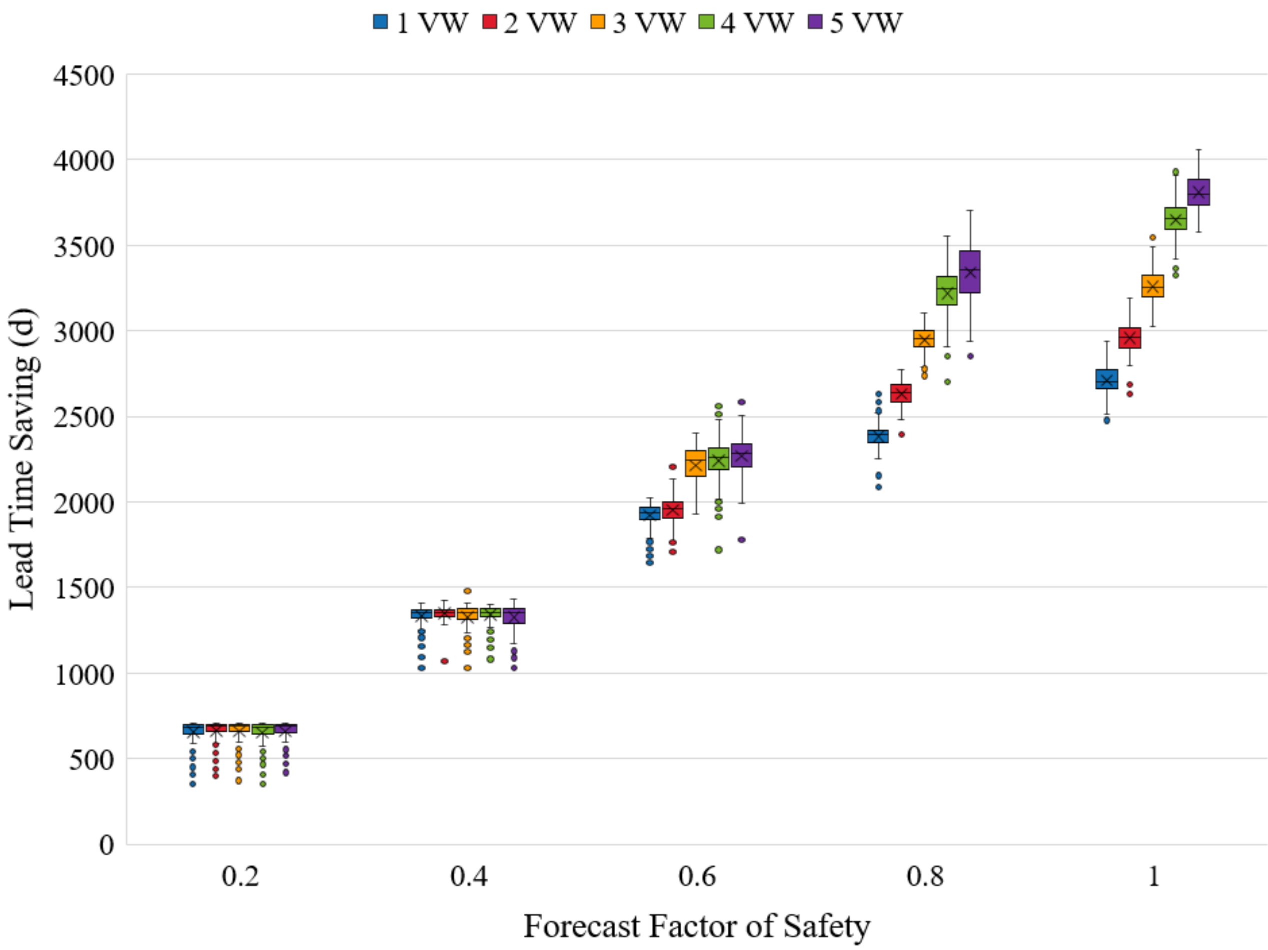

Figure 29: Lead time days saved per VW network as a function of factor of safety

This relationship contributed to the simulated lead time saving being more sensitive to the number of VWs utilized than the factor of safety value applied to the forecast values. Figure 70 shows that the use of a five-VW network with a factor of safety of 0.8 produced more benefit than the use of one, two or three VWs in conjunction with a factor of safety of one. The risk of demurrage associated with this scenario, however, was high and exceptionally variable. The four-VW network, when used with 0.8 factor of safety, produced a mean lead time saving comparable to that of the five-VW scenario (i.e. 96.33% of the five-VW saving value), while it achieved a significantly lower number of demurrage charges (i.e. 62.73% of the charges incurred by the five-VW network).

Figure 29 also shows that when a factor of safety vale of 0.6 or greater was used and, by extension, when the use of included second, third, fourth and fifth VWs was activated, the introduction of the third and fourth VWs produced a greater lead time saving than the establishment of the second. When factor of safety of 0.6 was used, the introduction of the Huye VW to simulate the use of two VWs increased the mean annual number of lead time days saved from 1922.43 to 1952.95. The subsequent simulated replacement of the Butamwa VW with a Kamonyi and Kicukiro VW, however, increased the mean day saving of the two-VW network to 2214.08, which represented an improvement of 261.13 days per year. The replacement of the Butamwa VW with two VWs therefore had more significant effect on customer waiting time than the introduction of the Huye VW by a factor 8.56.

Analysis of the simulated individual VW contributions to the total lead time saving when the five-VW network was used highlighted the relative ineffectiveness of the Huye VW in terms of reducing customer waiting time. When its use was activated by the use of a forecast factor of safety value of 0.6 or greater, it accounted for the least day saving in each scenario (see Figure 30).

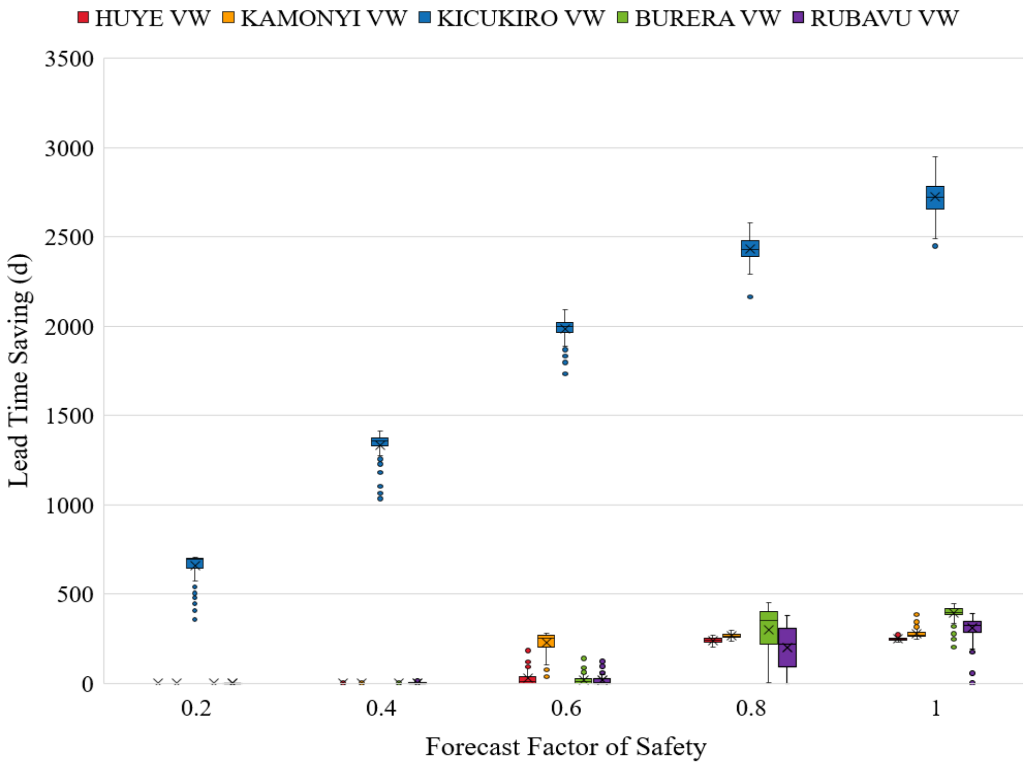

Figure 30: Lead time days saved per VW as a function of factor of safety

Most outliers on Figure 30 lie below their associated box-and-whisker plots, which indicates that the simulated system performed unusually poorly in terms of lead time days saved more often than it performed exceptionally well in this regard.

7.2.1.3 Relationship with Lead Time Days Saved per Demurrage Charge

Figure 31 shows that the simulated lead time saving per demurrage charge achieved by the system improved as the factor of safety value was reduced. The mean saving per charge aggregated across all VW networks decreased from 70.64 to 2.65 days per charge when the factor of safety was increased from 0.2 to one.

This indicated that the simulated increase in the negative effect (i.e. number of demurrage charges) of the expansion using the factor of safety value would have been more keenly experienced than the increase in the benefit (i.e. lead time saving). This was partially due to the exponential and linear natures of the relationships between the factor of safety, the demurrage charges and lead time savings respectively.

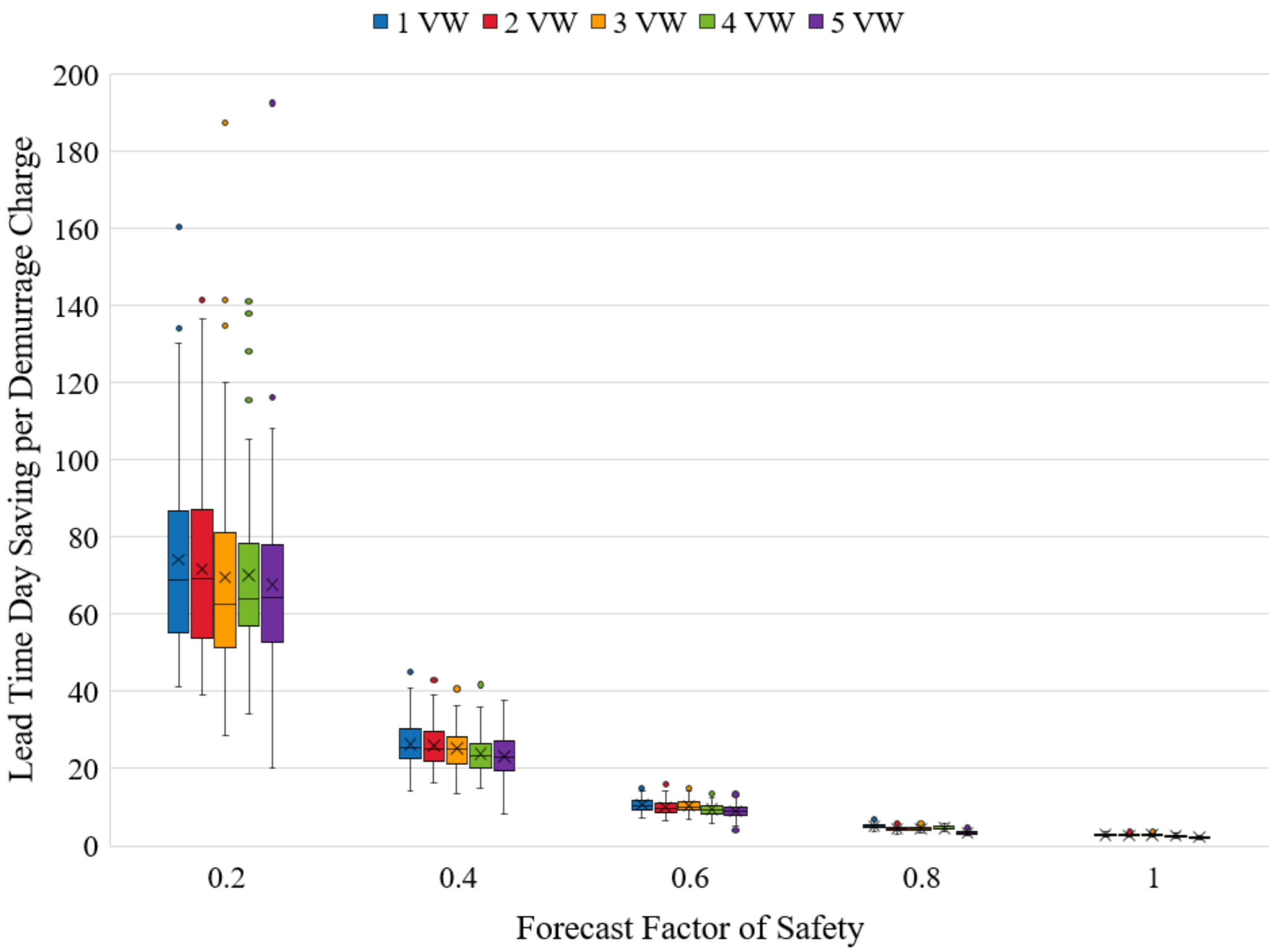

Figure 31: Lead time days saved per demurrage charge as a function of factor of safety

7.2.2 Downward Adjustment Value Relationships

Similar to the analysis of the relationships between the system's performance and the factor of safety value use, the same performance metrics were analysed in terms of their sensitivity to the amount by which the CIMERWA logistics office decreased the forecast value before determining the number of trucks to dispatch.

7.2.2.1 Relationship with Number of Demurrage Charges

The increase in the downward adjustment value used by the CIMERWA logistics office would represent a simulated shift toward a more conservative planning methodology. The behaviour of the 100 simulated years of operation showed that this change would produce the desired result. The number of demurrage charges incurred by the use of each VW network decreased with each increment of this planning method parameter (see Figure 32). The effect of each increment on this metric, however, decreased. The first increment of the downward adjustment value from zero to 0.2 decreased the mean number of demurrage charges, aggregated across all optimal VW networks, by 39.63%, while the last increment from 0.8 to one only decreased this mean value by 16.65%.

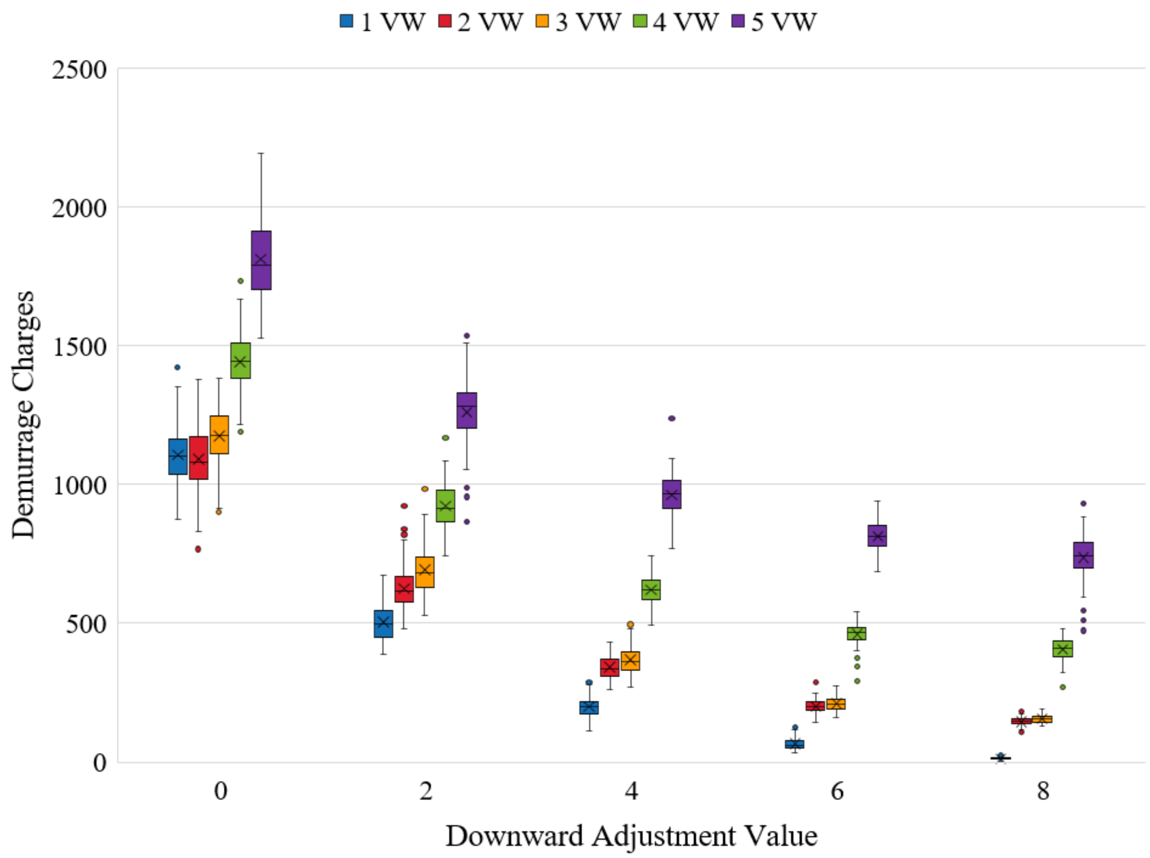

Figure 32: Demurrage charges per VW network as a function of downward adjustment value

Isolation of the one-VW network prior to a secondary analysis showed, however, that the observed tapering of the risk of demurrage was significantly more prominent for this scenario than when the use of the remaining four networks were simulated. When the use of the one-VW network was simulated, the first increment of the downward adjustment value from zero to 0.2 decreased the mean number of demurrage charges by 54.74%, while the last increment from 0.8 to one decreased the mean value by 14.19%. This showed that, when the use of Butamwa VW was simulated, the initial transition from an aggressive to a moderately conservative planning method had a less marked effect on the risk of demurrage than the transition from a moderately conservative method to a highly conservative one.

This was not the case for the remaining four networks. The first increment of the downward adjustment value from zero to 0.2 decreased the mean number of demurrage charges aggregated across the remain four VW networks by 36.57%, while the last increment from 0.8 to one only decreased this mean value by 24.88%.

This phenomenon was due to the stabilizing effect the relatively smaller delivery volume VW catchments had on the number of demurrage charges incurred by the simulated use of the VW networks in which they were included. Figure 33 refers to the use of the five-VW scenario and shows that the mean numbers of days spent by trucks parked overnight at the Huye, Burera and Rubavu VWs remained relatively stable as the downward adjustment value was increased, unlike the significant decline experienced for the Kicukiro VW. It could therefore be seen that as the number of VWs were increased, the introduction of the three smaller volume VWs decreased the sensitivity of the five-VW network to the downward adjustment value by introducing scope to the operation that was not affected by this planning method parameter.

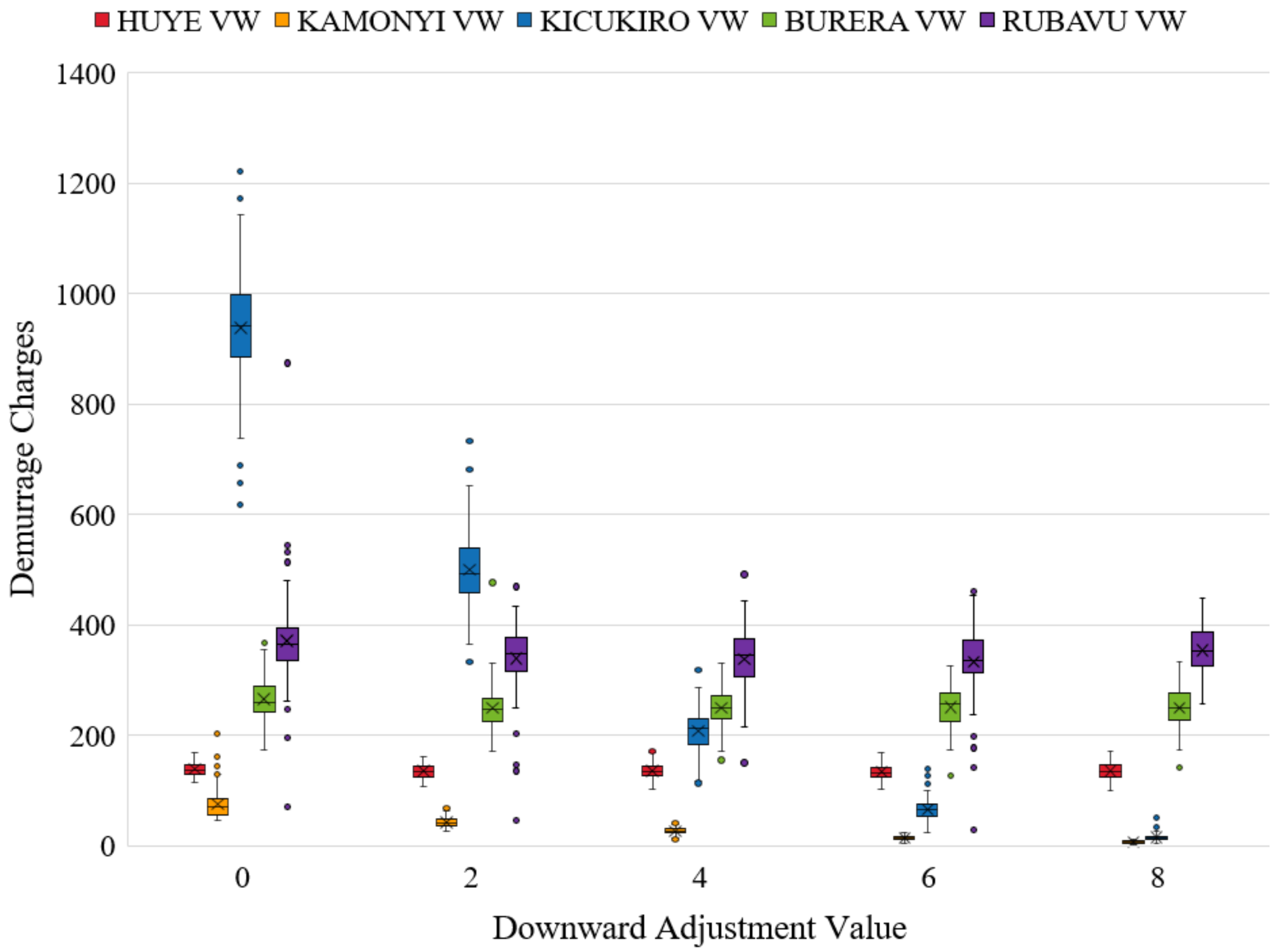

Figure 33: Demurrage charges per VW as a function of downward adjustment value

The independence of the demurrage charges incurred by the use of the Huye, Burera and Rubavu VWs from the downward adjustment value was due to the relatively low volumes of simulated orders placed for delivery to these VW's catchment areas. The model decision logic prevented the inevitable deactivation of these VWs that would have resulted when their downward adjusted moving average delivery forecasts converged to a value less than one. The rounding down step of the decision logic would have resulted in the failure of the model to ever trigger the dispatch of vehicles to VW in such cases.

The rule that prevented the abovementioned deactivation of low-volume VWs by triggering the dispatch of a vehicle to such a VW, on the condition that there were no vehicle already standing at the VW, was activated for these VWs regardless of the number by which the forecast was reduced. This decoupled the logistic office's simulated decisions regarding how many trucks to pre-emptively dispatch to these VWs from the downward adjustment value, which resulted in this parameter having no effect on the risk of demurrage associated with these VWs.

The abovementioned logic also meant that the simulated inclusion of the Huye, Burera and Rubavu VWs introduced a relatively high degree of risk of demurrage that could not be mitigated by the downward adjustment value in the same way that the forecast factor of safety did.

Figure 33 shows that the mean total number of demurrage charges associated with the use of any VW network that included any of the three low-volume VWs started to converge when a downward adjustment value of eight was used. This was due to the mean numbers of demurrage charges for the other VWs, namely Kamonyi and Kicukiro, tending to zero. These values for the Kamonyi and Kicukiro VWs equalled only 6 and 13, respectively, when this downward adjustment value was used. The values to which the total simulated number of charges for each VW network converged were the sum of the relatively constant charge totals for the Huye, Burera and Rubavu VWs that were included in the network.

7.2.2.2 Relationship with Lead Time Days Saved

The lead time savings achieved by the simulated use of each VW decreased with each increment of the downward adjustment value. Figure 34 shows that system performance with respect to this metric was also highly sensitive to the number of VWs introduced to the network. The average number of days by which total customer waiting time was reduced when the one-VW network was used, without any downward adjustment, was 2708.86, which was comparable to that achieved when the four-VW network was used with a downward adjustment value of six, which was 2674.31.

This sensitivity became more pronounced when the use of larger downward adjustment values was simulated. The use of the five-VW network when no downward adjustment was simulated produced a 40.71% improvement in the mean number of lead time days saved of that achieved when a one-VW network was used. When a downward adjustment value of 8 was used, however, this mean value increased from 708.41 days for the one-VW network to 2011.73 for the five-VW network. This increase represented a 183.98% improvement. This was partially due to the resilience of the number of trucks dispatched to the introduced VWs to the downward adjustment value discussed above.

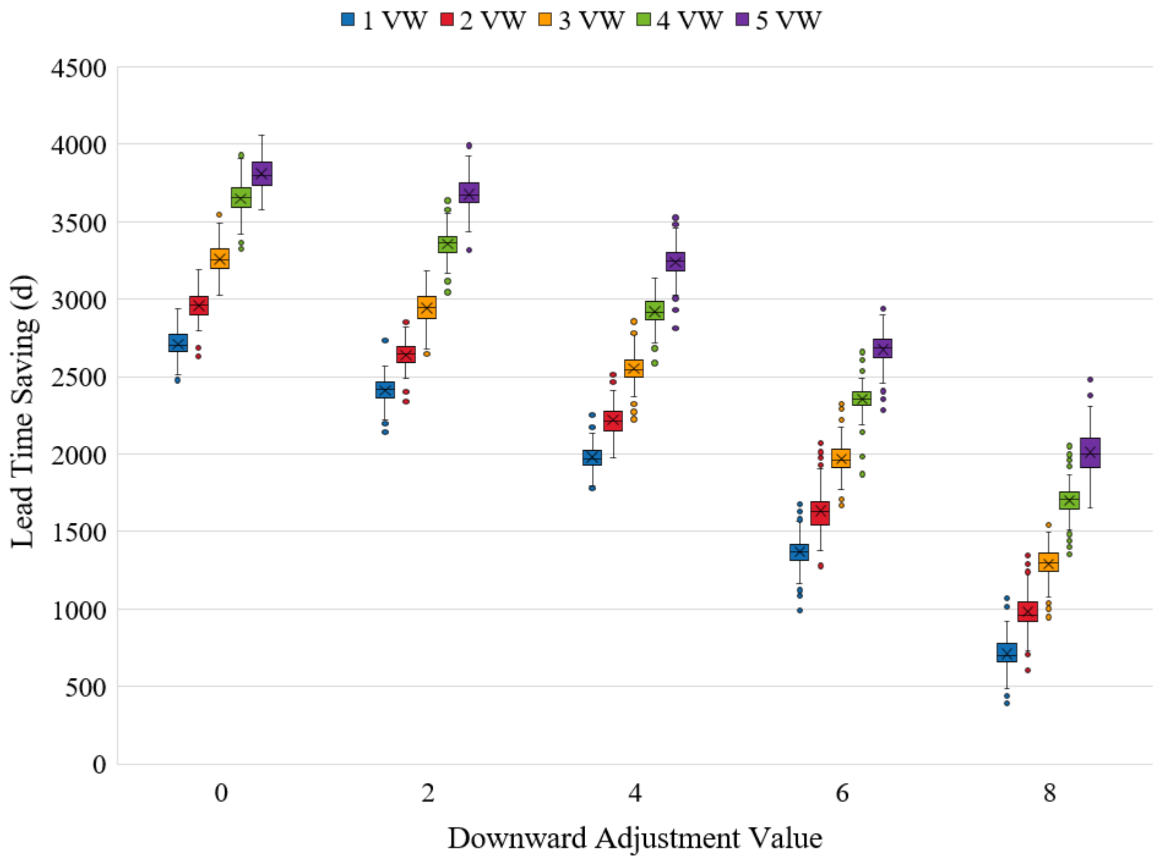

Figure 34: Lead time days saved per VW network as a function of downward adjustment value

7.2.2.3 Relationship with Lead Time Days Saved per Demurrage Charge

The lead time savings per demurrage charge for each scenario indicated that system performed better with respect to this KPI if the downward adjustment value was conservatively selected when the use of the one-VW network was simulated. The mean saving per charge for this network increased exponentially with the downward adjustment value. However, so too did the interquartile range. The exhibited interquartile range increased from 1.42 to 6.52 when a downward adjustment value was increased from four to six. This represented an increase of 5.10 days per charge. The subsequent increment of the downward adjustment value from six to eight, however, increased the interquartile range by 25.54 days per charge.

This degree of variability exhibited in terms of lead time savings per demurrage charge was such that the “whiskers” of each of the one-VW series of box-and-whisker plots overlapped adjacent “whiskers” when high downward adjustment values were used. This indicated that the same level of performance was achieved by the system during different simulated years of operation when the use of different downward adjustment values and the one-VW network was simulated.

This increasing effect of each increment of the downward adjustment value on the lead time savings per demurrage charge was less pronounced or, in some cases, non-existent when the use of other VW networks was simulated.

The system performance with respect to this KPI increased with the first three increments of the downward adjustment value when the use of two, three or four VWs was simulated. However, the degree to which they increased, 1.88, 2.16 and 2.53 per increment for the two-, three- and four-VW networks, respectively, was small relative to the rate at which the one-VW's saving per charge increased (i.e. 6.45 per increment). The final downward adjustment value increment produced no significant change in this metric for these three networks.

These values remained relatively unchanged with the final increments of the downward adjustment values for the two-, three- and four-VW networks. None of the downward adjustment value increments for the simulated use of the five-VW network produced a significant effect on the lead time days savings per demurrage charge.

This significantly lower sensitivity of the lead time savings per demurrage charge to the downward adjustment value when the use of more than one VW was simulated is shown in see Figure 35. It was was due to the simultaneous convergence of the number of demurrage charges to constant values and the steady decline of lead time saving as the downward adjustment values were increased.

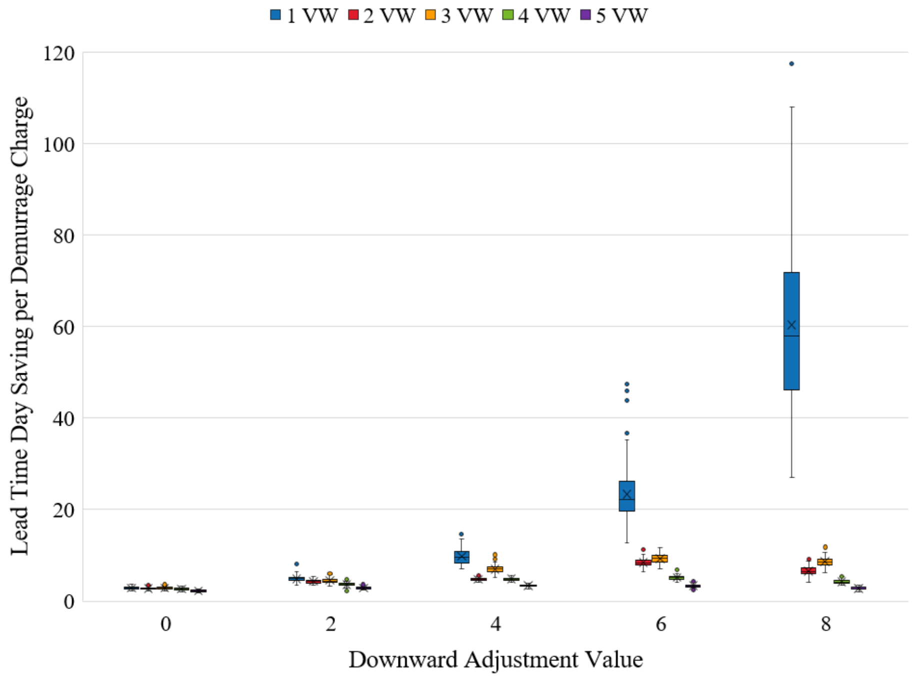

Figure 35: Lead time days saved per demurrage charge as a function of downward adjustment value

7.2.3 Dispatched Cement Strength Relationships

The cement strength grade used for loading virtual warehouse-bound vehicles could be easily overlooked as an element of the planning method, as it could be taken for granted that 42.5N strength cement could be used instead of the higher-selling 32.5N cement. The fact that the higher-strength cement could be delivered to a customer that had ordered 32.5N cement, but not vice versa, mean that the system dynamic with regard to the cement strength loaded required analysis.

7.2.3.1 Relationship with Number of Demurrage Charges

The 32.5N cement strength grade was used as the default dispatched cement used for the investigations into the relationships between the planning method parameters and system performance was selected. The simulated replacement of this grade of cement with 42.5N strength cement showed significant decreases in the risk of demurrage associated with the use of each optimal VW network (see Figure 36). This reduction in risk, however, was only achieved when the 42.5N cement delivery forecast was not added to the forecast of 32.5N deliveries when simulated decisions regarding the numbering of trucks for each VW was determined.

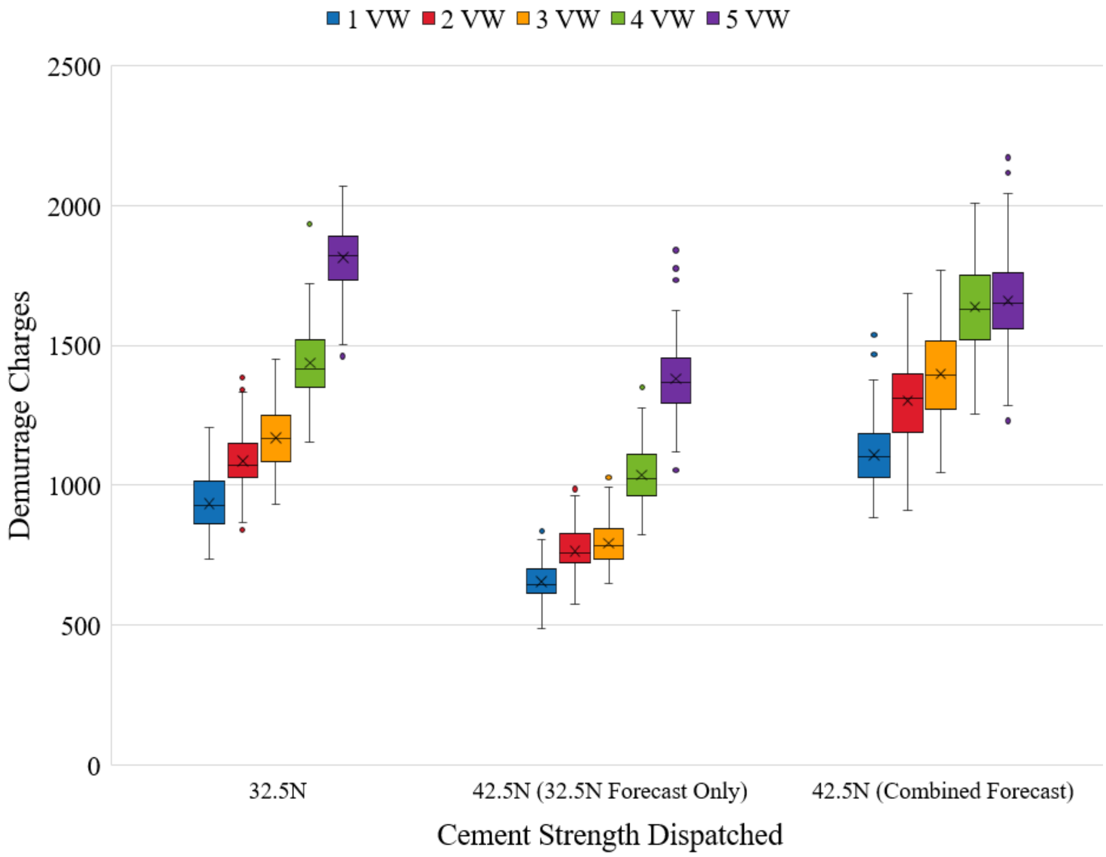

Figure 36: Demurrage charges per VW network as a function of cement strength dispatched

When the use of this cement strength grade was simulated using the 32.5N order forecast values, the mean number of demurrage charges incurred, aggregated across all five optimal VW networks, was 28.12% less than the KPI observed when the 32.5N strength cement was used to load VW-bound vehicles. This was due to the flexibility the 42.5N cement provided in terms of the types of deliveries that could have been executed by a VW truck after being committed to the VW. The logistics office was able to use the orders for 32.5N strength cement as a buffer by first using the vehicles en route to or stationed at the VW to satisfy orders for 42.5N strength cement in the catchment area and then, if surplus trucks were present at the VW, diverting them to deliver cement to customers that had ordered 32.5N strength cement. This increased the probability of securing demand for a vehicle en route to or stationed at a VW and thereby decreased the risk of demurrage.

This improvement in demurrage risk was only achieved if the use of the moving average forecasts was retained when the product loaded was substituted with 42.5N cement. If the decision made by the logistics office regarding the number of trucks to dispatch pre-emptively to each VW was simulated to include the forecasted number of 42.5N strength cement, the total number of trucks dispatched to VWs increased in every scenario. The variance value for the demand for 42.5N strength cement was 3621.79, while the variance of the 32.5N demand was 18857.5. Demand for 42.5N strength cement was therefore significantly more variable in nature. It follows that the additional vehicles dispatched to satisfy this demand exposed the operation to more risk of demurrage, which was observed in a 10.34% increase in the mean number of demurrage charges, aggregated across all VW networks, when this planning method was simulated.

7.2.3.2 Relationship with Lead Time Days Saved

When the use of 32.5N strength grade cement to load VW vehicles in conjunction with a forecast factor of safety of one and a downward adjustment value of zero was simulated, an average of 2697.84 deliveries were fulfilled via the aggregated VW network. Under the same conditions and using only the forecast value for 32.5N deliveries, the use of 42.5N cement for VW vehicles achieved a mean value of 2966.55 for this metric (see Figure 37). This increase which represented a 9.96% improvement of the VW networks' aggregated reach. This translated into an average lead time saving improvement, aggregated across all optimal VW networks, from 3277.77 to 3601.58 when 42.5N cement was used to load VW- bound vehicles instead of 32.5N cement.

If the orders for 32.5N cement were isolated for the comparison of the above two scenarios, it could be seen that the use of 32.5N strength cement to load VW vehicles resulted in an average of 285.14 more deliveries executed by VW trucks, aggregated across all VW networks, than when they were simulated to carry 42.5N cement. This, however, was due to the prioritization of 42.5N strength cement orders for delivery, which meant that there were fewer trucks available to fulfil demand for 32.5N cement when 42.5N cement was load on VW vehicles. The VW trucks carrying 42.5N strength cement were able to satisfy an average of 553.83 orders for 42.5N cement, which resulted in the use of 42.5N cement vehicles having a larger overall impact on the supply chain than 32.5N trucks. These orders for 42.5N cement represented demand could not have been satisfied by vehicles loaded with 32.5N cement, even if they were unutilized and had to park in the VW city overnight. The use of 42.5N strength cement to load VW-bound trucks thereby increased the benefit gained by each VW network, while adding no additional risk of demurrage.

The simulated consideration of the order forecast values of both 32.5N and 42.5N strength grades of cement further increased the lead time days saving associated with the use of each VW network. The average lead time saving, aggregated across all optimal VW networks, increased from 3601.58 to 3902.33 days when the forecasted values for 42.5N orders were assimilated into the values that drove the simulated decisions regarding the number of trucks to dispatch to each VW.

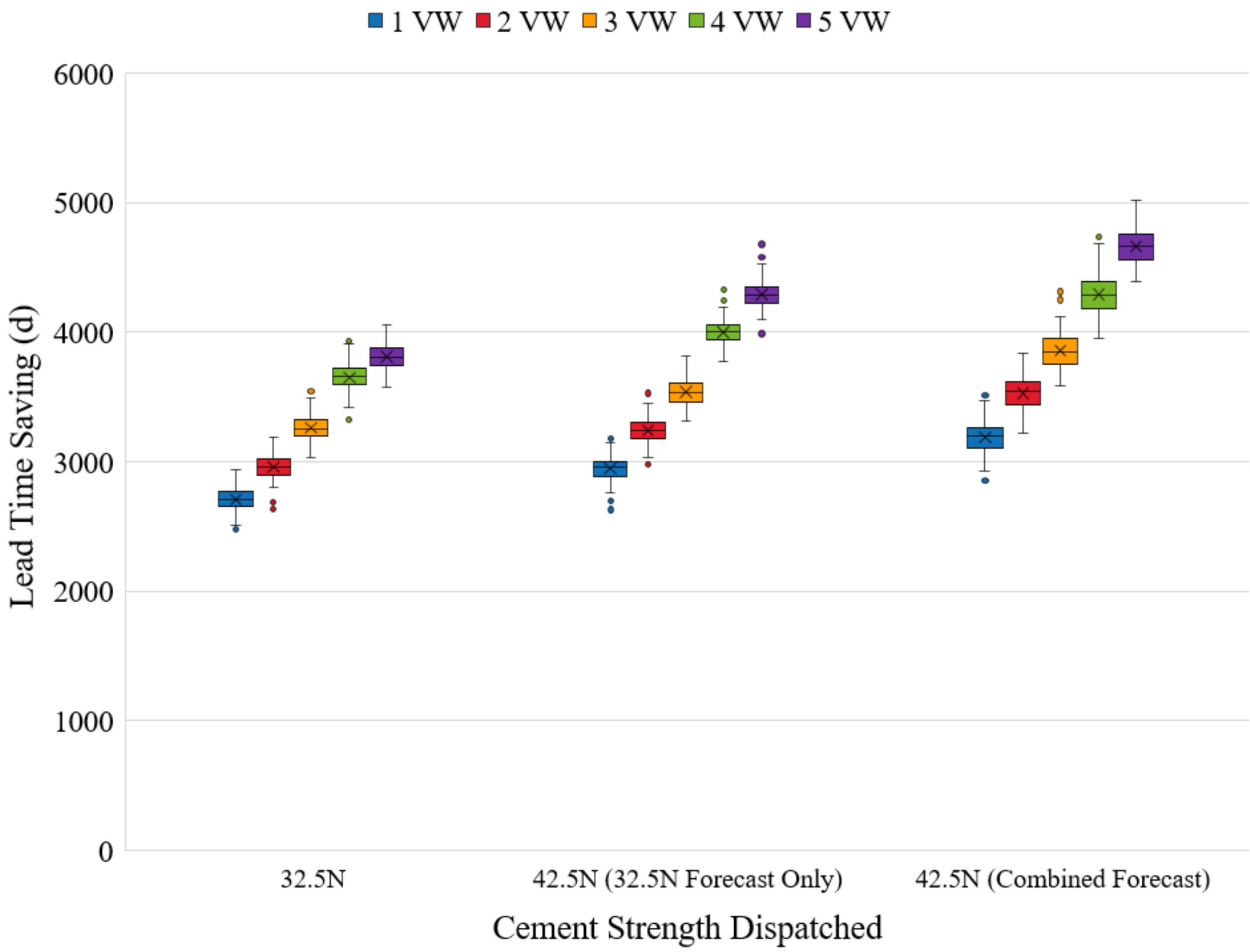

Figure 37: Lead time days saved per VW network as a function of cement strength dispatched

Figure 38 shows that a high degree of alignment between the simulated lead time savings and the percentages of orders satisfied via the VW network between corresponding sets of parameters, which confirmed that it was primarily this increased market reach of the VW networks that produced the lead time savings. The addition of the fourth VW for each scenario, however, produced a gain in lead time savings that was relatively larger than the improvement the percentage orders delivered by VW trucks. This was due to the greater modelled transit time to the Burera VW catchment.

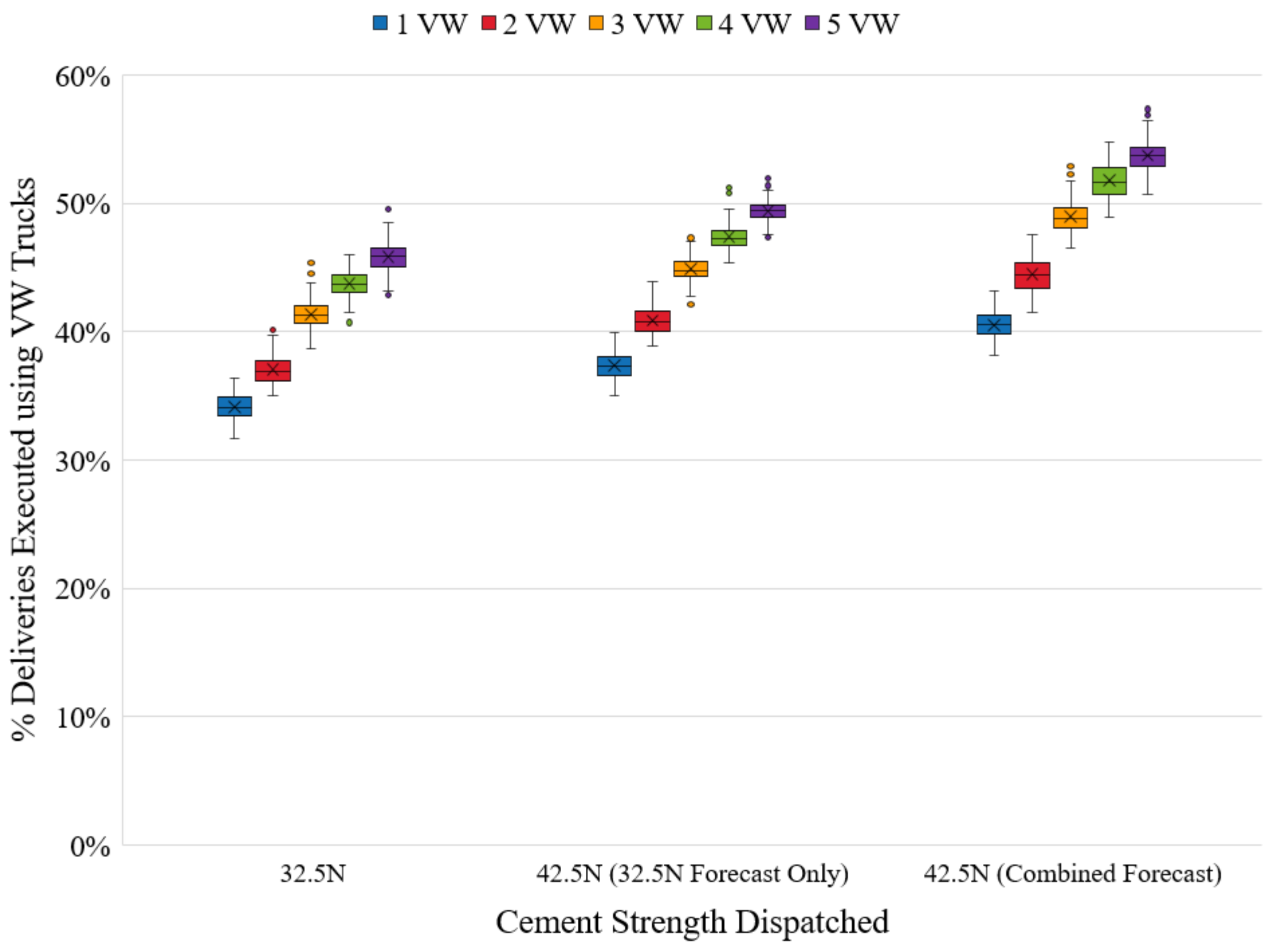

Figure 38: Percentage of total deliveries fulfilled using the VW network as a function of cement strength dispatched

7.2.3.3 Relationship with Lead Time Days Saved per Demurrage Charge

Figure 39 shows that the simulated number of days of lead time saved per demurrage charge incurred by each VW network decreased with the addition of each VW to the network for every strength of cement used. This indicated that the risk of demurrage associated with each introduced VW outweighed the number of days of customer waiting time they saved regardless of the cement strength used.

The simulated performance of the system with respect to this KPI was greatly enhanced when the 42.5N strength cement was used to load VW-bound vehicles as opposed to 32.5N cement. The mean number of days saved per demurrage charge, aggregated across all optimal VW networks, increased from 2.65 to 4.09 when the cement strength grade was substituted, which represented a 54.34% improvement in terms of this metric.

Such an improvement was not achieved if the use of the higher strength cement was coupled with the incorporation of the forecasted number of 42.5N strength cements orders into the figure used to inform the simulated truck numbering decisions made by the logistics office. The use of a combined 32.5N and 42.5N forecast negated the benefit of the cement type substitution, lowering the aggregated mean value to 2.68.

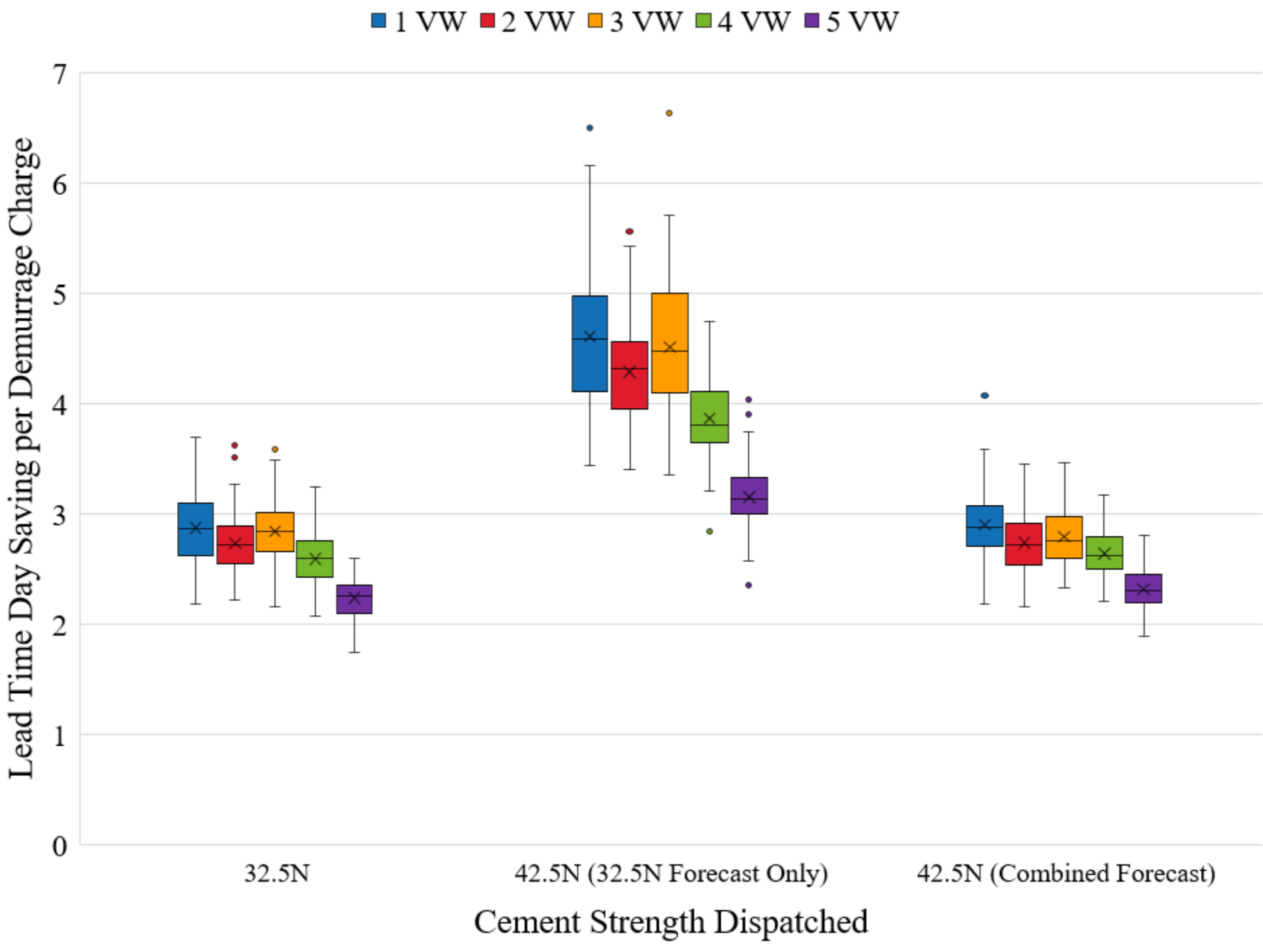

Figure 39: Lead time days saved per demurrage charge as a function of cement strength dispatched

8. DISCUSSION

Although the output of the network optimization and operation simulation models are explained separately in section 7, the results of these two components of the hybrid mathematical model are discussed together below. This was due to the high dependency of the models on each other of modelling decisions and inputs and outputs. However, the key points of discussion do, in general, follow the order in which the results were presented.

8.1 Placement of the Butamwa VW

The network optimization model was primarily developed such that the risk of demurrage associated with CIMERWA's expansion of the VW network would be minimized. Due the limitations of analytical methods with respect to modelling probabilistic processes, the system theory and assumption that the risk of demurrage was proportional to volume of CIMERWA's demand for delivered cement that could have been satisfied by the VW network was used and the model's objective function was developed such that each VW's market reach would be maximized (see Appendix 3). Figure 25 shows that the model did, indeed, aim to maximize this value, as each loosening of the number of VWs constraint resulted in an increase in the optimal VW network's market reach.

The model, however, could only improve the reach of the one-VW network by a further 52.7% when allowed to utilize five VWs. This diminishing return on the introduction of additional VWs after the first VW was expected, as the demand for delivered cement is highly concentrated in Rwanda's smallest province and could be accessed via a single VW.

The model's placement of the first VW at Butamwa therefore would have achieved the "low hanging fruit" of drawing Kigali and its immediate outlying areas into the VW network. It also validated the existing practice of pre-emptively directing vehicles to Kigali, as these two cities are only 14.1 kilometres apart and Butamwa is en route to Kigali for a truck travelling from the CIMERWA production plant in Muganza (see Figure 40). A sale for delivery in Kigali would have therefore added no additional travel for a truck diverted from a VW at Butamwa.

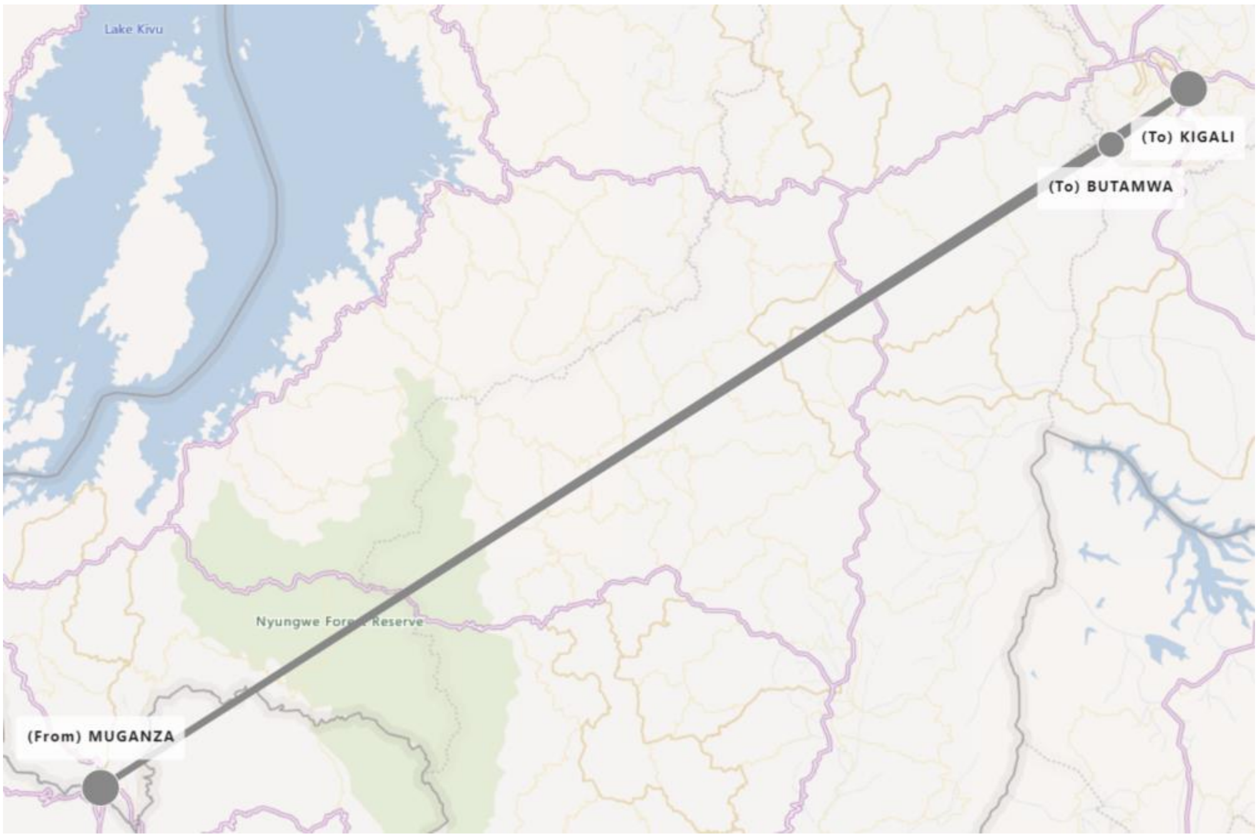

Figure 40: Relative positions of the CIMERWA production plant to Muganza, Butamwa and Kigali

Although the inclusion of demand into the VW network was the most heavily weighted factor in the optimization problem's objective function, the distribution network was deliberately modelled on EO such that the optimization algorithm would favour a candidate VW city such as Butamwa over one like Kigali due to this greater re-routing efficiency. Transportation costs directly proportional to straight-line distance were used to drive this behaviour of the algorithm (see Appendix 4).

The selection of Butamwa rather than Kigali as the first VW city could therefore be considered a successful result of the use of costs to drive the model, while being built primarily to maximize revenue, to consider the "divertability" of loads when selecting VW locations. The selection of Huye as the second VW city, however, was found to be a selection that was arguably sub-optimal in terms of the business problem being solved, in spite of it representing the optimal solution in terms of the model's objective function.

8.2 Selection of Huye as the Second VW Location

Figure 25 shows that the increase in VW network reach that would have been achieved by the introduction of the Huye VW would have been less than that associated with the replacement of the Butamwa VW by the Kamonyi and Kicukiro VWs. The latter option was only selected for the three-VW scenario even though it would have incorporated 8.1% more annual orders into the reach of CIMERWA's VWs than Huye's VW would have added. This suggests that the two-VW network should have included Kamonyi and Kicukiro VWs, with the Huye VW only to be introduced for the three-VW network.

The EO algorithm selected Huye as the second VW location due to its closer proximity to the CIMERWA production plant and this position's effect on transport costs and, in turn, the profitability of the VW. The lower costs associated with the initial legs to the Huye VW and diversions from this VW resulted in the profit generated by the 704 deliveries within the catchment being, according to the model, greater than that produced by the 761 orders that could have been delivered via the joint Kamonyi and Kicukiro VWs.

This behaviour resulted in the optimization model selecting a VW that was sub-optimal in terms of risk of demurrage when the system theory and assumption regarding the relationship between the market reach and risk of demurrage associated with a VW network is considered. It could be argued that the weighting of transport costs on the objective function was too great. However, the reduced transport cost associated with the use of the Huye VW and other unmodelled factors such as geographic diversity, carrier capacity and the nature of each region's markets may indeed have justified the selection of Huye as the second VW location.

A review session with CIMERWA management would have been required to assess the utility of each option from the business' perspective. If the dual Kamonyi and Kicurkiro VW option would have, indeed, been deemed more desirable, then some fine-tuning of the network optimization model's selling price for a truckload of cement and transport costs to drive the model toward a more intuitively desirable answer. This approach would have somewhat undermined the purpose of the optimization model. It would have been more beneficial to incorporate those additional factors that were considered by management during this discussion directly into the model and re-run the algorithm to determine a new optimal solution. However, the discussed limitations of analytical modelling with regard to modelling complex relationships would have probably prevented their inclusion to the model.

The primary objective of the project focussed on risk reduction. However, an important factor of the selection of Huye as the second VW location that was not considered by the network optimization model was the benefit it provided in terms of lead time reduction. Being located considerably closer to the CIMERWA production plant, the business case for establishing a VW in this region was significantly weaker than for the joint Kamonyi and Kicukiro VWs.

The incorporation of this level of detail into the operation simulation model, however, did mean that lead time reduction was accounted for by the hybrid mathematical model and reflected in the results. Figure 29 and Figure 30 highlight the relatively small contribution the Huye VW would make to improved customer service.

The two deficiencies of the network optimization model discussed above, namely the possibly undue biasing effect transportation costs had on the network optimization model towards candidate VW cities that were closer to the plant and the failure of the optimization model to consider the candidate cities' capability to improve lead time savings, meant that the Huye VW was arguably the incorrect selection for a second VW location both from a demurrage and lead time reduction perspective. The replacement of the Butamwa VW with the Kamoyi and Kicukiro VWs would have incorporated more demand into the VW network and produced a greater improvement in customer service while exposing CIMERWA to less risk of demurrage.

This incorrect result was a consequence of the sequential solving of the problem that was introduced by the linear use of both an analytical and a simulation model. This observation supports the claims made by Bowersox (2013) that S&OP should aim to *simultaneously* consider as many resources and constraints as possible so that the number of trade-offs considered during optimization would be maximized and the overall performance of the system optimized [3]. Further investigation into the feasibility of either optimizing the VW networks using the Monte Carlo simulation model or incorporating the stochastic demand and lead time days savings associated with each candidate VW city into the network optimization model would be needed to achieve this simultaneous consideration. If either option is implemented, the risk of the hybrid model failing to identify the trade-offs between the demand volume, transport costs and the lead time saved per delivery when the VW networks were optimized would be reduced.

Monte Carlo methods, however, provided a means to simulate the operation to the level at which the network optimization model was unable. They thereby allowed for the manual identification of this trade-off, albeit after the VW networks had been calculated by the network optimization model. The simulation of the implementation of the optimized VW networks within a variable environment generated the data necessary to highlight the questionability of the selection of Huye as the second VW location and thereby inform the adjustment of model parameters for a second iteration of the investigation. The merits of simulation modelling post-optimization were thereby demonstrated.

8.3 Selection of Burera and Rubavu as the Fourth and Fifth VW Locations

Unlike the transition from a one-VW to a two- and three-VW network using the Huye and Kamonyi/Kicukiro VWs, the transition to the four- and five-VW networks drew decreasing additional demand into the VW networks' collective catchments with each additional VW. Burera, which was selected by the EO algorithm as the fourth VW location, introduced the fourth most demand to the network, while the fifth-selected location, Rubavu, was the fifth largest contributor of demand. These selections therefore aligned closely with the focus placed on the objective function to maximize the demand within the collective networks' reaches.

Figure 27 and Figure 33 both show that each of these VW locations also would have introduced more risk of demurrage than the previously activated VW. The variability in the number of demurrage charge between simulated years was also increased by a larger degree when the Rubavu VW was introduced than when the Burera VW was activated. This, unlike the Huye VW activation, aligned with the system theory and assumption that by maximizing the reach of the network the risk of demurrage was reduced, which underpinned the way the objective function of the network optimization model was developed (see Appendix 3).

The relatively high degree of variation in the annual number of demurrage charges incurred by the Burera VW was due to the three-day transit time to this city. Under certain conditions that were brought about by the randomness of the model, the dispatch of trucks would be simulated prior to a dearth of orders. Even though the logistics office would have knowledge of the trucks standing overnight in this VW, the trucks were already dispatched, adding capacity in a catchment in which it was not needed. While this phenomenon would also be experienced at other VWs, the longer transit time to Burera meant there would be a longer period for which trucks would arrive unneeded at the city.

The stochastic nature of the model meant that this build-up of trucks occurred more frequently during some simulated years of operation than others, adding uncertainty to the expected outcome of implementation of this VW. Figure 41 shows the build-up occurring twice in one month of simulated operation. Note that prior to each period of elevated vehicle presence, the logistics office would steadily dispatch trucks to Burera. Although the vehicles were not sent as soon as an excess was experienced, the previously dispatched vehicles would continue to arrive each day, thus worsening the issue of trucks standing overnight.

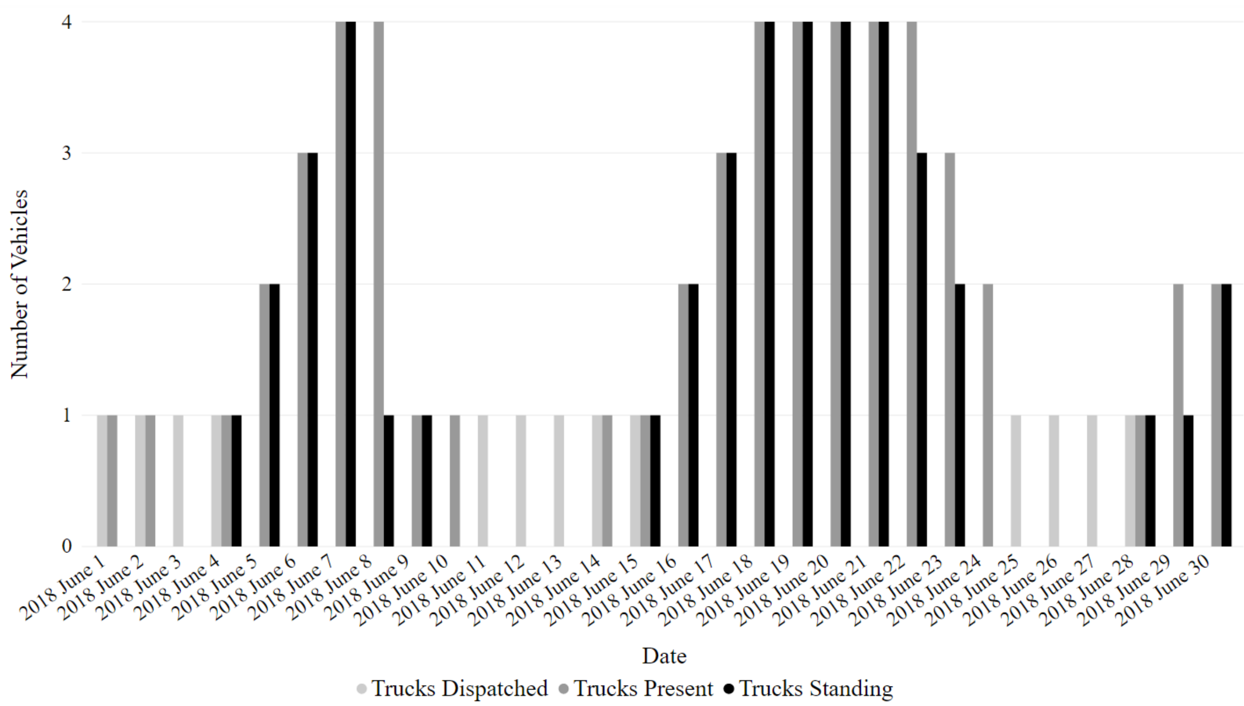

Figure 41: Numbers of trucks dispatched to, present at and standing overnight in the Burera VW for the simulated month of June 2018

8.4 Sensitivity of Performance to each Dimension of Expansion

CIMERWA could have expanded its VW operation along two different dimensions, namely the number of VWs utilized and the use of more speculative planning methods. The results of the hybrid mathematical model provide valuable insight into the relative sensitivity of the operation's risk of demurrage to expansion along each dimension. The multiple facets to expansion along the planning method dimension meant that the comparison of the introduction of new VWs to the use of more aggressive planning rules-of-thumbs had to be performed for each modelled type of planning method expansion.

Figure 26 shows the simulated risk of demurrage was increased to a greater extent by the use of higher forecast factors of safety than the introduction of new warehouses. This was partly due to the de-activating effect of low factors of safety on low volume VWs. If the factor of safety was low enough to prevent the logistics office from ever dispatching trucks to an additional VW, activation of this VW would not have resulted in any additional demurrage charges.

Nonetheless, when safety of factor values were large enough such that these low volume VWs were, in fact, used, the use of one VW resulted in a mean number of charges after a single increment in the factor of safety was always higher than the mean produced by the use of the five-VW network prior to the increment. This suggests that there is more risk associated with a more aggressive planning method than the use of more warehouses. However, the high degree of variation in the number of demurrage charges between simulated years of operation using the five-VW network and factors of safety of 0.8 and one meant that it was possible that the introduction of the fifth VW would have incurred more demurrage charges than an increase in the factor of safety value. This provided an example of the important recognition the results of the stochastic Monte Carlo simulation gave to the uncertainty of the outcomes of implementing a specific strategy in CIMERWA's distribution environment, which would be extensively unpacked when CIMERWA's management focussed in on smaller sets of candidate solutions for final selection.

The simulated performance of the system with respect to associated lead time day saving followed a different trend when the model was expanded, but only when the higher forecast factor of safety values were used (see Figure 29). The simulated savings achieved by increasing the number of VWs were greater than those attained by increasing the factor of safety from 0.8 to one. This suggested that the factor of safety had a greater impact on the customer service advantages associated with VW use than the number of VWs used. However, this was limited to low factor of safety values. When a threshold was reached, the saving in customer waiting time was enhanced to a greater extent when VWs were added to the network.

When the comparison between the sensitivity of the system to the number of VWs and the planning method was repeated using the downward adjustment value, the relationship was more consistent. Figure 32 and Figure 34 show that the operation would be more sensitive to the downward adjustment value with respect to both risk of demurrage and lead time day savings. Numerous instances occurred in which the simulated decrease of the downward adjustment value would have had a greater effect on the system's performance than if even two further VWs were added to the network. Recognition should be given, however, to the fact that the downward adjustment value was decreased by two for each run of the simulation model and, therefore, this conclusion was somewhat engineered by this modelling decision, albeit inadvertently.

There was, however, no such modelling decision to be made for the final facet for which the expansion along the planning method dimension's effect on system performance was compared to the introduction of additional VWs. The range of scenarios tested using different strength grade of cement for loading onto VW-bound vehicles was limited to CIMERWA's product range. Figure 36 shows that the risk of demurrage would have been more sensitive to the number of VWs utilized than the type of cement used for pre-emptive dispatching. Figure 39 shows, however, that the system's performance in terms of lead time savings per demurrage charge would have been more sensitive to the cement strength used than the number of warehouses.

8.5 Favouring Conservative Cement Strength Planning Methods

The high degree of sensitivity of the system's simulated performance with respect to number of demurrage charges and the number of VWs used somewhat masked the difference in the trends observed in the relationships between system performance metrics and the strength grade of cement used to load VW-bound vehicles. Figure 36 and Figure 37 show that the effect of cement strength on the number of demurrage charges and lead time day savings did not align. The use of 42.5N cement strength using the forecast for 32.5N cement sales would have introduced the lowest associated risk of demurrage. However, it would have not produced a greater improvement in customer service than the use of 32.5N strength cement for pre-emptive dispatching of vehicles.

This relationship was due to the unique way in which a direct substitution of the transported product for one of a higher saleability influenced a truck's prospects for finding a customer once already present in the market. 42.5N strength grade cement could have been sold to customers who ordered either 32.5N or 42.5N strength cement. This would increase the likelihood of a vehicle carrying this stock being able to satisfy an order without parking in the VW city overnight, which would simultaneously decrease the number of demurrage charges that would be incurred and increased the number of deliveries executed via the VW network. The latter increased the number of days spent by customers awaiting their product.

Simulated use of this higher strength cement for pre-emptive transport to VWs while incorporating anticipated 42.5N strength cement orders into the planning method achieved further improvements in lead time day savings. However, it would not have done so through the swappability of the product alone. This planning method would have involved the dispatch of more trucks which, in turn, increased the risk of demurrage and the lead time saving.

The points above support the use of 42.5N strength cement while not adjusting the planning method to consider 42.5N strength cement orders over the remaining two simulated options. However, there are some important considerations that CIMERWA management would have to take into account before adopting this tactic. The sale of 42.5N cement to a customer who ordered weaker cement would result in a loss of margin made on the product sold. The production line would also have to be modified to support increased manufacture of the stronger grade of cement. The hybrid mathematical model could be used to assist as a decision-making tool in this regard and the inclusion of production capacity constraints per product type into the model is an opportunity for further research. The model could be expanded to also calculate the loss in margin associated with each scenario.

Delivering 42.5N strength grade cement to customers that had ordered 32.5N strength cement would also require CIMERWA's S&OP function to shift focus from solely considering sales volumes per strength grade to also including the forecasted number of VW STOs predicted by the logistics office. The mathematical model would therefore be a key input to production planning, which would represent an important advancement toward CIMERWA's IBP.

8.6 Favouring Conservative VW Operations

The trade-off between cost and service is one that is frequently addressed in logistics management [42]. Expansion of CIMERWA's VW operation would introduce a similar trade-off, that being between the risk of demurrage charges, which would have been an additional cost, and savings in the lead time experienced by CIMERWA's customers, which would have been an improvement in customer service. The project statement required only an analysis of the risk associated with the expansion of the operation. However, as the operation simulation model provided a mechanism by which this saving in waiting time could be calculated, this beneficial aspect of expansion was also measured and analysed.

Simultaneous analysis of the effect of expansion of the VW model along the dimensions described by the project's supporting objectives on these two aspects of the system's performance provided valuable insight into behaviour of the expanded system, but also highlighted the caution with which trade-offs between cost and service should be considered. Selection of the best option for implementation would require the normalization of these two aspects of the system's performance into a single metric for consideration by CIMERWA management. This could be achieved by taking the ratio of the number of lead time days saved to the number of demurrage charges to reflect the number of days saved by the VW operation per charge incurred. Application of this approach with the results of the Monte Carlo simulation model runs strongly suggests that a conservative approach to the VW operational expansion would add the most value, while not considering many key benefits associated with more aggressive action.

Figure 26 and Figure 32 show the exponential relationships between the risk of demurrage and the expansion of the operation along the number of VWs dimension and the planning method dimension with respect to both the forecast factor safety and downward adjustment values. Figure 29 and Figure 34, however, show linear relationships between these aspects of operational expansion and the number of lead time days saved. This meant that as the expansion of the VW operation was simulated, the disadvantage associated with each expansion step increased at an increasing rate, while the benefit, in general, increased at a constant rate. This resulted in the quotient of these two KPIs, namely the days saved per charge, decreasing with each simulated degree of expansion (see Figure 31 and Figure 35).

If CIMERWA management address the issue of VW operational expansion as an optimization problem with the intention of maximizing the ratio of service improvement to cost, it would most likely interpret Figure 31 and Figure 35 such that the most conservative option, specifically the use of only the Butamwa VW with a factor of safety of 0.2 and a downward adjustment value of eight, was deemed the most desirable option. Furthermore, analysis of the effect of the choice of cement strength to be loaded on VW-bound vehicles (see Figure 35) also favours the more conservative approach and management would conclude that the use of 42.5N strength cement used with the 32.5N forecast would be the optimal selection with respect to this aspect of the planning method dimension.

The abovementioned conclusions fail to recognize the cost benefits associated with the VW concept that are discussed in section 1.1 but were not incorporated into the hybrid mathematical model or the saving per charge KPI. These included the facilitation of improved fleet sizing through the pre-emptive dispatching of trucks and the enhanced opportunity to make use of backhaul transport. These aspects of VW use were not modelled as they were strategic improvements to CIMERWA's logistics operation. The incorporation of the effects of strategic improvements into operational models can be problematic and were not included in the CIMERWA VW simulation model.

Another critical shortcoming of sole consideration of the lead time days saving per demurrage charge metric is that the measure only considers customer service benefits, while the VW concept does not only benefit CIMERWA from this perspective. It also advantages the business from a sales perspective. The increased revenue generated by the additional urgency that would be placed on the sales office to secure deliveries for more VW-bound trucks and the enhanced market share CIMERWA would be enjoyed due to reaching more customers before competitors would have also been difficult to quantify and were not modelled. The approach of maximizing the lead time days saved per demurrage charge would therefore also neglect these unquantified, sales-related benefits of VW operation expansion.

Consideration of these strategic and qualitative benefits of VW should also be used to temper the use of the number of lead time days saved as the single measure of each simulated expanded VW operation's utility. This system performance metric should be interpreted in conjunction with other KPIs that have a stronger correlation with the unmodelled beneficial aspects of VW use.

For example, Figure 27 shows the number of vehicles dispatched to each VW while and Figure 29 shows the contribution of each VW to the lead time days saved by the VW network. The former is a better measure of the strategic cost and sales-related benefits of VW expansion, while the latter is a better indicator of customer service improvements. The simulated relative performance of the Burera VW with respect to these two metrics when 32.5N strength cement was used differed considerably. When viewed purely from a customer service perspective, the Burera VW would be more beneficial than the Huye and Kamonyi VWs when used with forecast factors of safety of 0.8 and one. However, the number of vehicles dispatched to this VW under these conditions was lower than that to Huye and Kamonyi. It could therefore be said that the Burera VW would have been less significant in terms of fleet sizing, backhaul benefits and market penetration benefits even though it would have had a bigger influence on overall customer service levels. The difficulties described above with respect to simultaneous consideration of cost and service to determine a single optimized solution without management input was the reason why the project's problem statement and objectives were stated to exclude the development of an explicit recommendation of an expanded VW operation for implementation. Nonetheless, some recommendations in terms of how to use the data generated by the exercise undertaken for the project are given in section **Error! Reference source not found.**.

8.7 Solution Selection and Implementation Considerations

Section 8.6 cautions an analyst against the sole use of the data produced by the VW hybrid mathematical model to make specific recommendations with respect to the extent of expansion management should implement along each dimension. Analysis of cost versus performance for each dimension of expansion that was simulated, in most cases, strongly favoured a conservative approach while key benefits associated with aggressive expansion were not considered by the model. The enhancement of the model to include these benefits would arguably reduce the analyst's ability to use the tool to make conclusions, as the incorporation of sales-related and strategic benefits would significantly increase the complexity of the model and its dependency on highly accurate data and sound assumptions.

These additional complexities would, most likely, reduce the validity of the model. The outcome of attempting to capture every aspect of the VW operation would likely transform the hybrid model from a tool that provides useful insight into the system's dynamics to support discussion and decision-making to a model that produces output that was inherently questionable.

For example, every degree of expansion to the VW operation would increase the benefits associated with dedicated fleet fixed and variable costing, but these were not modelled. Nonetheless, the output of the developed model would support decisions regarding the number of dedicated vehicles to contract. The cost of demurrage could therefore be weighed against the cost benefit with each additional vehicle added to the fleet outside of the model in the context of a management discussion. If the concept of a fixed and variable fleet were built into the model, new logic with associated assumptions regarding the use of the dedicated trucks and the way they are costed would have to be developed and validated. Furthermore, contracting terms are varied and flexible and the development of rules that could cater for all these terms, many of which may never be implemented, would increase the model's complexity significantly. The introduction of this complexity would put the validity of the model at risk for other analyses for which CIMERWA management might wish to use it.

The sole use of a model to provide recommendations would also require fictional costs or revenues to be associated with unquantifiable benefits and disadvantages associated with VW expansion. This would be a highly subjective exercise, with many stakeholders deserving input. These stakeholders would most likely not fully understand the sensitivity of the results of the hybrid model to the values and a highly iterative modelling approach involving each role-player in each cycle would be needed.

The stakeholder discussion regarding the unquantifiable aspects of VW expansion would be more useful in the context of analysing the output of a model that does not consider these aspects, rather than deciding on values for input values to a model that does consider them. Figure 20 to Figure 39 should rather be presented to management, who can debate the merits and shortcomings of each simulated scenario until a consensus is reached in terms of which expanded operation to implement.

Nonetheless, the trade-offs between cost and customer service that are evident in the analysis of the output of the CIMERWA hybrid model, as well as the scope of operations that are affected by VW expansion may, however, result in lengthy and ultimately unsuccessful attempts to settle on a single solution for implementation. Bowersox (2013) presented a method by which this difficulty experienced during operations analysis exercises might be overcome. By defining a minimum customer service threshold, an analyst can focus on developing a solution focussed solely on minimizing cost while adhering to the threshold as a constraint. This removes the trade-off and the subjectivity associated with the benefits of improved customer service. This approach should be applied to analysis of the output data of the CIMERWA VW expansion modelling exercise.

CIMERWA management should state the minimum number of lead time days saved that should be achieved by the expanded VW operation and the output data should be used to determine the expanded operation that would achieve that minimum with the fewest simulated instances of demurrage[23]. The number of

[23]The customer service threshold need not be defined in terms of reduced waiting time experienced by further customers, but rather as the number of VW trucks dispatched annually or the percentage of demand fulfilled by VW trucks. This may be deemed a preferable threshold measure of the organizational benefit CIMERWA would derive

demurrage charges associated with the expansion should then be considered by management and then the customer service adjusted if the demurrage charges are deemed too many.

This analysis was performed for certain hypothetical values to demonstrate the method and the results presented in
Table 4. It should be noted that there are three facets to each planning method, which results in 75 different planning methods that could be tested per optimal VW network (see Appendix 8). Testing each combination for each threshold value would be overly onerous and would typically only be performed if CIMERWA management expresses an appetite for exhaustive exploration of the solution space after confirming the threshold. The demonstration therefore only considered the planning methods tested and presented in section 7.2, which involved adjusting one parameter value while the remaining planning remained fixed.

Determinations were based on mean values. Recognition should be given to the simulated variability of the outcomes during management discussions when the number of options is narrowed.

Table 4: Recommended expanded VW operations for different customer service thresholds

Annual Customer Service Threshold (Lead Time Days Saved)	**Recommended Expanded VW Operation**				**Mean Annual Demurrage Charges**
		Planning Method			
	Number of VWs	**Forecast Factor of Safety**	**Downward Adjustment Value**	**Cement Strength Grade**	
500	1	0.2	0	32.5N	9
1000	1	0.4	0	32.5N	51
2000	3	0.6	0	32.5N	220
3000	4	0.8	0	32.5N	645
4000	5	1	0	42.5N (32.5N Forecast)	1367

Table 4 shows that manipulation of the moving average forecast value using the factor of safety resulted in the customer service threshold being met with the fewest demurrage charges for all but one customer

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from the VW concept as it is a more direct measure of the expansion of the VW concept, which yields benefits that are not necessarily experienced by the customer, such as increased backhaul opportunities.

threshold value. It could be said that the adjustment of this facet of the planning method would be a better mechanism for controlling demurrage charge risk than the downward adjustment value.

An exception to this trend was when the threshold was set to 4000. This number of lead time day savings cannot, according to the simulation results, be achieved when 32.5N strength grade cement is loaded on VW-bound vehicles[24]. As such, the use of 42.5N strength cement, while using the default values for the factor of safety and adjustment values, was the only option available if this level of waiting time reduction were to be realized. There were only three scenarios that could have met this threshold (see Figure 37). If was found that, in this case, the use of the five-VW network while using only the 32.5N forecast would result in the fewest demurrage charges being incurred.

Table 4 also shows the exponential increase in demurrage charges for equal increments in the customer service threshold. This echoes the exponential nature of the demurrage risk relationships analysed in section 7.2.

The VW operation could be easily expanded along each dimension as a phased approach until the desired option is implemented. The recommendation to CIMERWA management is therefore to first implement the identified lowest risk solution that would achieve the lowest threshold customer service improvement, that being 500 lead time days saved. According to Table 4, this would comprise a network of a single VW. The solitary VW for this network was placed by the optimization model in Butamwa, which is close to Kigali. The current VW used by the logistics office is in Kigali. Implementation of this solution would therefore not require the introduction of any new VWs. It would, however, include the implementation of the moving average forecast used with a factor of safety value of 0.2 and downward adjustment value of 0.

After the operation stabilizes with the proposed planning method, it should be expanded in a stepwise manner until the desired customer service improvement threshold is reached. The timing and extent of the threshold increments should be decided by management while considering all S&OP factors that influence and are influenced by the VW operation, such as promotions, known future customer construction projects and planned plant maintenance. The output of this exercise would be similar to Table 4, except an implementation date should be added for each threshold, which would serve to outline the expansion plan

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[24]Strictly from a mean perspective. The upper whisker for the five-VW box plot when the forecast factor of safety value is equal to one on Figure 30 reaches the value of 4060 days saved. This shows that, for this expanded operation, the 4000 threshold value could be reached, but not reliably achieved.

for the VW operation. The solution that is implemented at each step should be identified by analysing the hybrid model's output data in the same manner used for generating Table 4.

Should CIMERWA management prefer to seek the maximum customer service benefits of the VW operation while stating a maximum demurrage charge threshold, the analyst can reverse the perspective of the analysis demonstrated by Table 4. The number of lead time days saved would not be the constraint, but rather the value the analyst would be seeking to optimize and the combination of planning method parameter values would be chosen such that this value is maximized while the number of demurrage charges incurred by its implementation is not exceeded.

9. CONCLUSIONS

9.1 Summations

The quantitative method that was developed for generating alternative expanded VW network designs for CIMERWA and determining the risk of demurrage associated with each design was demonstrated and produced a set of results that was analysed.

The optimal VW networks that were generated were analysed critically in terms of their utility from a market reach and lead time day saving perspective. It was found that the selected method, namely analytic modelling using River Logic's APS, EO, produced sensible selections of VW cities that aligned well with the geographic distribution of CIMERWA's national demand for delivered cement.

As the numbers of VWs introduced into the network were increased, the market reach of the optimized network increased as expected. It was found that 50.94% of CIMERWA's demand could be satisfied via a single VW, while 87.43% of its total demand could be delivered pre-emptively if five VWs were used according to the optimal networks calculated by EO. The first supporting objective of the project, being the development and use of a model for determining the most desirable VW positions for CIMERWA, was therefore met.

EO was not modelled to consider the difference in lead time day saving achieved by trucks sent to different activated VWs. The objective function was developed such that only market reach and, by extension, risk of demurrage, was minimized. This retained the focus of the exercise on cost minimization, as opposed to customer service enhancement, as per the objective of the project.

The only anomaly experienced during this first modelling activity was the activation of the Huye VW for the two-VW scenario. It was found that the division of the Butamwa VW into the Kamonyi and Kicukiro VWs would result in the market reach of the two-VW network being greater than the placement of the second VW at Huye. This was caused by the modelled transport costs, which were intended to only drive the model's consideration of "divertability" of trucks directed to candidate VW cities. Some fine-tuning of the modelled costs would correct this issue.

While the network optimization model adeptly simultaneously considered the entire set of constraints and decision variables and produced an optimal layout for each number of VWs, it did not consider the stochastic nature of the order patterns in different candidate cities and the logistics office's ability to respond to changing conditions due to differences in transit times to each city. This was a shortcoming that was anticipated when an analytic technique was selected for the first supporting objective of the project.

The second component of the hybrid mathematical model, namely the Monte Carlo simulation model, addressed this shortcoming, but only to a limited extent. The use of sequential modelling of the CIMERWA VW network meant that the advantages of analytic and simulation techniques could both be leveraged. However, it also meant that the simulation modelling activity used, as inputs, network designs that might have been sub-optimal in terms of the additional business conditions and rules that were being simulated. In order for the VW networks to be optimized according to these additional considerations, a method of transforming the results of the simulation model into EO parameter values for iterative running of the model would have to be developed. It may be necessary to redesign the EO model structure itself to support this feedback loop.

The simulation model was, nonetheless, run for each of the five optimized VW networks while each planning method parameter was incremented by discrete, constant amounts with the other parameters fixed at their default values. The sensitivity of the performance of the system was thereby investigated per planning method parameter in isolation, which provided insight into the relationships between each dimension of VW expansion and risk of demurrage. Graphical representation of the generated data showed both linear and exponential relationships between VW expansion parameters and number of demurrage charges, while highlighting scenarios for which the results were highly variable. The second supporting objective of the project, being the development and use of a model for determining the relationship between expansion of the VW operation and the risk of incurring demurrage charges, was therefore met.

The simulation model was expanded to provide insight into a specific aspect of the customer service benefits each expanded VW operation would provide, namely the lead time days saved by VW trucks. The relationships between this KPI and the expanded aspects of the operation was also investigated. The model was thereby able to simultaneously indicate a positive and negative effect of the use of VWs for each scenario tested.

The ratio of the lead time day saving and number of demurrage charges was calculated to give an indication of the benefit versus cost per scenario in a single metric. Further investigation was made into the feasibility of using the generated data, and possibly the saving per charge metric, to not only provide insight into the relationships underpinning the VW operation, but to also provide a specific recommendation to management of a scenario for implementation.

Upon closer consideration of the modelling approach, it was found that the use of the output data to make specific recommendations to management without their further input would be problematic. First, the optimal solution may have existed for a parameter value that lay between or outside the range the tested values, as two of the three planning method parameters were continuous in nature, namely the forecast factor of safety and the downward adjustment value[25]. Second, the optimal expanded operation may have been at an intersection of two or all of the planning method facets that would not have been tested due to only one value being adjusted while the others were controlled. For example, the best solution may have been when a forecast factor of safety of 0.6 and a downward adjustment value of 4 are simultaneously used. This scenario was not tested, as testing of all combinations of all three planning method parameter values would have been overly onerous. This highlighted the shortcoming of simulation modelling to determine solutions when the solution space is large.

Input from management would therefore be required to use the simulation model to simulated targeted scenarios around the area of the solution space that aligns with CIMERWA's appetite for risk. Management and analysts should iteratively work together in this way toward a VW operational design for implementation with which all stakeholders are comfortable.

To expedite the process, the concept of a customer service threshold was introduced, and recommendations were generated for different threshold values to demonstrate the concept. It was found that the downward adjustment of the calculated number of trucks for dispatch to control the level of aggression in the planning method introduced more risk of demurrage than the use of the forecast factor of safety. The factor of safety value and VW network that adhered to the stated minimum lead time day that minimized demurrage charges was determined for each hypothetical threshold value. For example, a saving of 500 days per year would come at an average cost of nine demurrage charges if a single VW and forecast factor of safety of 0.2 was used. Four VWs and a factor of safety of 0.8 would be required to achieve a saving of 3000 days, which incur an average of 645 demurrage charges annually. This highlighted the exponential relationship between of demurrage risk and waiting time reduction.

To achieve annual lead time savings greater than 3810, however, VW-bound trucks would require 42.5N cement strength grade to increase the number of customers to which they can be diverted. It was found that loading this grade of cement while using the 32.5N forecast would result in 4828 days saved by CIMERWA's customers waiting for cement, but incur 1367 cases of trucks standing overnight in the network awaiting orders.

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[25] Although the downward adjustment value is an integer value and not strictly continuous in nature, the parameter was adjusted in increments of two, which meant that there was a value for each increment that was not tested.

9.2 Recommendations for Future Work

The hybrid modelling approach that was developed to address the primary objective of this study comprised of two components, each with multiple sub-components and governed by numerous rules all modelled according to the discretion of the modeller. It follows that for each of these facets of the completed model, both the technique selection and specific modelling decisions utilized could be scrutinized and alternatives researched further.

9.2.1 Optimization of the Planning Method

Only one aspect of the hybrid model utilized analytical optimization methods. It was decided that only the positioning of the VW locations for various networks would be optimized, as it was the only dimension of future expansion that was deemed practical to optimize on an ongoing basis. However, it should be noted that another key decision that was simulated could have been optimized even though the decision-making process was not modelled as one that uses analytical techniques.

The daily decision made by the logistics office of how many vehicles to dispatch to each VW using forecast was simulated as a simple heuristic decision for this study. However, that decision could be made such that the risk of demurrage would be minimized or customer benefit would be maximized by using more sophisticated techniques. The best method of determining the optimal solution to this problem would have to be investigated, but candidate techniques would include linear programming, probabilistic dynamic programming or the use or Markov chains. Not only should the applicability each optimization method be assessed, but the feasibility of implementing its use should also be considered.

If an analytical method of numbering the trucks for VW dispatch is indeed identified, its use by the logistics office would have to be replicated as part of the operating simulation model. The mechanism by which this can be achieved would have to be researched and Microsoft Excel as a Monte Carlo simulation tool would have to be reassessed if the chosen optimize technique must be incorporated. Other simulation software may therefore need to be researched.

9.2.2 Advanced Forecasting Methods

There is also considerable opportunity to enhance the calculation method of a key input to the abovementioned truck numbering decision that was simulated. The method used by the developed model to generate the forecasted number of cement sales in each demand city was rudimentary. Further research into other, more sophisticated forecasting methods that could be employed by the logistics office could undertaken. These would include exponential smoothing and machine learning.

The forecasting method could be added as a parameter of the planning method. The Monte Carlo simulation model can then be run using the identified feasible forecasting methods and the suitability of each method can be investigated. The simulation model can also be used to fine-tune the forecasting input parameters, such as smoothing factors, as well.

9.2.3 Modelling Assumptions

Many simplifying assumptions were made to allow the simulation model to make use of deterministic computations, which are simpler to model and less demanding in terms of computing power than probabilistic calculations, to govern stochastic processes. Replacement of these deterministic calculations with formulae that incorporation pseudo-random variables could result in more accurate modelling of variable processes within the CIMERWA VW operation. For example, using a probability distribution instead of single value for modelled vehicle transit times could increase the validity of the results. Whether this would indeed do so would have to be investigated. The effect this would have on the time it takes for the model to generate results would need to be investigated as well.

Other assumptions that were used to model the CIMERWA VW operation gave rise to constraints. Whether each of these assumptions are indeed “hard” constraints could be investigated further, as the removal of some may greatly influence the level of optimization that could be implemented into an expanded VW operation. For example, if the assumptions that supported the development of a set of VW locations that cannot be changed dynamically are challenged and found to be “soft” constraints, there is an opportunity for the logistics office to optimize the VW network configuration and truck numbering simultaneously. The model would be able to consider changes in demand patterns and numbers of trucking standing at various VW cities when determining where the next set of VWs should position while simultaneously considering how many vehicles to dispatch to each candidate VW city. This would preferable to the sequential solving of the optimization problem, as this method of optimization often yields sub-optimal solutions [3].

The Monte Carlo simulation model could be used to generate data to support the business case for using a dynamic VW network that changes one day to the next. The dynamic re-jigging of the network could be used as an additional parameter of the planning method and thereby be deemed another dimension along which the VW operation could be expanded.

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11. APPENDICES

The assumptions regarding the CIMERWA VW operation that were made while modelling the environment are detailed in this section. Where simplifying assumptions were made, some justification is given. Some validation of assumptions is also included.

11.1 Appendix 1: Modelling Assumptions

11.1.1 Business Assumptions

1. A customer that orders 32.5N/mm^2 strength cement can accept 42.5N/mm^2 strength cement if the agreed invoiced price for the purchased 32.5N/mm^2 strength cement is retained for the stronger cement.
2. Bulk cement sales volumes comprise a relatively small percentage of CIMERWA's sales of delivered cement[26].
3. Bulk cement can only be transported using bulk tanker vehicles. The transport industry is less equipped with this type of asset. Tankers can therefore only be secured by CIMERWA as dedicated fleets.
4. An order for bulk cement cannot be converted into an order for bagged cement by delivering the product using a VW truck. A customer that orders bulk cement is usually equipped with a silo at its site of consumption into which the dry cement is pump upon delivery. These customers often do not have dry, safe facilities at the ship-to address for the storage of bags of cement. Furthermore, bulk cement is sold at a lower price per ton than bagged cement. A customer that orders bulk cement would most likely insist on the bulk cement price being retained if the order is fulfilled using bagged cement. The loss in margin incurred by the fulfilment of bulk orders with bagged cement would render the use of VW trucks for this purpose infeasible.
5. An order for collected cement can be converted into an order for delivered cement by delivering the product using a VW truck.
6. The statistical distributions of transit times to VW cities for trucks transporting VW STOs are the same as those experienced by trucks transporting customer SOs. This can be seen visually when graphically representing the transit times observed from 1 April 2018 to 31 March 2019 for SOs and STOs from the production plant in Muganza to Kigali as histograms (see Figure 42 and Figure 43). The mean transit times are 1.03 and 0.90 days for sales orders and stock transfer orders respectively, which both rounded to a value of one day.

[26] 7.04% of CIMWERA sales for delivery placed between 1 April 2018 and 31 March 2019 were for bulk cement. The remaining 92.96% were for bagged cement.

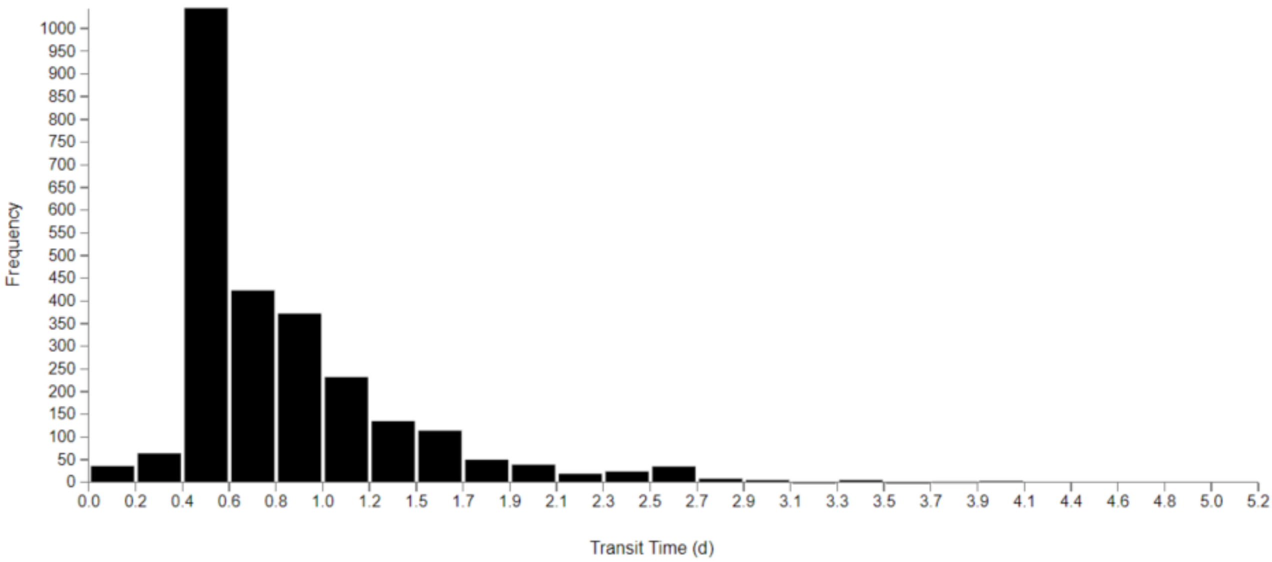

Figure 42: Transit times from Muganza to Kigali for sales orders

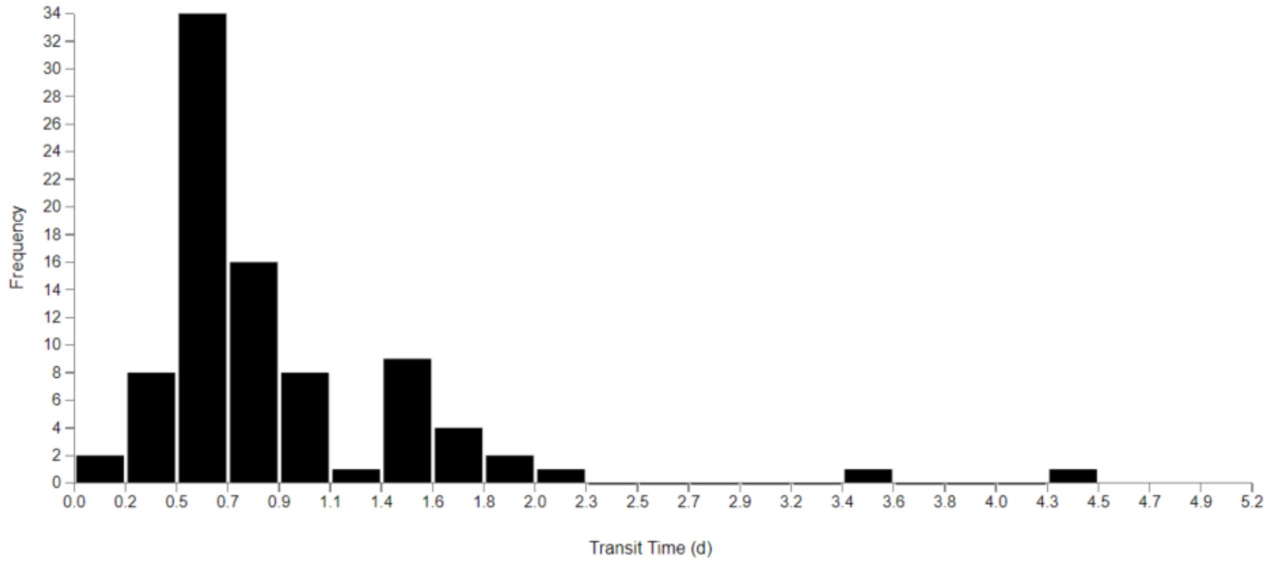

Figure 43: Transit times from Muganza to Kigali for stock transfer orders

7. The further a VW is located from the production plant, the wider the radius of surrounding customers to which a VW truck in the city could be feasibly diverted (i.e. the VW's catchment area). Carriers typically charge a higher rate for providing a longer transport leg and, as such, are less likely to claim for further compensation for the same additional distance travelled for a diversion if the initial leg is further. A carrier would typically object to a diversion that would require more than one day of additional utilization of a vehicle.
8. Transport rates to different cities differ between carriers. It follows that transport rates for different loads to different VWs also differ between carriers.

9. Most customers are receptive to orders that were delivered using VW trucks despite the requirement to wait for the separate delivery of their invoices.
10. Little seasonality exists in the number of deliveries executed by CIMERWA's logistics office, although *ad hoc* spikes in demand do occur due to major construction projects (e.g. CIMERWA was the primary supplier of cement for the construction of the international airport built in Bugesera). This consistency in demand per delivery province can be seen in Figure 44. The relatively low volume of deliveries planned during April 2017 was due to a lack of available product caused by maintenance conducted on one of the factory's two mills.

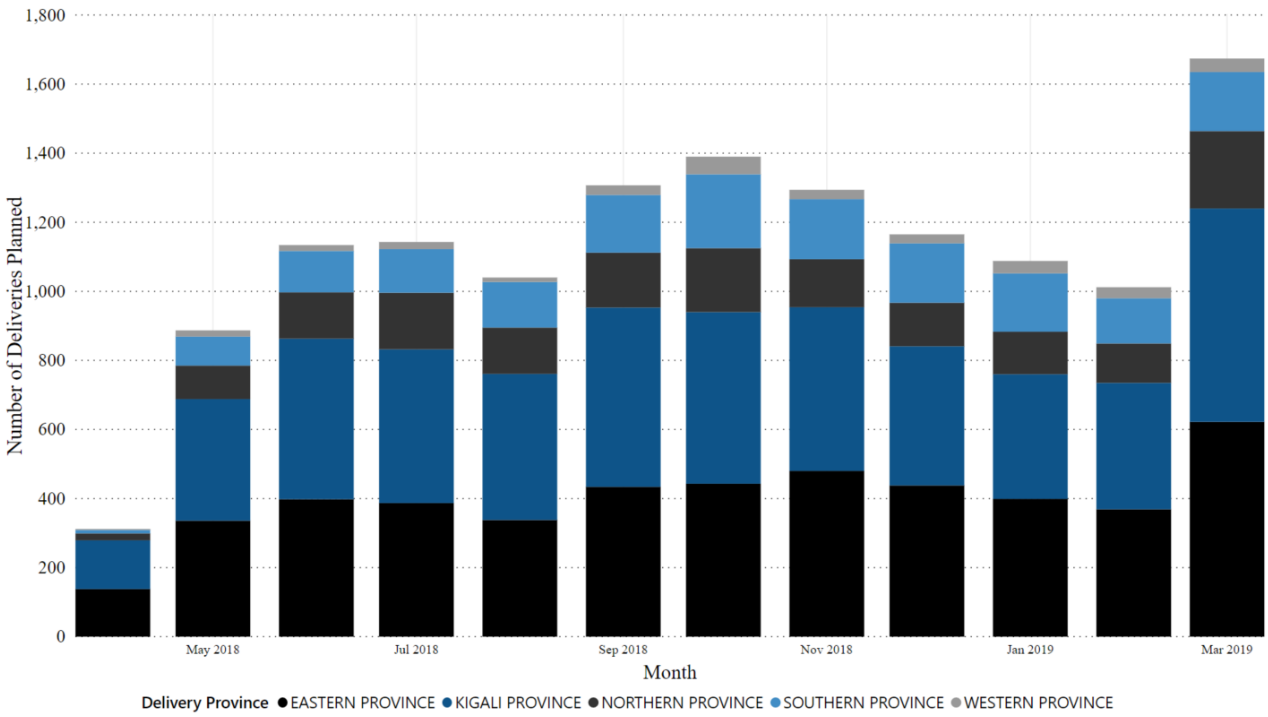

Figure 44: Deliveries planned by CIMERWA per month

11. The factor by which actual travelled distances were greater than straight-line distances due to Rwanda's road network varies negligibly between different lanes (i.e. combinations of origins cities and destination cities). The road network distance for a sample of six different customer cities were obtained using Google Maps and plotted against the calculated straight-line distance (see Figure 45). The relationship was found to be linear, thus validating this assumption.

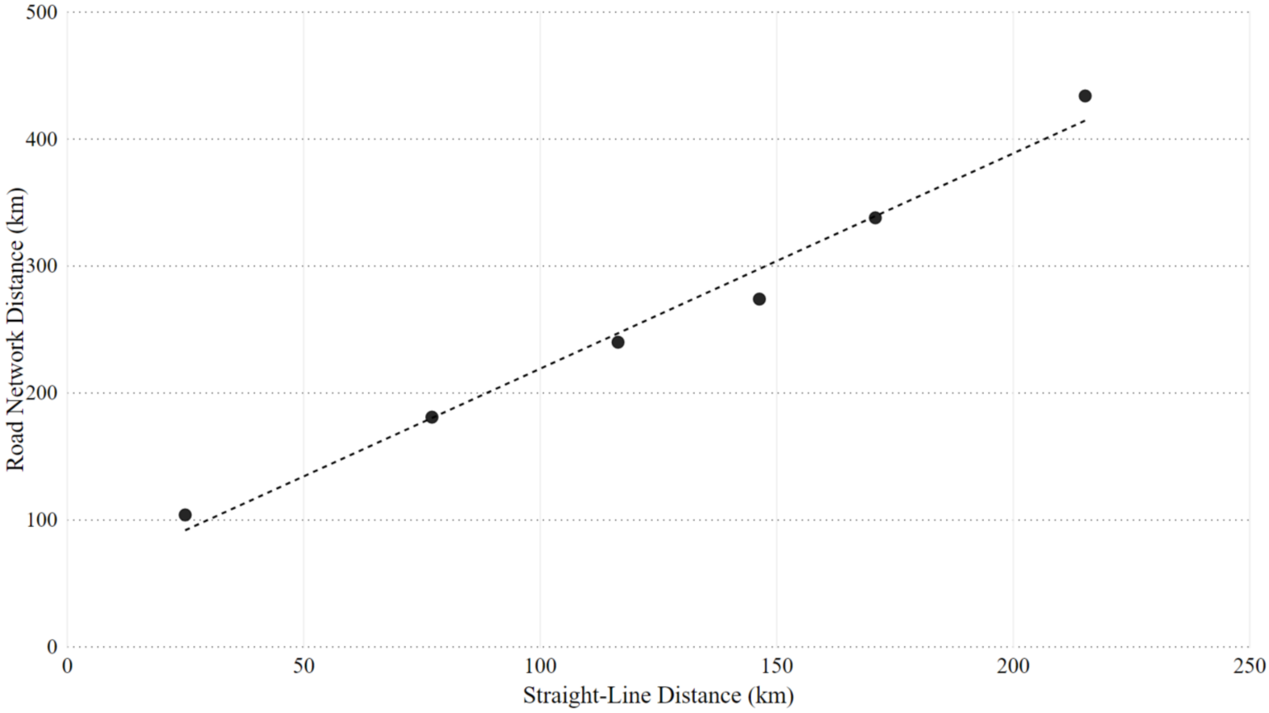

Figure 45: Road network distance as a function of straight-line distance

12. The Rwandan market for less-than-truckload cement is saturated and impenetrable due to the entrenchment of distributers in that particular market.
13. The cost-to-serve of fulfilment of demand for less-than-truckload cement directly from the production plant is relatively high due to the geographic distance of the production plant from the major centres of demand. This cost is inhibitive to less-than-truckload delivery of cement by CIMERWA in the absence of a physical warehouse network.
14. Few Rwandan carriers make use of GPS tracking service providers to record stop arrival times. Those carriers that do use GPS tracking do not integrate these systems with CIMERWA systems for reliable on-time collection and delivery performance reporting. While actual on-time collection data is captured by the production plant's weighbridge, the logistics office relies on the carriers to manually insert the actual times of arrival at customers to the TMS. The accuracy of these carrier-entered actual times is questionable.
15. The CIMERWA production plant and sales office operate year-round, including weekends, except on Christmas Day and New Year's Day. Product can be issued from the plant and orders can be placed by customers on all days of the year, except on these two public holidays. This was validated by analysis of historical data (see Figure 46).

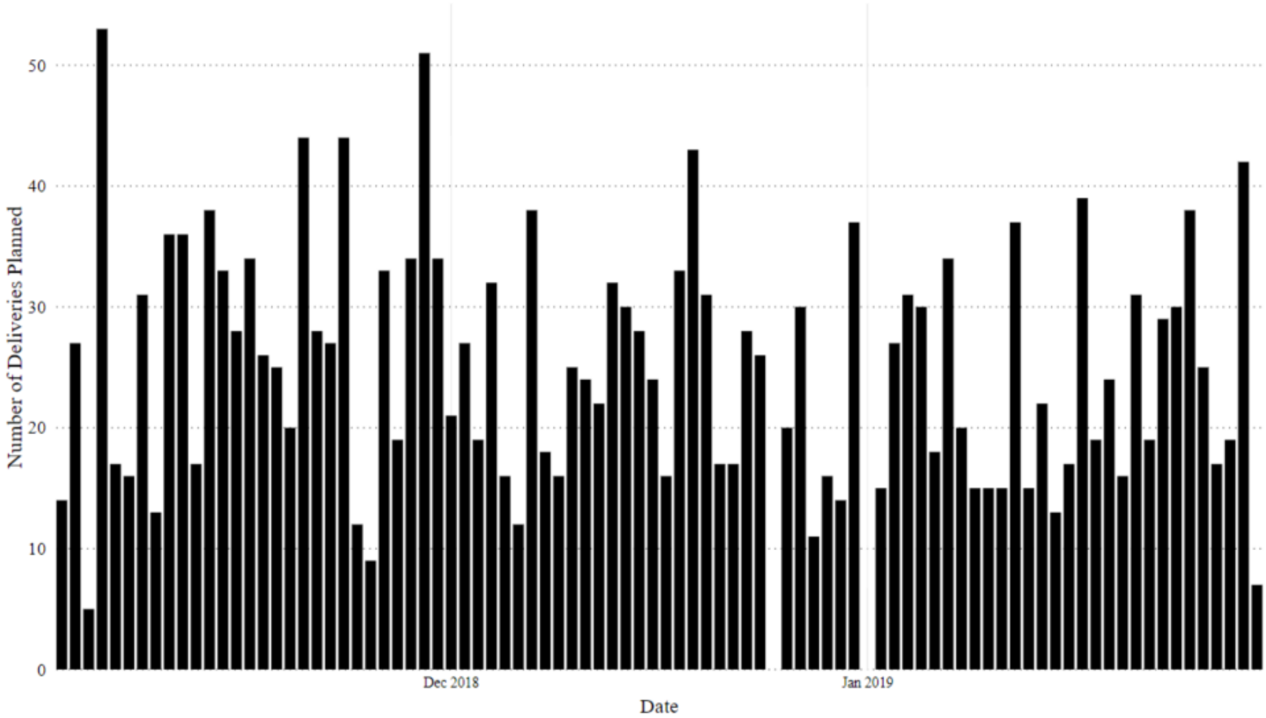

Figure 46: Deliveries planned during December 2018 and January 2019

16. A customer invoice must be with the cement delivery vehicle for cross border transport.
17. The fulfilment of an order is always profitable. There exists no reasonably likely circumstance under which the dispatch of a vehicle to deliver an order would incur more cost to the business than the revenue it would gain through the sale of the stock.
18. The transport market is sufficiently equipped with assets to support CIMERWA's outbound transportation requirements. This capacity is not affected by how the trucks were originally routed. For example, CIMERWA's transport supplier base's capability to deliver cement to city *A* was not hindered by the practice of first directing vehicles to a VW at city *B* and diverting them to city *A* at a later stage.
19. Demurrage charges are not invoiced by carriers. However, expansion of the VW operation such that vehicles would be regularly parked overnight awaiting orders would require a structured demurrage policy to be included in carrier contracts.

11.1.2 Management Assumptions

1. Bulk cement is delivered using the VW concept, but the relatively low sales volumes for this package type and specialized vehicle equipment required for its transport meant that VW loads are planned to enhance bulk tanker utilization. There is therefore no decision made by the logistics office to source more bulk tankers for pre-emptively dispatching bulk cement to VWs (this follows business assumption 1).

2. A VW truck that arrives at its destination city cannot be diverted to a sales order to which another truck has already been assigned and dispatched from the production plant. The latter would be carrying an invoice for the customer that placed the order. Should the customer receive its cement from the VW truck, its invoice would have been on a vehicle that would, in turn, be diverted to a different customer. Delivery of this invoice would be cumbersome and the risk of a driver issuing an invoice to the wrong customer would be significant.
3. A VW truck that arrived at its destination city can only be diverted to customers within the VW's catchment area. A carrier is selected to transport a load to a particular VW based on its rate and performance level associated with the destination's geography (this follows business assumption 8). Diverting a VW truck to a location outside the VW's catchment area to satisfy a sales order would incur a sub-optimal payable rate for the fulfilment of the SO. It is therefore preferable to instruct the VW vehicle to remain in the VW city and await a closer order to be placed and assign another vehicle at the plant to the existing sales order using a carrier that provides the best rate for the SO's destination city.
4. The likelihood of secondary movements of VW trucks due to diversions to customers within the VW's catchment area are explained to and understood by carriers and are factored into the agreed transport rate. Carrier contracts stipulate the maximum additional distance by which their trucks could be diverted[27].
5. Only full truckloads of cement are dispatched for delivery from the production plant to customers or VWs. The route-to-market for less-than-truckload orders of cement must continue to rely on distributers and wholesalers (this follows business assumptions 12 and 13)
6. CIMERWA does not and will not rent, own or operate physical warehouses. External distributers fulfil the customer-facing warehousing function in the CIMERWA supply chain.
7. No customers receive special priority or expedited service. There is therefore no differentiation between customers in terms of preferential allocation of product or agreed delivery lead times.
8. Only orders for delivery within the borders of Rwanda are fulfilled by VW trucks (this followed business assumption 16).
9. VWs can only be established in cities in which demand existed according to historical data.
10. Many drivers do not have a GPS navigation device. It would therefore be difficult to communicate the position to which a truck driver should drive and for the driver to navigate to the VW if the destination cannot be defined using a city name.
11. Definition of transport lanes and subsequent rate negotiations with carriers are easier if the destinations of loads were defined in terms of well-known Rwandan cities.

[27] The typical agreed allowable diversion distanced range between 65 to 170 kilometres.

12. New rates must be sourced from the transport industry if new cities are introduced to CIMERWA's logistics network.
13. An attempt was made to fulfil every order placed. An order was never rejected by CIMERWA based on a profitability assessment after entry to SAP (this follows business assumption 17).
14. Invoicing of demurrage charges, when included in carrier contracts, would be on a per day basis, the values of which are independent of the number of days already spent by the vehicle waiting to offload its cargo (i.e. a flat per day rate was used).

11.1.3 Analysis Assumptions

1. All VW trucks carrying 45.5N[28] strength cement can be diverted to fulfil orders for 35.5N strength cement, which would be accepted by the customer (this follows business assumption 1).
2. Inclusion of bulk cement in the expansion of CIMWERWA's VW operation is infeasible, both from the perspective of dispatching bulk tanker vehicles to VW cities and the use of bagged cement on VW trucks to satisfy demand for bulk cement (this follows business assumptions 2, 3 and 4 and management assumption 1). Sales order placement for and delivery of bulk cement is therefore out of scope for the expansion of the VW operation and was not modelled.
3. Transit times for transport legs from the production plant to VWs are constant and predictable to within an accuracy of one day. This is a simplifying assumption made to remove the model's dependence on reliable carrier performance data (this follows business assumption 14)[29]. While road transport transit times in Africa generally experience high degrees of variation and delays were frequent, incorporating this variation to the model would achieve little in terms of establishing the relationship between VW operation expansion and risk of demurrage. The assumption was therefore justifiable when the following points were considered.
    - CIMERWA's logistics office was modelled to consider only the number of VW trucks located at VW cities when determining how many to simulate to dispatch and not to anticipate the arrival of en route vehicles when making this decision. Transit time was therefore not an input to the planning method and in-transit delays would not have affected the dispatch of VW vehicles.

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[28] "N" was a commonly used short-hand representation of the unit of measurement for cement strength.

[29] While some quality control was exercised by the team, the volume of deliveries that had to be checked and the time required to perform a thorough check of the entered times meant that only random checks could be conducted. As such, there was no existing system of record that provided reliable data that would have indicated the probability and extent of in-transit delays per geographic area.

- The logistics office was modelled to only divert trucks that had arrived at the VW city. Modelling transit time variation would therefore neither favour nor disadvantage the feasibility of implementation of a more aggressive planning method.
- A truck en route to a VW is as likely to experience a delay as a truck en route to a customer in the same city (see business assumption 6). This fairness of comparison meant the validity of the simulation results with respect to the improvement in lead times due to VW operation expansion was unaffected by transit time variation.

4. Transit times were modelled according to the SLAs entered with all carriers by CIMERWA.
5. The time of day at which a sales order was placed does not affect the logistics office's ability to divert a VW truck to the order's delivery location.
6. Only sales orders for delivered cement can be fulfilled by VW trucks (this followed business assumption 5). Order placement for collected cement is out of scope for the expansion of the VW operation and was not modelled.
7. No customers refuse orders of the cement, even if they were delivered on VW trucks, provided it was of a strength equal to or higher than that ordered and the package type was in line with that ordered. This was a simplification of business assumption 9, as data was not available to show which or what percentage of customers required their invoices on the truck that delivered the ordered cement.
8. The utility of VW placement was defined in terms of the number of orders that could be fulfilled by a truck in the VW city (this follows management assumption 3). Optimal VW placement was not defined in terms of the distance of secondary movements of trucks from VW cities to fulfil orders, as these legs did would not incur additional cost if they were within the VW's catchment area (this followed management assumption 4). However, reduction of the distance travelled for these secondary movements was considered as a tie-breaker if the market reach of two candidate VW cities was identical.
9. Continued upward or downward trends and seasonality in demand would have a negligible effect on the risk of demurrage incurred by the expansion of CIMERWA's VW operation. While the inherent variation of demand was modelled, steady movement in the average demand and defined periods of higher or lower than average demand was excluded from the scope for the expansion of the VW operation and was not modelled. This was a simplification of business assumption 10, which allowed monthly or weekly demand variations to be ignored when historical data was used to define the demand experienced in each city. This assumption was deemed justifiable when the following points were considered:
    - Modelling different sales volumes for different individual time segments of the simulated year of operation instead of the entire year holistically would drastically reduce the sample

size of historical data used to define the probability distributions that replicated each city's order patterns per time period. This would have reduced the confidence intervals associated with the inferences made and used to define the characteristics of the modelled system [27].

- Analysis of the demand on a provincial level showed that the spikes observed in some cities due to unusually active customers during certain periods were often balanced out by depressed demand in others.
- The real implemented forecast method that would have informed the planning method would have had the ability to respond to a trend. The forecasting method would also have been adjusted continually to better respond seasonality if it had been detected after deployment[30].

10. Each candidate VW city's catchment area was determined using straight-line distances. This was a simplifying assumption made to remove the dependency of the model on road network distance data, which is usually introduced to the model at a high cost of development [3]. Although straight-line distances were not fully accurate predictions of the distance of secondary motions made by diverted trucks, the consistency of the error factor for all lanes meant that comparisons between different cities and their respective feasibilities for inclusion in a candidate city's catchment area could be assumed as fair. Furthermore, use of road network distances to model the movement of VW trucks would have introduced another assumption, that being that the driver would have always selected the route used by the modeller to determine the distance between the origin and destination. This assumption would have compromised the fairness of comparisons between cities when determining catchment areas, which would have been more detrimental to the validity of the model than the use of straight-line distances for this purpose.
11. Only orders for full truckloads of cement can fulfilled by VW trucks (this follows management assumption 5). The number of sales units (i.e. tons) sold and dispatched per truck is uniform. Order placement for less-than-truckload cement is therefore out of scope for the expansion of the VW operation and was not to be modelled.
12. All orders that were delivered by CIMERWA originate from the production plant and are transported to the customer directly or via a VW. Stock that was dispatched and reached its

[30] The chosen forecasting method, namely moving average, is slow to respond to sustained fluctuations or trends [3]. This method was chosen based on the simplifying assumption that there were no significant sudden spikes in demand. If an expanded VW operation was implemented, this forecasting method would have been replaced by exponential smoothing which overcomes the above mentioned deficiency of moving average forecasting [3]. It can be said that while exponential smoothing would have been a preferable method for the real-world environment, the moving average method was better suited to the simplified modelled environment as it was a simpler method to replicate and fluctuations were not modelled.

destination without a confirmed sales order had to remain on the vehicle, which incurred a standing (i.e. demurrage) charge (this follows management assumption 6).

13. Demand for delivered cement, from a logistics perspective, is customer agnostic (this follows business assumption 9 and management assumption 7). As such, only the geography (i.e. city) of the order's ship-to address is relevant to logistics decisions such as carrier selection or modelled variables such as transit time.
14. CIMERWA sustains an inventory of every grade of cement such that there is always stock available to fulfil sales orders and VW warehouse stock transfer orders as per the logistics office's VW truck planning method. This is known to be untrue. However, this simplifying assumption was necessary to ensure the simulation experiment addressed the primary objective by intentionally investigating the relationship between VW operation expansion and risk of demurrage. This expansion of the operation would have depended on the production line remaining ahead of the order book. If the historical variation of the production line's capacity was introduced to the model and simulated VW loads were held back due to unavailable stock, this constraint would have masked the relationship under investigation. However, a high-level consideration was given to the production capacity of the plant in order to ensure that the model did not simulate more orders being fulfilled by trucks than what could have been fulfilled by the production line. The historical data analysed to define the demand patterns for the model only included fulfilled orders and thereby took production capacity into account. However, the accumulation of sales orders when demand exceeded supply was not modelled, as this would have impinged on the simulated operation's ability to dispatch trucks pre-emptively and allow the modeller to fully explore the risk of demurrage.
15. VW fulfilment of cross border orders were out of scope for the expansion of the VW operation and was not modelled (this follows management assumption 8).
16. Candidate VW cities had to be derived from CIMERWA's existing distribution network (this follows management assumptions 10, 11 and 12).
17. Transportation costs are a function of the straight-line distance travelled from the origin of the leg to the destination. The relationship between transport cost and distance travelled is linear. While this contradicts the widely applied principle of economy of distance, which states that the rate of increase in transport cost decreases as distance increases [3], a number of factors other than distance affect CIMERWA's transport contract rates, such as fixed and variable pricing models that depended on volume promises to carriers. These are subject to constant renegotiation and would have been sensitive to the changes to CIMERWA's distribution strategy that an expansion of the VW operation would have introduced. The assumption of linearity therefore simplified the model significantly. Section 11.3.1 describes the function of transport costs within the VW network

optimization model as a tie-breaker for VW selection when two candidate VW cities would have serviced similar volumes of demand. The modelling of a linear relationship between cost and distance sufficed to favour cities that were better positioned from a distance and cost perspective, which justified this simplifying assumption.

18. While a customer that orders bulk cement would not accept an order of bagged cement and vice versa, relative geographic demand for cement is package type agnostic. For example, if demand for *all* types of cement in city A is twice as great in city B, the demand for *each* type of cement in city A could be assumed to be twice as great for each corresponding type of cement in city B. While historical data showed that differences in the markets' preferences in terms of package type exist (see Figure 47), this simplifying assumption allowed the historical sales volumes per package type in each geographic area to be aggregated. This gave rise to greater confidence in the demand patterns per geographic point of delivery described by the historical data, which was considered more beneficial to the model's accuracy than the differentiation between products in terms of package type.

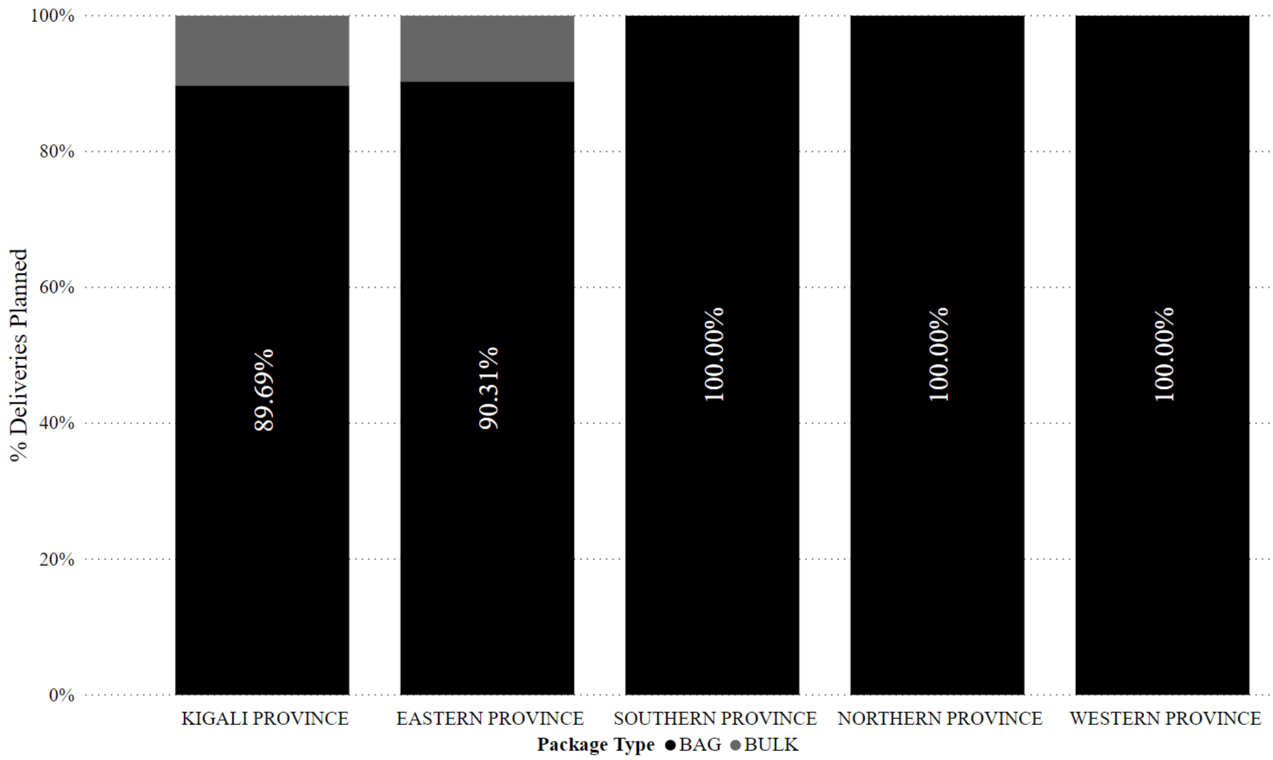


Figure 47: Percentage of orders for each cement package type by delivery province from 1 April 2018 to 31 March 2019

19. Although the ordered cement strength and grade of product dispatched on a VW vehicle affected the feasibility of diverting the truck to the customer, the relative demand for cement per city is the

same per cement strength grade. For example, if the number of orders placed for cement of *all* grades is twice as great city A as in city B, the demand for each corresponding grade of cement in city A is twice as great for *each* cement grade in city B. While the markets' preferences in terms of strength grades may have varied (see Figure 48), ignoring the strength grade specified on the historical sales orders meant this data was aggregated. This produced greater confidence in the relative demand patterns per geographic point of delivery described by the historical data, which was deemed more beneficial than the greater degree of granularity modelled by incorporating cement strength into the analysis.

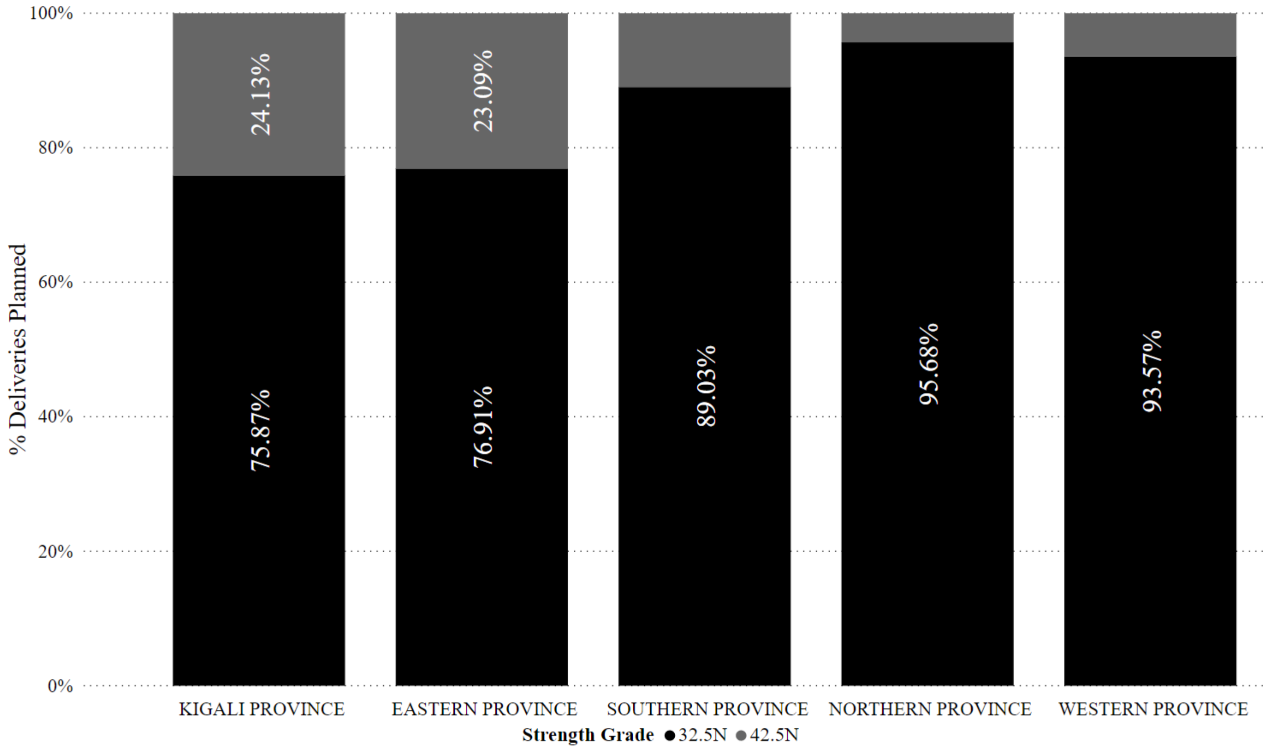


Figure 48: Percentage of orders for each cement strength grade by delivery province from 1 April 2018 to 31 March 2019

20. Vehicles are always available for the dispatch of cement, regardless of the date, day of week and destination of the order. Temporary shortages of trucks do not occur and were not modelled (this followed business assumption 18).
21. Product is never required to stand on a VW truck for such extensive time periods that hydration of the cement occurred.

11.2 Appendix 2: Data Preparation Steps

The following steps were executed to prepare and cleanse the data for data requirement 1:

1. If a SAP order number existed for a load, the original SAP order number was replaced by the diverted order number. The diverted SAP order number was therefore used as the reference to actual order fulfilled by the truck, the ship-to address of which being the true representation of the geographic position of the demand for the product.
2. Package type values that were not "BAG" or "BULK" were investigated and replaced. Only one such record existed, for which the value was "TON". This value resulted from the field mapping used prior to integration between the TMS and SAP and provided an example of a data error that was not corrected as it was not critical to the transportation management process. The TMS product name also indicates whether the ordered cement is bagged or bulk. This record's product name was therefore used to determine the actual package type and the value was corrected. Records with a package type value of "BULK" were then removed from the dataset (as per analysis assumption 2).
3. Product values were aligned where different naming conventions resulted in the same product having different text descriptions on different records. An example are the values "CEM II B-P 32.5 N Bags" and "CEM II B-P 32.5 N BAGGED" which represent same type of product, would be managed by a model as different products if not modified to use a single value.
4. Time values were removed from the order origination date values. This simplification followed analysis assumption 5 and allowed the data for this field to be managed as date values and aggregated as such.
5. Records with a load status value of "VOIDED" were removed from the dataset. Such loads represented orders that were cancelled by the customer or VW loads that were replaced by sales order loads and therefore did not represent actual demand for delivered cement.
6. Records with a load status value of "MONTHLY FIXED COST" were removed. These loads were entered on the TMS in order to capture fixed contractual amounts payable to carriers and therefore did not represent demand for CIMERWA's products.
7. Records with a load group value of "VWH_STOCK TRANSFER" with a load status value of value of "ACCEPTED" or "COMPLETED" were removed. Such loads were entered on the TMS to plan the dispatch of trucks to the Kigali and are usually voided when the truck is diverted. These loads therefore represent VW loads for which a new sales order load was built on the TMS, which would be included elsewhere in the dataset, without following the correct diversion system steps.
8. Last drop location city values that did not correspond to the last drop location reference were investigated and the city values may have been modified subject to the outcome of the investigation.

9. Records with last drop location city values that represent locations outside of Rwanda were removed.

The following steps are executed to prepare and cleanse the data for data requirement 2:

1. A list of the unique delivery city names was derived from the last drop location city values[31] on the consolidated ad hoc TMS report.
2. The city in which the CIMERWA production plant is located (i.e. Muganza) was inserted to the list of city names.
3. Longitudes and latitudes were obtained for each city name using Google Maps.
4. The collected longitudes and latitudes were represented visually on a map of Rwanda using Power BI.
5. City locations were analysed to identify the city names that represented the same geographic location. If values represented the same city[32], the city names on the master and transactional data were modified such that only one name existed for all locations. These duplications were caused by the use of alternative names for the same city or spelling errors upon data entry to SAP or the TMS. An example of such a duplication was the existence of the "Gastibo" and "Gatsibo" city values, which represented the same city. These were identified for further investigation using inspection of the Power BI visualization (see Figure 49). It was found that "Gastibo" is the more conventional spelling of the city name, which was used to replace all instances of the value "Gatsibo" on the master and transactional data.

[31] The location city field on the TMS is populated on the order file transmitted by SAP using the SAP order's ship-to address city value. If the stop location does not already exist on the TMS, the TMS inserts the stop location to its master data using this value on the order file, which is then returned as the last drop location city whenever that ship-to address is entered on a SAP order transmitted to the TMS and built into a load.

[32] This determination was subject to the modeler's discretion. Proximity between the locations was simultaneously considered with the distance of the cluster of locations from other delivery cities to determine whether the locations were indeed recognized as distinct cities or the same location was duplicated on the TMS using different names.

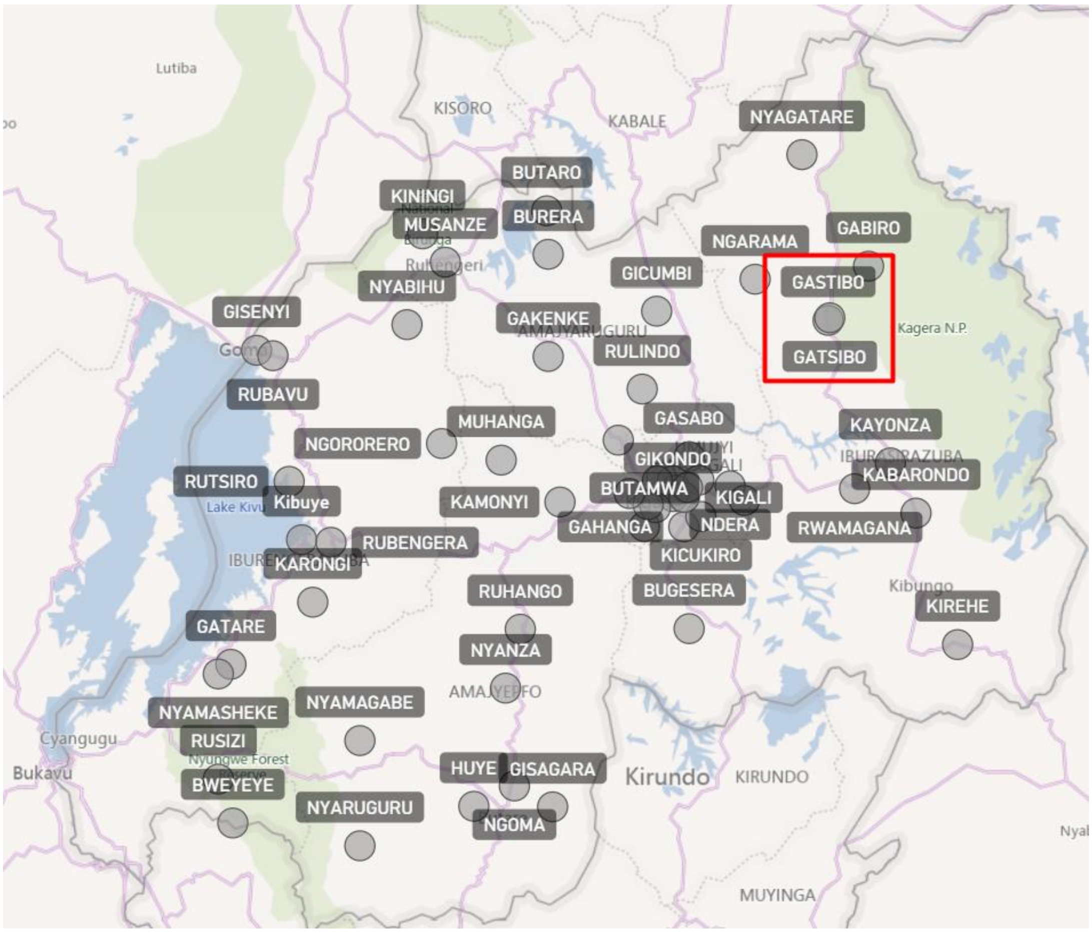


Figure 49: CIMERWA's delivery cities showing a city naming error

6. The visualized city locations were analysed to identify the any cities that were not successfully previously excluded from the dataset for lying outside the borders of Rwanda. An example of such a cross border location was Namoya, which could be seen lying in the Democratic Republic of Congo on the Power BI visualization (see Figure 50). Orders for delivery to this city were out of scope and should have been removed from the data prior to the collection of city longitudes and latitudes. However, the collected co-ordinates of the city revealed the error, which was corrected.

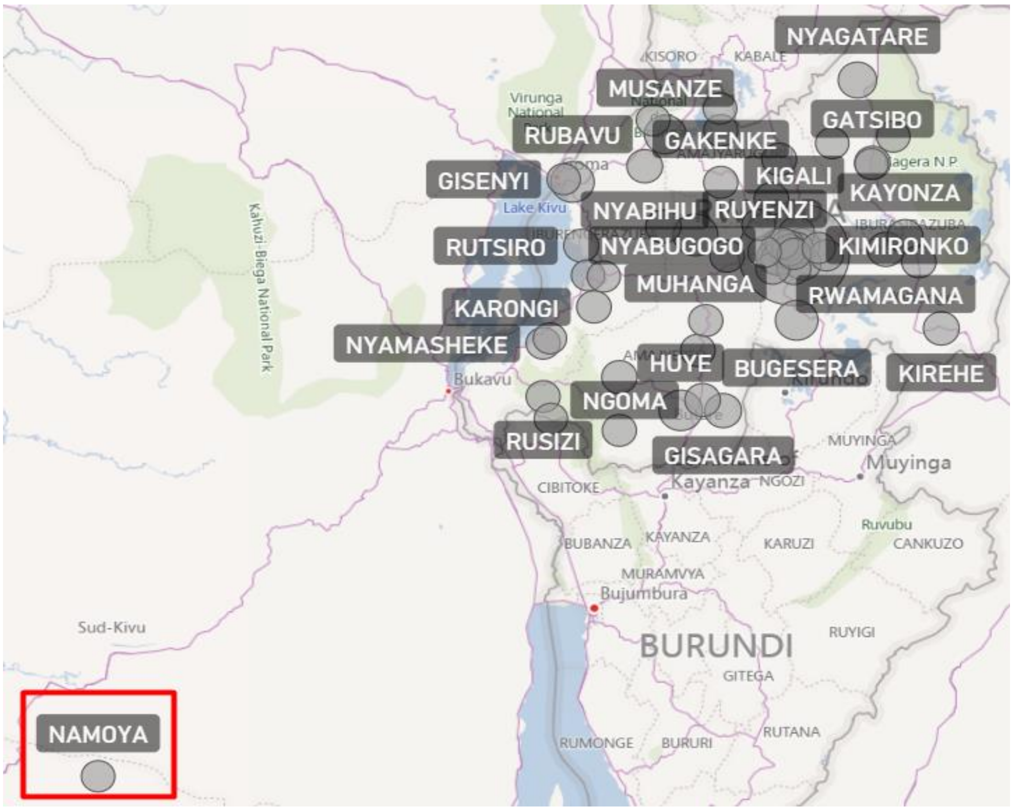


Figure 50: CIMERWA's delivery cities showing a cross border location

1. The city in which the CIMERWA production plant is located, Muganza, was inserted to the cleansed list of delivery cities to produce a list of network cities.
2. A distance matrix was constructed using the list of network cities.
3. The straight-line distance, measured in degrees, between each pairing of cities was calculated using the longitudes and latitudes of each city as inputs to the straight-line distance formula (see Equation 1). The output of the straight-line formula was multiplied by a factor to convert the distance from degrees to kilometres.

Equation 1: Straight-line distance formula used to determine distances between demand nodes

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \times 111.139 \qquad (1)$$

where

- d is distance between city x and city y in kilometres
- x_1 is the longitude of city x in degrees
- x_1 is the longitude of city y in degrees
- x_1 is the longitude of city x in degrees
- x_1 is the longitude of city y in degrees

4. The calculated distances were inserted to the distance matrix.
5. The distance travelled to execute each order in the transactional dataset was inserted as an additional column to the cleansed consolidated ad hoc TMS report.

The following steps are executed to prepare and cleanse the data for data requirement 3:

1. The contractual SLA transit times per delivery province were obtained from the transit time profile on the TMS[33] (see analysis assumption 4) and tabulated (see Table 5).

Table 5: Transit times from the CIMERWA production plant as per carrier SLAs

Province	Transit Time (d)
Eastern Province	3
Kigali Province	2
Northern Province	3
Southern Province	2
Western Province	2

2. The province in which each demand city is located was obtained from the consolidated ad hoc TMS report and added to the demand city master data.
3. The transit time for the execution of each order in the transactional dataset was inserted as an additional column to the cleansed consolidated ad hoc TMS report.

[33] The transit time profile is used by the TMS to calculate the planned delivery date for each load. On-time delivery is calculated using this date as the latest acceptable date by which the vehicle must arrive at the customer.

11.3 Appendix 3: Network Optimization Model Formulation

11.3.1 Objective Function

An optimization model seeks to maximize or minimize a specific system performance metric [3]. A mathematical expression is required to define the relationships that affect this value.

The CIMERWA network optimization model aimed to establish the best possible placement of VWs. The objective function was required to define "best" in terms of the problem being addressed and thereby direct the optimization algorithm toward the best possible answer to the problem modelled.

The primary purpose of a VW is to reduce the lead time for delivered cement experienced by CIMERWA's immediate customers. The most significant disadvantage of VW use is the risk of demurrage charges incurred if demand for cement on a pre-emptively dispatched truck is not secured by the time the truck arrives at the VW city. It could therefore be inferred that the best placement of VWs would maximize the benefit to CIMERWA's customers in the form of reduced lead times and minimize the risk of demurrage.

An optimization problem, however, cannot simultaneously maximize and minimize different values. The manner in which the objective function defines the calculation of the value of interest must cater for the simultaneous consideration of competing objectives such as service level maximization and cost minimization. For this project, this limitation translated into the L.P. technique not being able to both maximize the number lead days saved by each VW network and minimize the demurrage charges incurred through its use.

Although review of the project's primary objective indicated the minimization of demurrage risk is the focus of the investigation, as opposed to the maximization of customer benefit, the network optimization model simultaneously catered for both these objectives. This was achieved by defining the objective function such that the market reach of all VWs in the network was maximized. By maximizing the amount of demand that could be serviced by trucks directed to VWs (i.e. the number of orders for delivered cement placed annually that lie within VW catchment areas), both the number of order lead time days saved annually and the proportion of orders eligible for VW truck delivery were, in turn, optimized. The latter maximized the probability of an order being placed for a truck en route to a VW, which in turn minimized risk of demurrage charges.

Management assumption 7 states that no customers are given priority by CIMERWA's logistics office. It follows that the placement of a VW such that a customer was included in a VW catchment area should have only considered the volume of cement that could be sold to the customer, not the nature of the customer.

The demand could therefore be aggregated and cities, not customers, were used to define the market reach of the VW network on the objective function. This also simplified the model in terms of how the relationships that governed interactions were defined and the computational requirements for calculating solutions.

A third consideration made by the optimization model in terms of what constituted the optimal VW networks was the cost of transport associated with the use of the VWs as positioned. While the benefit of reducing the transport cost incurred by servicing customers using the VW network is outweighed by the avoidance of the cost and other negative intangible implications associated with an instance of demurrage, a relatively small weighting of the objective function was allocated to the transport cost associated with satisfying demand from each candidate VW city. A city was to only be selected by the model for the establishment of a VW over a neighboring city due to transport cost considerations only if the difference in the volume of demand that resides within both cities' catchment areas was negligible.

The catchment areas of Huye, Ngoma and Gisagara provide an apt example of three candidate cities in which transport cost would be the deciding factor for the model when determining the best location for a VW. The catchment areas for all three cities are identical (i.e. the total demand that can be fulfilled by a VW in Huye, Ngoma or Gisagara is the sum of the demand of all three cities) and a VW in any of these cities would contribute equally to market reach of the network as defined by the objective function. However, Huye's closer proximity to the CIMERWA production plant in Muganza makes it the preferred candidate for a VW as trucks diverted from Huye to Ngoma or Gisagara would not backtrack toward the production plant during the secondary movement (see Figure 51).

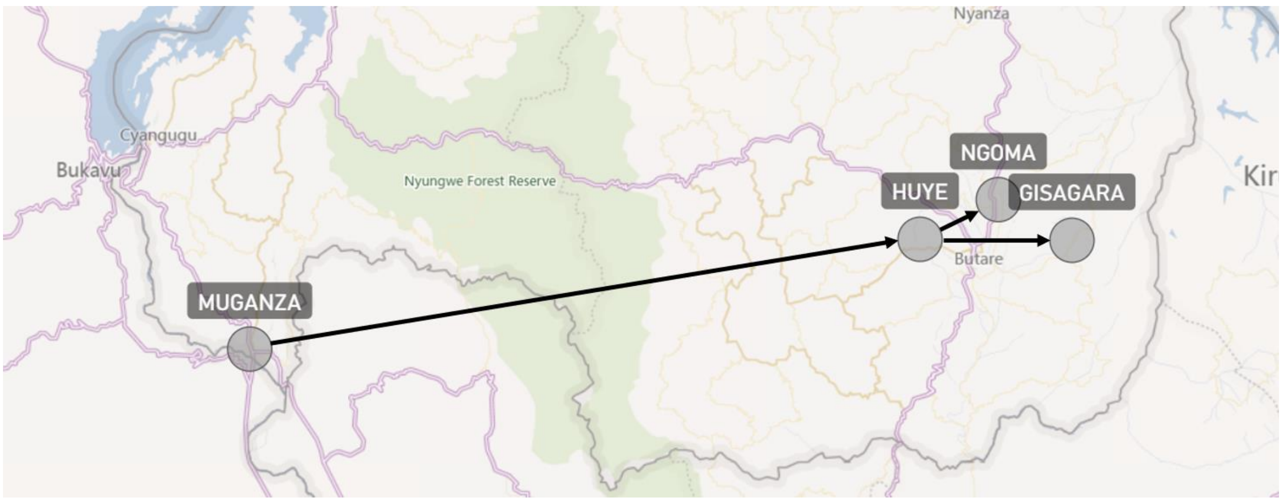


Figure 51: Movements made by a VW truck diverted from Huye to fulfil demand elsewhere in the VW's catchment area

This transport could be considered highly efficient when compared to the diversion of a truck at a VW in Gisgara to meet demand in Ngoma or Huye. The diversion in this scenario would involve the truck travelling back in the general direction of the production plant from which it was originally dispatched (see Figure 52). This same form of inefficiency would be evident if a VW were positioned in Ngoma and a truck were diverted from there to Huye. It follows that Huye's position in relation to the plant and the other cities in its catchment area would result in fewer total kilometres travelled to meet demand in the area if the VW were established there as opposed to Gisagara or Ngoma.

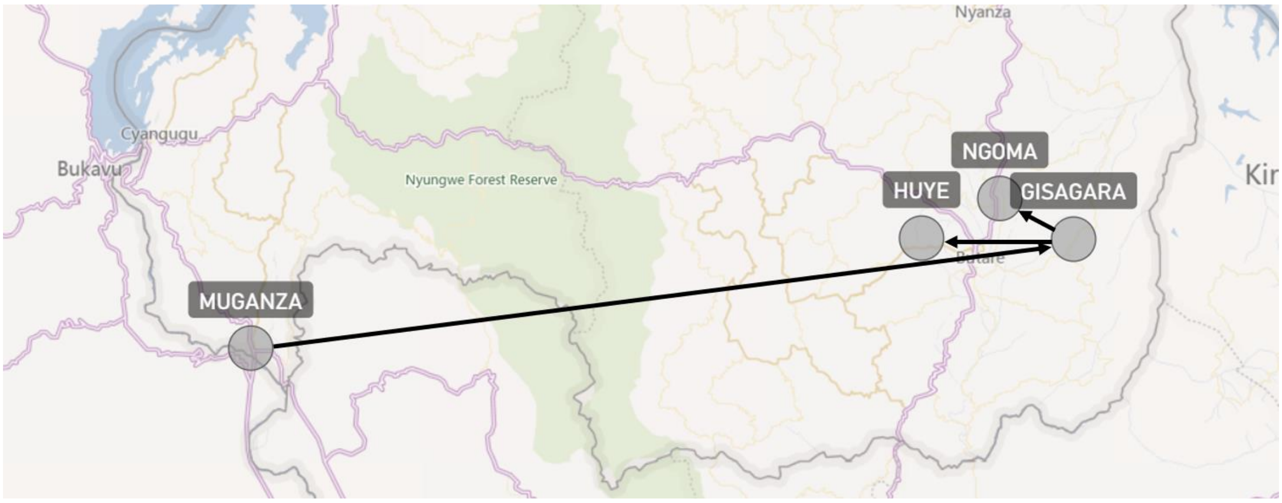


Figure 52: Movements made by a VW truck diverted from Gisagara to fulfil demand elsewhere in the VW's catchment area

Transport costs were incorporated to the objective function to ensure the less efficient scenario would result in a lower utility calculated by the model and thereby favour the placement of a VW at Huye over Ngoma or Gisgara. The focus of the objective function was therefore directed from the volume of orders placed within VW catchment areas to the profit made by fulfilling those orders. The formula therefore included both the transport cost incurred and the revenue generated by fulfilling orders in VW catchment areas. These transport costs, however, were small values relative to the sales price chosen for a truckload of cement, which ensured the algorithm strongly favoured the fulfilment of demand using VW trucks over the reduction of transport cost associated with VW use.

The transport cost associated with the fulfilment of demand using the VW network would be highly dependent on the city in which the demand resides. Furthermore, these values would depend on the city's position relative to the VW from which the truck is diverted as well as the position of the VW relative to the production plant. A transport cost value was therefore required for each link in the distribution network.

Transport costs were modelled by multiplying the average cost per kilometer in Rwandan francs (RWF) of all loads reflected on the TMS transactional dataset and the straight-line distance of the lanes (see Equation 1). The cost values per link were therefore directly proportional to distance and ensured the effective use of transport costs as a tiebreaker for VW placement when candidate city catchment areas serviced comparable volumes of demand while maintaining the simplicity of the model. This consideration supported analysis assumption 17, thus providing an example of the modelling method informing modelling assumptions and a feedback loop from a step in the seven-step process to a previously executed step (see Figure 7).

The use of fictitious transport costs meant that that the optimized values of the objective function for each number of VWs were not true representations of the margin made on orders fulfilled via the VW delivery mechanism. The profit represented by the objective function value is therefore best described as a profitability indicator that incorporated the weighted costs and revenues that were chosen to drive the behaviour of the model, not accurately calculate projected profits. It follows that any validation of the model performed using the objective function values and historically reported profit would be meaningless and were therefore excluded from the scope of the project.

The sales price per truckload of sold cement delivered by a VW vehicle was chosen as an arbitrability high number. This ensured that that the model's algorithm would aggressively pursue as many sales as possible and only consider transported costs when selecting one city as a VW location rather than another if the amounts of cement delivered using either VW network was immaterially affected. A single sales price was chosen for all orders to model the customer agonistic service methodology employed by CIMERWA and described by management assumption 7.

The amount of revenue and cost associated with the establishment of a VW at a candidate city was dependent on the amount of the demand within the VW's catchment area that could be fulfilled via the VW. This, in turn, was a function of the sets of demand nodes that could form part of each possible VW's catchment area. The boundaries of each city's catchment area therefore had to be defined to complete the model's objective function.

Business assumption 7 is stated intentionally vaguely. This is done so to reflect the looseness of the rule that is typically applied to determine the upper boundary of the additional distances carriers allow their vehicles to be diverted without invoicing CIMERWA for the additional kilometres travelled[34]. This assumption does, however, state that the carrier would typically be agreeable to a diversion that requires a day or less of further usage of his/her asset. This suggests that a fixed radius may be used to determine the demand nodes that fall into each city's potential VW catchment area.

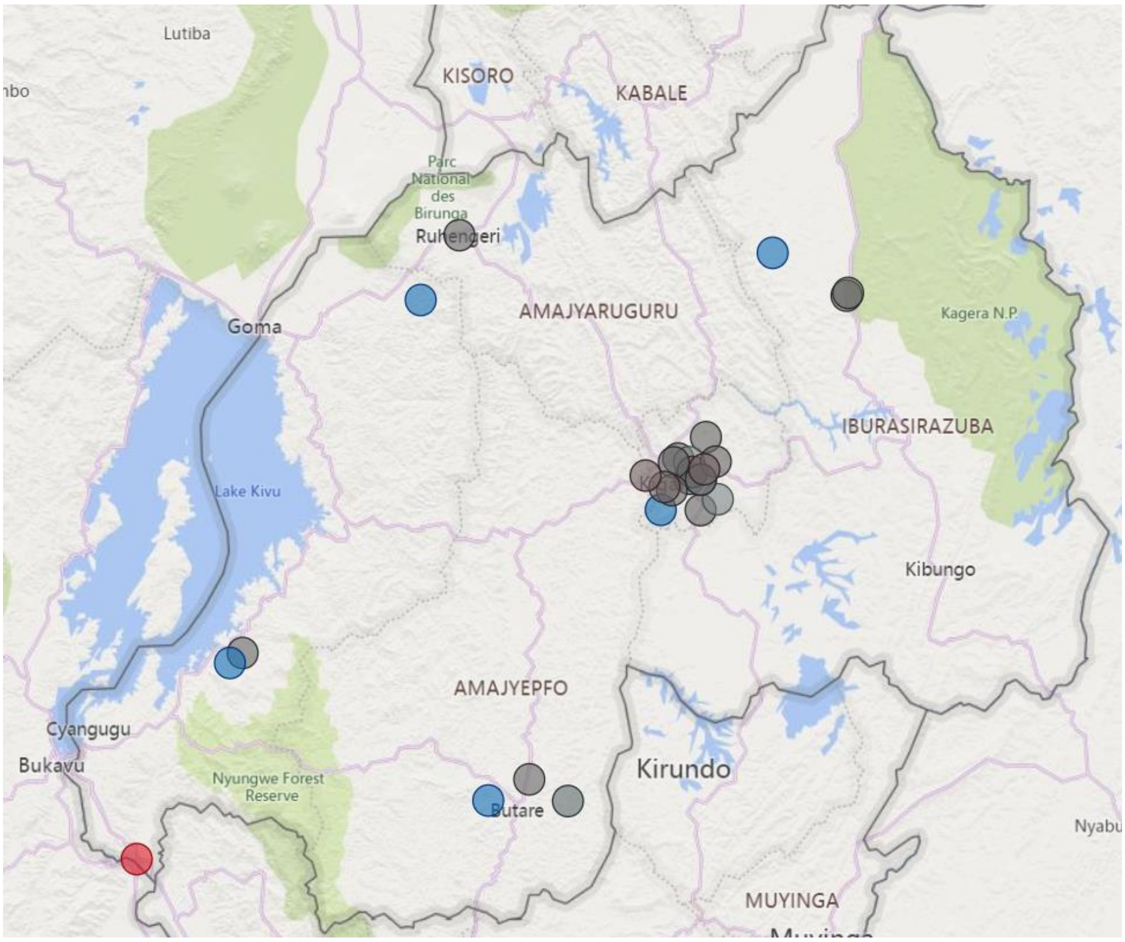


Figure 53: Catchment areas of VWs (blue) defined using a fixed radial distance independent of the VWs proximity the production plant (red)

Business assumption 7 also states, however, that carriers are more lenient regarding the extra distance that their vehicles can be diverted as the length of the initial leg (i.e. the movement for which CIMERWA is invoiced for transport of the load) increases. It was therefore more appropriate to define each candidate

[34] A total distance travelled by a vehicle to a customer is greater if it reaches the delivery location via a VW. If the carrier does not invoice CIMERWA for these additional kilometres, these additional kilometres are executed free of charge and the cost-to-serve is not affected by the indirect delivery. The extra distances travelled by vehicle due to the position of VWs are relevant, however, to the optimization model if the market reach of two or more candidate VW locations differ insignificantly.

VW's catchment areas using a radius that was a function of the distance of the would-be VW from the production plant. A vehicle that has travelled a greater distance to arrive at the VW could, according to the optimization model, therefore be diverted further to fulfil an order. This simulated an increased reach of candidate VWs that are positioned further from the plant and, by extension, the utility of these VWs according to the objective function.

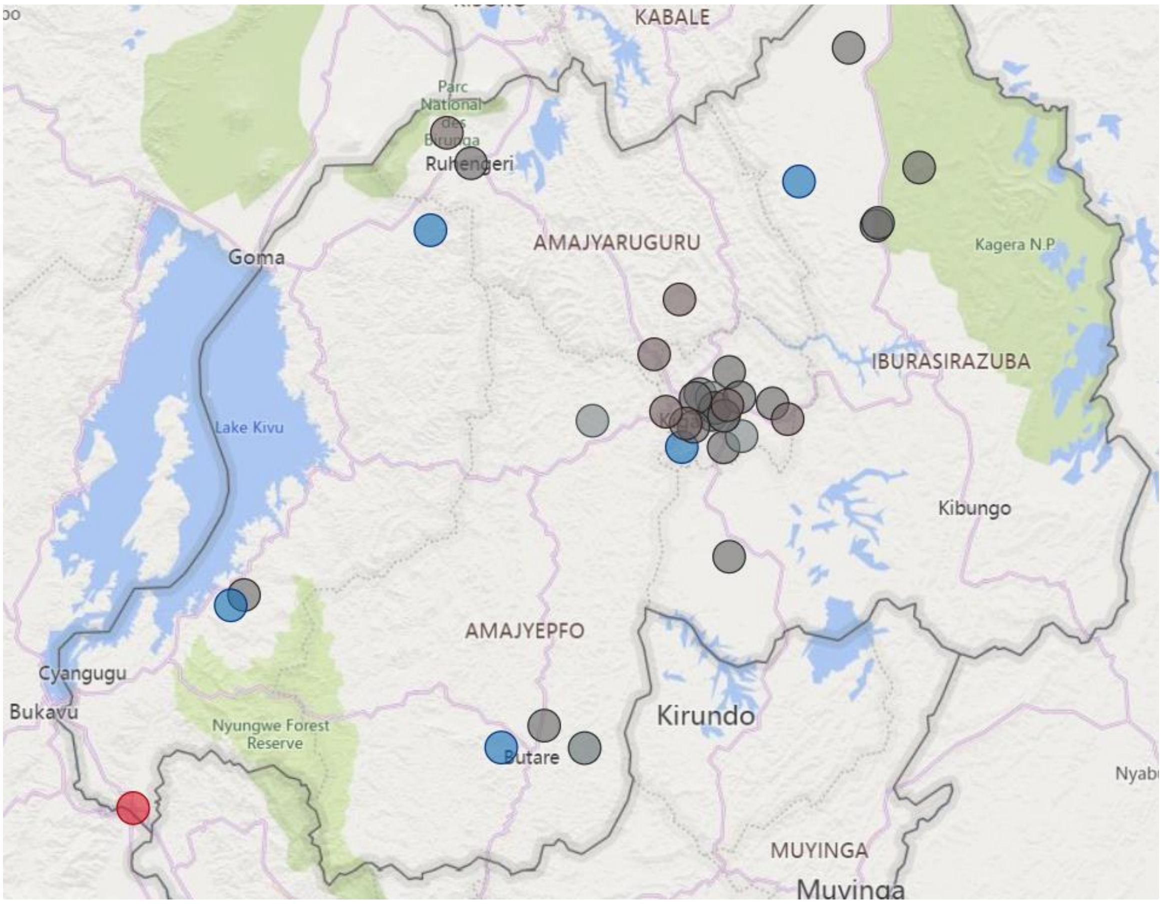
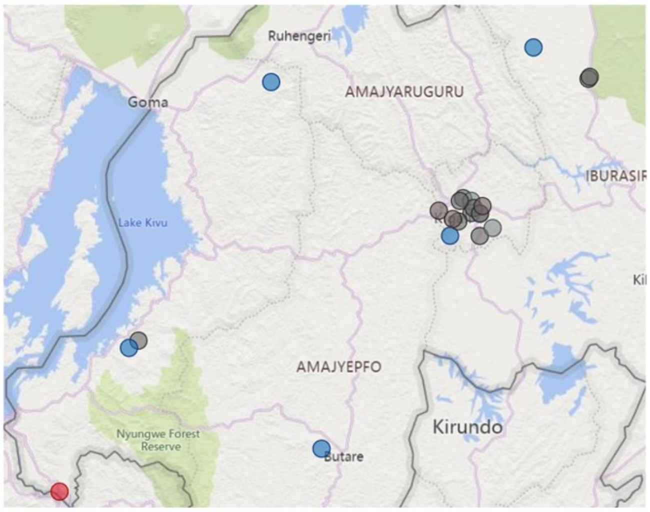


Figure 54: Catchment areas of VWs (blue) defined using the distance of the VW from the production plant (red)

The factor by which the initial leg distances were multiplied to calculate each candidate VW's catchment area radius was determined using the modeler's discretion and visual inspection. The catchment areas had to reflect reasonable sets of destinations to which a carrier would allow the logistics office to direct a VW truck. These areas were visually represented using Power BI for different factor values.

It was decided that the best results were produced when the distance of the candidate VW from the plant was multiplied by a factor of 0.2 to determine the catchment area radius. Examples of the catchment areas generated using this factor are shown on Figure 54. Examples of results generated using other factor values and subsequently deemed less suitable are shown below in Figure 55. Catchment areas generated using a factor value of 0.1 were considered overly restrictive, while those generated using a value of 0.4 were deemed too large to be reached by trucks at VWs without incurring additional costs. The latter would result in more payable kilometres travelled to customers that might have been reached using cheaper delivery direct from the factory, as well as sub-optimal carrier selection[35].

a) Catchment areas of VWs defined using different an initial leg radius factor of 0.1



b) Catchment areas of VWs defined using different an initial leg radius factor of 0.4

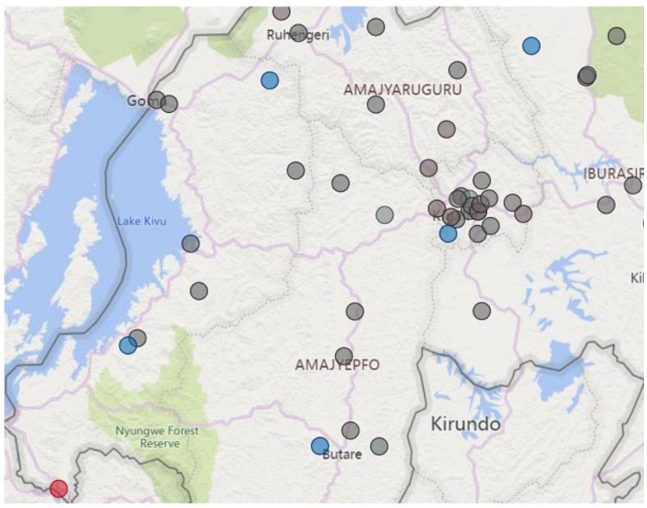


Figure 55: Catchment areas of VWs (blue) defined using different initial leg radius factors

[35] The selection of a carrier for a load to a VW is made using the payable rates database on the TMS. Rates differ between carriers and between destination cities. If a VW truck is diverted without incurring other costs, the original selection of the cheapest carrier for the load remains valid. If the truck is diverted to a city outside the VW's catchment and attracts an additional cost, the parameters of the original comparison of the carriers' rates change and the chosen carrier may not have been the cheapest selection available after all.

11.3.2 Decision Variables

Decision variables are those that are under the control of management and affect the performance of the system [15]. The purpose of an optimization model is to assign values to the decision variables such that the system is optimized (i.e. the maximum or minimum value for the objective function is obtained). These assigned values constitute the solution to the modelled problem and, in a business context, can be thought of as the model's recommendations to management.

It was therefore necessary to consider the function of the CIMERWA network optimization model as a component of the hybrid mathematical model when defining these decision variables. The optimization model was developed to determine the optimal placement of VWs as the operation is expanded along the dimension of number of VWs, as these placement decisions affect the risk of demurrage. The decision variables of the model had to be defined in such a way that their assigned values simulated the effect the VW network design would have on the objective function and represent the model's recommendations for the placement of VWs for different numbers of network VWs.

Management assumption 16 states that VWs can only be positioned in cities within the existing CIMERWA distribution network. It follows that a network of VWs can be exclusively defined in terms of the existing CIMERWA delivery cities. The cleansed and validated list of ship-to address cities was comprised of 57 records, each of which represented a distinct node of demand and hence a candidate city for a VW.

Each of these candidate VW cities was formulated as a binary decision variable (i.e. the assigned value could either be one or zero). The value for each decision variable denoted whether or not the optimization model selected the variable's corresponding city as a recommended VW position. If the optimization algorithm model activated a candidate VW city, the value of the city's corresponding decision variable was set to one and the revenue and cost associated with the establishment of the VW were activated within the objective function.

The effect of such toggling of these decision variables (i.e. activating and deactivating candidate VW cities) on the objective function was considered by the optimization algorithm and produced a set of decision variables values (i.e. VW networks) that maximized the objective function value (i.e. the VW sales profitability indicator).

Equation 2 describes how cities were defined as decision variables. This equation was not used directly by the modeller to establish the decision variables for the optimization engine, as would have been the case if a modelling system such as LINDO was used to solve the problem. However, the construction of the supply chain model using the chosen APS concepts produced such a set of variables with which the APS back-end algorithm could work to produce an optimal solution. The method by which the decision variables were defined using the APS framework is discussed in section 11.3.2.

Equation 2: VW network optimization model decision variables

$$c_i = \begin{cases} 0, & \text{if a VW is not established in city} \\ 1, & \text{if a VW is established in city } i \end{cases} \qquad (2)$$

for every candidate VW city i in the CIMERWA distribution network (i=1,2,…,57)

11.3.3 Constraints

Defined rules were required to restrict the values of decision variables chosen by the optimization algorithm. These bounded the VW network optimization model such that the generated decision variable values for each scenario (i.e. number of network VWs) represented feasible solution that adhered to the business, management and analysis assumptions (see Appendix 1).

The VW network optimization process involved the modeller's manipulation of the number of VWs to be chosen by the algorithm to be established in the CIMERWA distribution network prior to each run of the of the optimization model. By defining this parameter as a constraint, the modeller was provided with an efficient method of producing an optimal VW network for each degree of expansion along the dimension of the number of VWs introduced to the operation.

Equation 3 shows how these degrees of expansion were formulated. By modelling the decision of whether or not to activate a VW in each candidate city as a binary variables, defining the abovementioned constraint as an inequality allows the expansion CIMERWA's VW operation to be emulated by changing only one value prior to running the algorithm: the right-hand side of the inequality. Similar to Equation 2, Equation 3 is included below for illustrative purposes only. The way this constraint was modelled using APS concepts is addressed in Appendix 4.

Equation 3: Maximum VW number constraint

$$\sum_{i=1}^{57} c_i \leq v \text{ , } c_i = 0 \text{ or } 1 \qquad (3)$$

for every candidate VW city i in the CIMERWA distribution network (i=1,2,…,57)

where

- v is the maximum number of VWs that can be established in CIMERWA's distribution network

Failure to constrain the model in this regard would result in the model recommending that a VW be established in candidate city as the model would seek to maximize objective function by maximizing the collective reach of the VWs while minimizing the number of secondary movements and their associated transport costs. This would undermine the purpose of the network optimization model.

It was also critical to define how to govern how the model algorithm could “choose” to generate revenue by satisfying demand through its assignment of decision variable values. This was achieved by defining which the delivery cities could be accessed from each candidate VW city. This restriction was not modelled as a constraint but was rather enforced using data[36]. An arbitrary high value, multiple degrees of magnitude higher than that chosen for the sales price of a truckload of cement, was selected for the cost associated with all transport legs that did not represent feasible VW diversions (i.e. represented truck movements from VWs to cities outside the VWs’ catchment areas). The fulfilment of demand by the algorithm using these infeasible channels thereby produced an extreme negative effect on the objective function such that model would not consider the revenue available in nodes outside a candidate VW city’s catchment area when determining the value of the city’s corresponding decision variable.

Figure 56 illustrates how transport costs were defined to restrict the optimization algorithm’s utilization of VW trucks to meet demand outside their cities’ catchment areas. The modelled transport cost values are shown on each city’s label on the visualization.

[36] The EO modelling framework and the structure of the prepared data informed this modelling decision, as opposed to the elegance of the formulated solution.

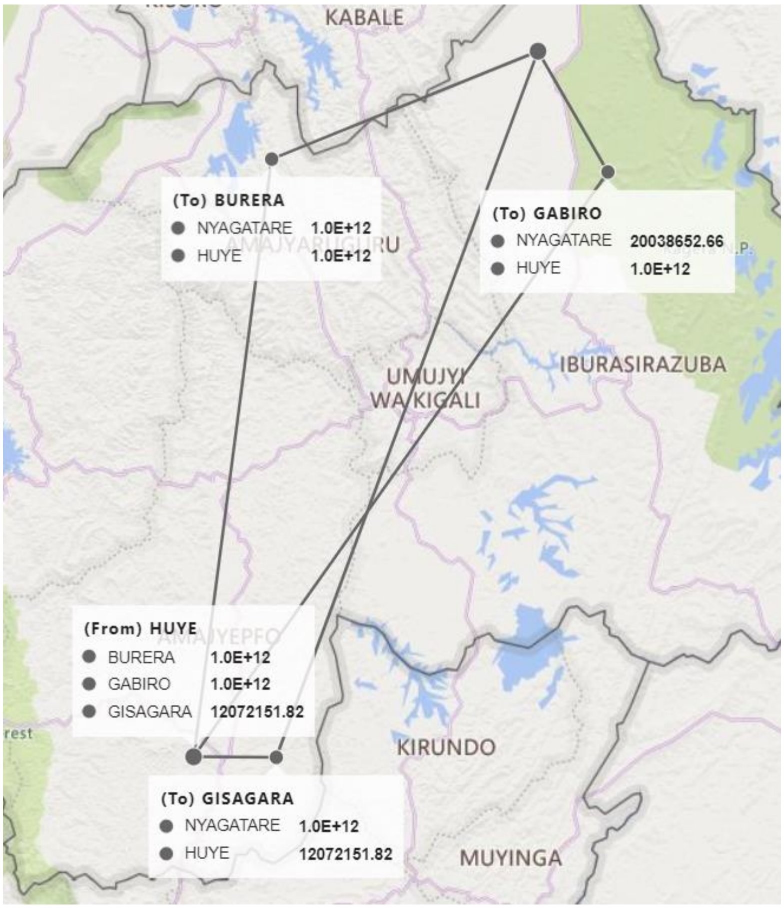


Figure 56: Modelled transport costs per link

Huye, the southernmost city on the map as shown, and Nyagatare, the northernmost city shown, each have one catchment city displayed. The easternmost city shown, Gabiro, lies within Nyagatare's catchment area, but outside of Huye's catchment. The transport cost from Nyagatere to Gabiro was determined by multiplying the straight-line distance between the two cities by the average cost per kilometre and was found to be 20 038 652.66 RWF. This transport cost was small in comparison to the value of the orders placed in Gabiro, due to the large sales price assigned to an order of delivered cement. The model was therefore incentivized to fulfil the demand in Gabiro using VW trucks from Nyagatare if the Nyagatare candidate VW was activated. This would result in the objective function always increasing due to the value of Gabiro's orders if Nyagatare was selected as a VW location.

The transport cost for a leg from Huye to Gabiro, however, was not calculated, but rather assigned an arbitrability high value (i.e. 10^{12}). This resulted in a decrease in the value of the objective function if Gabiro orders were fulfilled by the model using trucks diverted from the Huye VW. This technique ensured that only demand within a candidate VW city's catchment area increased the utility of a VW established in the city. Although not modelled as a constraint, the model was thusly restricted to only consider the sale of stock from a VW truck if delivered to a city within the VW's catchment.

Figure 56 also shows how the transport costs from Nyagatere and Huye to Gisagara, which lies within Huye's catchment area, and to Burera, which lies in neither cities' catchment, were similarly modelled.

11.4 Appendix 4: Enterprise Optimizer Model

Assumption 14 states that the rate of production achieved by the CIMERWA factory allows the company's production line to remain ahead of its order book. The model was therefore required to assume that product was always available to dispatch, whether to fulfil an existing sales order or to position the product closer to the anticipated demand using a VW stock transfer order. It follows that any decisions regarding the inbound logistics of raw materials and manufacturing would therefore have no bearing on the VW operation. All activities upstream of the plant's outbound transport, including the harvesting, sourcing and transportation of raw materials such as gypsum, lime and pozzolana, and the use of those raw materials to produce the cement were therefore not modelled.

Similarly, the activities downstream of the customer, such as the sale and delivery of CIMERWA products to the customer's customer, were out of scope. The boundaries of the EO model therefore only included the factory outbound transport to customer segment of the Rwandan cement supply chain in which CIMERWA operates.

This leg was modelled using three different EO objects, namely a purchase, inventory and customer object, which represented the distinct supply chain levels of relevance to the optimization problem. The three EO objects were joined by "sort" links. These were used to define the flow of cement between the objects.

Figure 57 shows a screenshot of the full design view of the finished EO model. While only three objects are represented (i.e. a purchase object called "Factory", an inventory object called "Virtual Warehouse" and a sales object called "Customer), this number did not represent number of supply chain nodes through which material was modelled to move. Multiple records were created on each object and link, which shaped a supply chain consisting of multiple inventory holding facilities and customers. The creation and modification of these object records could be executed using linked Excel spreadsheets, which expedited the modelling process by removing the requirement for the modeller to graphically create and join large numbers of VWs and demand nodes individually.

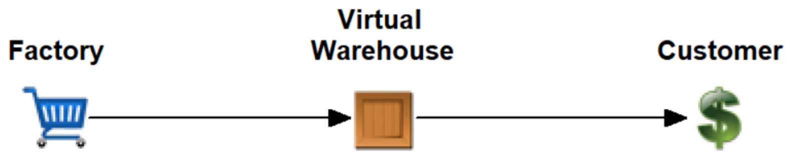
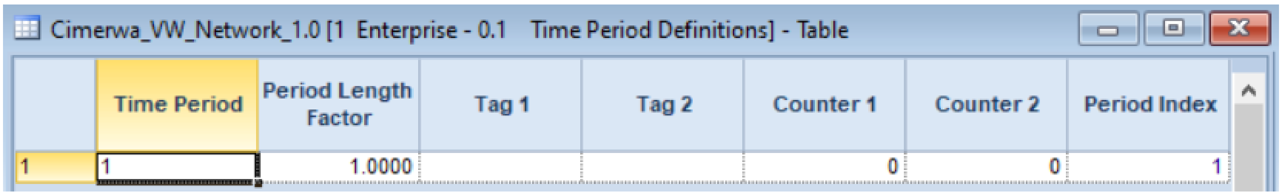


Figure 57: EO design view of the CIMERWA VW network optimization model

The most notable absentee from the model was a conversion object. These are typically used to specify the parameters of different resources (i.e. machines, people, etc.) that convert raw materials into finished goods [32]. The exclusion of the manufacturing process from the bounds EO model made the use of such an object redundant.

An early decision made by an EO modeller is the period definitions used to define objects and their behaviour. There are two broad categories of EO models, namely STP and MTP models. Analysis assumption 9 allows for the disregard of any changes in patterns of relative demand during the year. This allowed the construction of the EO model to be as an STP model. Only one time period was therefore defined for the model, which represented a single year. All historical demand was aggregated as annual demand and inputted to the model as such.


Cimerwa_VW_Network_1.0 [1 Enterprise - 0.1 Time Period Definitions] - Table

	Time Period	Period Length Factor	Tag 1	Tag 2	Counter 1	Counter 2	Period Index
1	1	1.0000			0	0	1

Figure 58: EO time period table of the CIMERWA VW network optimization model

Another early decision taken was the currency used to define revenue and costs. EO supports advanced financial modelling and caters for currency conversion factors that are necessary when modelling global supply chains. The exclusion of cross border logistics from the scope of the model (see analysis assumption 15) meant that only one currency would be required for the EO model. Furthermore, many of the financial parameters for the CIMERWA VW EO model were arbitrarily chosen to drive the behaviour of the model, which rendered most of the actual financial inputs and outputs of the model meaningless. Nonetheless, the use of an actual transport cost per kilometer measured in Rwandan francs (RWF), using TMS data to model the cost for feasible VW-to-customer transport legs, informed the decision to select RWF as the base currency for the model.

11.4.1 Purchase Object

The actual procurement of the materials required for CIMERWA's manufacture of cement is critical to the logistics office and its ability to pre-emptively dispatch cement to VWs. However, the execution of this function is assumed to be such that the management decisions that govern it would make no significant impact on the VW operation nor its expansion[37]. The use of purchase objects to model CIMERWA's procurement of material was therefore unnecessary.

Nonetheless, an APS model requires an entry point for materials, be they raw materials or finished goods, to the supply chain. Materials are introduced to an EO model using purchase nodes. As all activities upstream of factory outbound transport were deemed out of scope for the network optimization model, the CIMERWA's production plant's silos[38] as the starting point of the modelled flow of goods. The factory was therefore modelled as the single record of the EO sales object that would generate the materials that would move through the modelled network.

EO required an exact definition of these materials. It was decided to model only one type of unit that would move through the constructed supply chain, namely a truckload of delivered cement. This somewhat broad definition of the selling and handling unit simplified the optimization model and allowed the historical order volumes for delivered cement to be aggregated before being uploaded to the model as demand. This was supported by assumptions that are discussed in Appendix 1:

- Analysis assumption 18 states that by ignoring the package type of the ordered cement, historical sales volumes provide a better view of relative demand for bagged cement in each city. Although the simulation model was constructed such that only orders for bagged cement could be fulfilled by VW vehicles (see analysis assumption 2), the network optimization model was focused more on answering a specific question rather than modelling reality to a high degree of accuracy. The sales volume per delivery city derived from the consolidated TMS ad hoc report were therefore collapsed into a single, non-descriptive package type for the network optimization.
- Analysis assumption 19 similarly justified the non-differentiation of sales volumes based on cement strength grade. The benefit of combining sales volumes for each grade of cement in each demand node was deemed to outweigh the optimization model's consideration of differing ratios of 32.5N

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[37] One of the key objectives of procurement as a business function is to ensure smooth functioning of business activities through adequate and uninterrupted flow of goods and services to the firm [33]. This was assumed to be fulfilled continuously and no disruptions would be experienced by the logistics office due to a failure of the procurement office to secure materials and supplies. Other key sourcing KPIs, such as the raw material quality and price secured for the business, are more sensitive to the optimization of management decisions. The effect of changes in performance in these areas on the expansion of the VW operation, however, were deemed too immaterial to justify modelling the decisions that influence these changes.

[38] CIMERWA utilizes a bag-to-order production strategy. Cement of various strength grades are produced and stored in silos. Cement for orders for bagged cement is packaged immediately before the bags are loaded onto the vehicle. Cement for orders for bulk cement is loaded directly from the silo into the bulk tanker vehicle.

and 42.5N sales placed at each node. Furthermore, the logic described by analysis assumption 1 (i.e. the willingness of customers to accept consignments of cement of a higher grade of cement than that ordered) would be particularly difficult to model using an analytical method such as EO modelling. Analysis assumption 19 therefore provides an apt example of a simplifying assumption that is required for an analytical method, but which can be modelled easily using simulation methods [15].

- Analysis assumption 11 removes the requirement to model the unit of measure for demand and transport at a level lower than a truckload. Although the standard weight and number of bags sold per sales order and loaded on a single vehicle are 35 tons and 700 bags respectively, modelling a single CIMERWA sale as one truckload as opposed to 35 tons or 700 bags simplified the input data preparation and analysis of the results. A unit conversion of the results to tons or number of bags was done after the model was run when necessary. Calculating and inputting other model parameters, such as costs, were also simplified by using this material definition. For example, the cost per unit of transporting a truckload of cement from the factory to the candidate VWs could be entered as a flat rate instead of a cost per kilometre or cost per bag. Verifying the model and troubleshooting issues were especially simplified by using truckloads as the unit of measure, as errant orders and trucks observed in the results were represented by numbers of orders or trucks, not the quantity of cement. For example, if three orders for cement in Kigali were unfilled using a nearby VW by the model, the shortfall would be represented in the results by a figure of three, not 105 000 or 2100 (i.e. the weight and number of bags of cement the three orders represented). This representation was more intuitive, which made debugging exercises to determine the root cause of the shortfall easier to perform.

Other required purchase object parameters were chosen such that the object continuously supplied the model with sufficient truckloads of cement to develop alternative solutions[39]. These parameters were configured as follows:

- A cost per unit of one (i.e. one RWF per truckload). This low purchase price ensured vehicles were not held back by the model based on the profitability of the order when demand could be met by dispatching the truck to an activated VW (this follows management assumption 13).

[39] The availability of cement was not a constraint for the model. The divergence of the number of VW trucks dispatched to infinity was prevented by the transportation costs associated with the transport of stock from the production plant and the finiteness of demand that could offset that cost.

- An arbitrary high number (i.e. 10^8) for the maximum number of units per period. This high upper limit ensured vehicles were not held back by the model due to an annual production limit being reached (this follows analysis assumption 14).
- An integer variable type. This ensured that no fractions of truckloads were dispatched by the logistics office (this follows analysis assumption 11).

Cimerwa_VW_Network_1.0 [Factory - 1. Purchase Activity] - Table

	Facility	Location	Item Description	Cost/ Unit	Other Cost/ Unit	Min Units/ Period	Max Units/ Period
1	CIMERWA Factory - Muganza	CIMERWA Factory - Muganza_Loc1	Truckload	1.0000	0.0000	0.0000	100000000.0000

Figure 59: EO purchase activity table of the CIMERWA VW network optimization model

11.4.2 Inventory Object

The storage of finished goods at the CIMERWA production plant was not modelled, as analysis assumption 14 states the dispatching of trucks to fulfil sales orders and VW stock transfer orders is never impeded by the silo cement levels. The values to be assigned to the model decision variables were therefore not affected by factory inventory levels or decisions. Introduction of an inventory holding element to the model to account for cement storage before the vehicles were dispatched would therefore not enhance the effectiveness of the model to answer the question asked of it.

Similarly, analysis assumption 7, which states that customers do not refuse orders, implies that the inventory position of the customer would not affect the decisions made by the logistics office in any way. The EO model therefore excluded any concept related to the holding of cement on the customer's side of the delivery leg.

There was, however, a requirement to introduce one inventory element to the network optimization model. While the premise of the CIMERWA VW concept is that inventory is not physically held in a conventional storage facility, a standing vehicle located at a VW city may be considered a temporary inventory holding facility. Each VW candidate city was therefore modelled as an inventory holding facility using a single EO inventory object. This tiered the supply chain model such that primary (i.e. from the factory to the VW) and secondary (i.e. from the VW to the customer) transport legs could be modelled as two distinct activities, each with their own parameters. If the model results showed any stock entering or exiting a record on the inventory object representing a candidate VW city, this indicated that the city was selected for VW establishment. The solution inventory activity for each record on the inventory object thereby constituted the primary output of the network optimization component of the hybrid mathematical model.

Modelling a city as an inventory holding facility required careful consideration of the possible differences between physical warehouses and VWs during the selection of the object's parameters. One such difference is that a physical warehouse has an associated inventory holding restriction, usually imposed by physical space restrictions or stock valuation insurance limits. A VW's capacity to store stock, however, can be safely considered as infinite, as the demand levels and the planning method would certainly limit the amount of stock held in a city before the physical space in which the trucks can park becomes inhibitive.

If the operation was modelled as an MTP EO model, the inventory limit of each VW represented on the inventory object would therefore have been assigned an arbitrarily large value to ensure that the standing room available in each VW city would not restrict the dispatch of stock transfer orders to these cities. However, closer consideration of the STP nature of the EO model revealed that the absence of a time period concept shorter than one year rendered this capacity issue moot. Stock levels on each modelled facility must rise and fall within the modelled time range as material is moved in and out to make the concept of an inventory holding limit relevant. The VW operation was modelled for a single time period, which meant that fluctuations of inventory levels within the year of operation were not simulated. The capacity of each VW was therefore irrelevant. However, as EO requires a value for this limit (i.e. the "Max Carryforward Units" variable) regardless of the MTP or STP classification of the model in order to run the optimization engine, an arbitrarily large value was used to populate this field (i.e. 10^9).

Another similarity between physical and VWs that was made irrelevant by the STP nature of the EO model was that of holding costs. The cost of carrying inventory in actual facilities include the working capital, tax, insurance and obsolesce and storage cost associated with keeping stock in actual facilities. These can be difficult to quantify in such a way that they can be considered by the EO optimization algorithm [3], as many components of these costs are fixed, while the modelled costs must be defined as a per unit value that is activated if a unit of material is kept at the facility for a unit of time.

The cost of keeping stock at a VW, however, is easier to quantity as the vehicle is used as the storage facility. Use of a vehicle for storage is invoiced to CIMERWA by the carrier as a demurrage charge without a fixed component. While this demurrage charge would have been an appropriate value to insert as the inventory holding cost value for each record on the inventory object, the absence of modelled multiple time periods meant that standing vehicles at candidate VW cities would never be simulated and this cost would therefore never be activated and thereby affect the objective function value.

Cimerwa_VW_Network_1.0 [Virtual Warehouse - 1. Inventory Activity] - Table

	Facility	Location	Material	Attribute 1	Max Carryforward Units	Holding Cost/ Unit
1	BUGESERA VW	BUGESERA VWH_Loc1	Truckload	BUGESERA	1000000000.0000	0.0000
2	BURERA VWH	BURERA VWH_Loc1	Truckload	BURERA VW	1000000000.0000	0.0000
3	BUTAMWA VW	BUTAMWA VWH_Loc1	Truckload	BUTAMWA V	1000000000.0000	0.0000
4	BUTARO VWH	BUTARO VWH_Loc1	Truckload	BUTARO VW	1000000000.0000	0.0000
5	BWEYEYE VWH	BWEYEYE VWH_Loc1	Truckload	BWEYEYE V	1000000000.0000	0.0000
6	GABIRO VWH	GABIRO VWH_Loc1	Truckload	GABIRO VW	1000000000.0000	0.0000
7	GAHANGA VW	GAHANGA VWH_Loc1	Truckload	GAHANGA V	1000000000.0000	0.0000
8	GAKENKE VWH	GAKENKE VWH_Loc1	Truckload	GAKENKE V	1000000000.0000	0.0000
9	GASABO VWH	GASABO VWH_Loc1	Truckload	GASABO V	1000000000.0000	0.0000
10	GASTIBO VWH	GASTIBO VWH_Loc1	Truckload	GASTIBO V	1000000000.0000	0.0000
11	GATARE VWH	GATARE VWH_Loc1	Truckload	GATARE VW	1000000000.0000	0.0000
12	GATSIBO VWH	GATSIBO VWH_Loc1	Truckload	GATSIBO V	1000000000.0000	0.0000
13	GICUMBI VWH	GICUMBI VWH_Loc1	Truckload	GICUMBI VW	1000000000.0000	0.0000
14	GIKONDO VWH	GIKONDO VWH_Loc1	Truckload	GIKONDO V	1000000000.0000	0.0000

Figure 60: EO inventory activity table of the CIMERWA VW network optimization model

The STP nature of the EO model also simplified modelling decisions related to the starting conditions of the model. The absence of time as a concept within the model removed the requirement to model logistical performance cycles associated with each activity performed on the material as it moved through the supply chain. It follows that the model could be constructed such that the supply chain would be empty of cement before any material was introduced to the model via the purchase object without any failures to meet demand due to leads times associated with moving the material from the purchase object to the sales object. The minimum and maximum beginning number of units parameters were therefore set as zero for each record on the inventory object.

11.4.3 Sales Object

EO sales objects represent the exit points for materials that have entered a model via purchase objects and moved through supply chain as it was constructed. These objects are also responsible for materials registering a revenue to the enterprise or, in more general terms, increasing the value of the optimization model's objective function.

The boundaries of the CIMERWA VW network EO model meant that any supply chain activity downstream of CIMERWA's immediate customers' point of receipt was out of scope. These locations therefore represented the end point of a material's useful life with respect to the optimization problem being addressed by the EO model. Arrival of the material at these locations represents the event at which the order is deemed complete by the business and revenue is accrued to CIMERWA. It follows that the material should exit the model at this point. A sales object was therefore used to model ship-to addresses[40] for truckloads of delivered cement.

Only one sales object was required, as the various points of consumption of the material were modelled on the same object as different records. The way these consumption points were modelled involved some aggregation. Analysis assumption 13 states that the logistics office does not consider the customer when planning the transport of the customer's ordered cement. Management assumption 11 implies that transportation rates are defined according to the origin and destination cities of the shipment leg. Both these assumptions supported the modelling of demand as the total number of truckload orders per ship-to address city. This represented a further aggregation of demand, having already been aggregated by package type and cement grade, which further enhanced the confidence levels associated with the data inputted EO model.

Each delivery was modelled as a sales activity on the EO sales object. Each activity's parameters were chosen to drive the behaviour of the optimization algorithm to answer to the correct question. These included:

- An arbitrability high number (i.e. 10^{10}) for the price per unit. This high value ensured vehicles were not held back by the model due to the transportation costs associated with orders' route-to-market (this follows management assumption 13).
- A minimum number of sold units per period of zero. This ensured that the model could elect to not fulfil any city's demand using VW trucks. A non-zero value would have rendered the optimization problem infeasible. Since the model was constrained in terms of the number of VWs it could activate and the restriction imposed in terms of delivering to customers outside VWs' catchment areas (see management assumption 3), it follows that each some demand would have to be unfilled for each scenario solved by the EO algorithm.
- A maximum number of sold units per period that correlates to the sales records' cities' corresponding number of annual orders for truckloads of delivered cement fulfilled in the city described according to the cleansed, prepared transactional data on the consolidated TMS ad hoc report. Due to the high sales price and the low purchase and transport costs modelled, this value

[40] A customer may have more than one ship-to address to which cement is delivered. However, few operators within the CIMERWA logistics operation distinguish between customers and ship-to addresses, as most orders' ship-to addresses specify the same city as the orders' bill-to addresses (i.e. where the customers' offices are located). "Customer" is a more widely used term within the CIMERWA logistics environment than any other that might more specifically reference the location to which the cement is delivered. The sales object on the EO model was therefore labelled "customer".

was expected to the correspond to the actual number of sales registered by the model if the city was within the catchment area of any of the candidate VW activated by the algorithm.

- An integer variable type. This ensured that no fractions of truckloads were delivered by the logistics office to a particular city of demand (this follows analysis assumption 11).

Cimerwa_VW_Network_1.0 [Customer - 1. Sales Activity] - Table

	Facility	Location	Item Description	Price/ Unit	Disc, Ret & Comm Rate	Min Units/ Period	Max Units/ Period
1	BUGESERA Customer	BUGESERA Customer_Loc1	Truckload	10000000000.0000	0.0000	0.0000	421.0000
2	BURERA Customer	BURERA Customer_Loc1	Truckload	10000000000.0000	0.0000	0.0000	36.0000
3	BUTAMWA Customer	BUTAMWA Customer_Loc1	Truckload	10000000000.0000	0.0000	0.0000	19.0000
4	BUTARO Customer	BUTARO Customer_Loc1	Truckload	10000000000.0000	0.0000	0.0000	12.0000
5	BWEYEYE Customer	BWEYEYE Customer_Loc1	Truckload	10000000000.0000	0.0000	0.0000	2.0000
6	GABIRO Customer	GABIRO Customer_Loc1	Truckload	10000000000.0000	0.0000	0.0000	2.0000
7	GAHANGA Customer	GAHANGA Customer_Loc1	Truckload	10000000000.0000	0.0000	0.0000	30.0000
8	GAKENKE Customer	GAKENKE Customer_Loc1	Truckload	10000000000.0000	0.0000	0.0000	44.0000
9	GASABO Customer	GASABO Customer_Loc1	Truckload	10000000000.0000	0.0000	0.0000	107.0000
10	GASTIBO Customer	GASTIBO Customer_Loc1	Truckload	10000000000.0000	0.0000	0.0000	2.0000
11	GATARE Customer	GATARE Customer_Loc1	Truckload	10000000000.0000	0.0000	0.0000	1.0000
12	GATSIBO Customer	GATSIBO Customer_Loc1	Truckload	10000000000.0000	0.0000	0.0000	102.0000
13	GICUMBI Customer	GICUMBI Customer_Loc1	Truckload	10000000000.0000	0.0000	0.0000	66.0000
14	GIKONDO Customer	GIKONDO Customer_Loc1	Truckload	10000000000.0000	0.0000	0.0000	51.0000

Figure 61: EO sales activity table of the CIMERWA VW network optimization model

11.4.4 Purchase-to-Inventory Link

An EO link was created to allow the movement of material (i.e. truckloads of delivered cement) from the purchase object, used to model the CIMERWA production plant cement silos, to the inventory object, used to model VWs in each candidate city. Records were created on this link to establish a pathway for the material from the factory to each candidate VW. The absence of such a record would cut off the flow of material from the factory to the VW inventory record, which would be considered as a constraint by the EO optimization engine when determining which candidate VWs to activate.

The cost associated with the transport leg from the production plant to each candidate VW was modelled as the cost per unit for each record. The calculation method for these costs values is discussed in Appendix 3. A different cost was incurred for truckloads directed by the model from the plant to the different candidate VWs defined on the inventory object. This translated to a decrease of the objective function value equal to the number of truckloads moved multiplied by the cost per unit defined on the record. This parameter thereby incentivized the algorithm to activate a candidate VW that is cheaper to reach by truck from the plant than an alternate VW that would generate the same or similar amount of revenue by providing a less costly pathway to the same or similar set of delivery cities.

Other parameters of interest set on the purchase-to-inventory link included:

- A minimum number of units per period of zero. This ensured that the model could elect to not direct any material to an inventory object record from the purchase object. A non-zero value for this variable for these records would have forced the flow of trucks to candidate VWs regardless of whether the VWs were activated by the model. This would invalidate the algorithm's consideration of the effect of the costs associated with the initial leg to candidate VWs.
- An arbitrary high number (i.e. 10^8) for the minimum number of units per period. This high value ensured vehicles were not held back by the model due to an annual transport limit being reached for the lane (this follows analysis assumption 20).

Cimerwa_VW_Network_1.0 [Sort (Purch To Inv)1 - 1. Sort Yield] - Table

	From Facility	To Facility	From Location	To Location	Material	Cost/ Unit
1	CIMERWA Factory - Muganza	BUGESERA VW	CIMERWA Factory - Muganza_Loc1	BUGESERA VWH_Lo	Truckload	93527.0000
2	CIMERWA Factory - Muganza	BURERA VWH	CIMERWA Factory - Muganza_Loc1	BURERA VWH_Loc1	Truckload	114117.0000
3	CIMERWA Factory - Muganza	BUTAMWA VW	CIMERWA Factory - Muganza_Loc1	BUTAMWA VWH_Lo	Truckload	94884.0000
4	CIMERWA Factory - Muganza	BUTARO VWH	CIMERWA Factory - Muganza_Loc1	BUTARO VWH_Loc1	Truckload	119592.0000
5	CIMERWA Factory - Muganza	BWEYEYE VWH	CIMERWA Factory - Muganza_Loc1	BWEYEYE VWH_Loc	Truckload	17454.0000
6	CIMERWA Factory - Muganza	GABIRO VWH	CIMERWA Factory - Muganza_Loc1	GABIRO VWH_Loc1	Truckload	146413.0000
7	CIMERWA Factory - Muganza	GAHANGA VW	CIMERWA Factory - Muganza_Loc1	GAHANGA VWH_Lo	Truckload	99969.0000
8	CIMERWA Factory - Muganza	GAKENKE VWH	CIMERWA Factory - Muganza_Loc1	GAKENKE VWH_Loc	Truckload	101494.0000
9	CIMERWA Factory - Muganza	GASABO VWH	CIMERWA Factory - Muganza_Loc1	GASABO VWH_Loc1	Truckload	106666.0000
10	CIMERWA Factory - Muganza	GASTIBO VWH	CIMERWA Factory - Muganza_Loc1	GASTIBO VWH_Loc1	Truckload	136354.0000
11	CIMERWA Factory - Muganza	GATARE VWH	CIMERWA Factory - Muganza_Loc1	GATARE VWH_Loc1	Truckload	34601.0000
12	CIMERWA Factory - Muganza	GATSIBO VWH	CIMERWA Factory - Muganza_Loc1	GATSIBO VWH_Loc1	Truckload	136790.0000
13	CIMERWA Factory - Muganza	GICUMBI VWH	CIMERWA Factory - Muganza_Loc1	GICUMBI VWH_Loc1	Truckload	117777.0000
14	CIMERWA Factory - Muganza	GIKONDO VWH	CIMERWA Factory - Muganza_Loc1	GIKONDO VWH_Loc	Truckload	101078.0000

Figure 62: EO purchase-to-inventory link table of the CIMERWA VW network optimization model

11.4.5 Inventory-to-Sales Link

The model required a means by while material could move from the purchase object to the sales object to activate sales activity and generate revenue. Without such revenue, the model would only be incurring cost by purchasing material and directing it elsewhere and the algorithm would therefore be incentivized to not purchase truckloads at all. While the purchase-to-inventory link facilitated the delivery of truckloads of cement to the candidate VW cities, another link was required to allow the model to subsequently direct these trucks to points of demand where revenue was generated.

An inventory-to-sales link was therefore created on the EO model, through which material would flow to the customer sales object. A record was created on this link for every combination of candidate VW city, defined as the "from location" (i.e. origin) for each record, and delivery city, defined as the "to location" (i.e. destination).

The configuration of this link's parameters was similar to that of the purchase-to-inventory link. The minimum and maximum number of units per period were similarly set as zero and 10^8 respectively for the same reasons as the purchase-to-inventory link. The key difference, however, between the setup of these two links is observable in how the cost per unit values were defined.

Many of the records' cost per unit values were determined using the same technique used to populate this parameter on the purchase-to-inventory link. For these records, the transport cost associated with a leg from record's origin on the inventory object (i.e. the candidate VW city) to the record's destination on the sales object (i.e. the demand node) was used as the cost per unit value. As the transport cost values were calculated using the straight line distance between cities (see Equation 1), it follows that some of these link records were modelled to incur a zero cost when material was moved from the records' origins to their destinations, as records existed for which the from location and to locations were identical. In such cases, the distance is zero, which translated to a calculated transport cost of zero. This correctly represented a scenario in which the model fulfilled demand in the same city as an activated VW[41].

For example, row one shown on Figure 63 shows an inventory-to-sales link record from the Bugesera VW to the Bugesera demand node. The algorithm's decision to fulfil demand by directing truckloads through this link should not incur a cost to the enterprise, as this flow of material does not represent the physical movement of cement between cities and therefore not incur any significant transport costs to CIMERWA or the carrier.

However, this method of defining the costs per unit was only used for records that represented the feasible legs within the VW's catchment area. For all records that represented movements that would be to cities outside of the VW's catchment, the cost per unit was overwritten with an arbitrarily high value (i.e. 10^{11}). This high value had to be higher than the sales price defined on the sales object (i.e. 10^8) to ensure that any material directed by the algorithm in a way that violated management assumption 3 would incur a loss to the enterprise. The negative impact such a decision made by the optimization engine would have on the objective function resulted in the model never activating the inventory-to-sales link records that represented such movements.

[41] The zero-cost associated with the second leg from a VW city to satisfy demand in the same city ensured that this activity had the same effect on the objective function as a direct delivery from the factory to the customer. While a purchase-to-sales link directly joining the factory and customer objects would have been a more intuitive method of inserting this logic to the model, the material would have by-passed the EO VW in these cases, which would have introduced unnecessary complexity to how the utility of each activated VW would be determined by the algorithm.

For example, all rows shown on Figure 63 except rows one, three and seven show cost per unit values of 10 000 000 000. These costs effectively prevented the algorithm from directing material through these channels and thereby introduced the constraint that VW trucks can only be diverted to meet demand that resides within the trucks' VWs' catchment areas. The "to locations" for rows one, three and seven therefore represent the only link records shown on Figure 63 that can be utilized by the model for moving truckloads from the inventory object to the sales object without incurring a loss. The modelled cost values shown can therefore be used to infer that Bugesera, Butamwa and Gahanga are the only cities of the shown set of 14 cities that are located within Bugesera's catchment. This inference is verified using a Power BI map visualisation (see Figure 64).

Cimerwa_VW_Network_1.0 [Sort (Inv to Sales)1 - 1. Sort Distribution] - Table

	From Location	To Location	Material	Cost/ Unit
1	BUGESERA VWH_Loc1	BUGESERA Customer_Loc1	Truckload	0.0000
2	BUGESERA VWH_Loc1	BURERA Customer_Loc1	Truckload	100000000000.0000
3	BUGESERA VWH_Loc1	BUTAMWA Customer_Loc1	Truckload	17201.0000
4	BUGESERA VWH_Loc1	BUTARO Customer_Loc1	Truckload	100000000000.0000
5	BUGESERA VWH_Loc1	BWEYEYE Customer_Loc1	Truckload	100000000000.0000
6	BUGESERA VWH_Loc1	GABIRO Customer_Loc1	Truckload	100000000000.0000
7	BUGESERA VWH_Loc1	GAHANGA Customer_Loc1	Truckload	15759.0000
8	BUGESERA VWH_Loc1	GAKENKE Customer_Loc1	Truckload	100000000000.0000
9	BUGESERA VWH_Loc1	GASABO Customer_Loc1	Truckload	100000000000.0000
10	BUGESERA VWH_Loc1	GASTIBO Customer_Loc1	Truckload	100000000000.0000
11	BUGESERA VWH_Loc1	GATARE Customer_Loc1	Truckload	100000000000.0000
12	BUGESERA VWH_Loc1	GATSIBO Customer_Loc1	Truckload	100000000000.0000
13	BUGESERA VWH_Loc1	GICUMBI Customer_Loc1	Truckload	100000000000.0000
14	BUGESERA VWH_Loc1	GIKONDO Customer_Loc1	Truckload	100000000000.0000

Figure 63: EO inventory to sales link table of the CIMERWA VW network optimization model

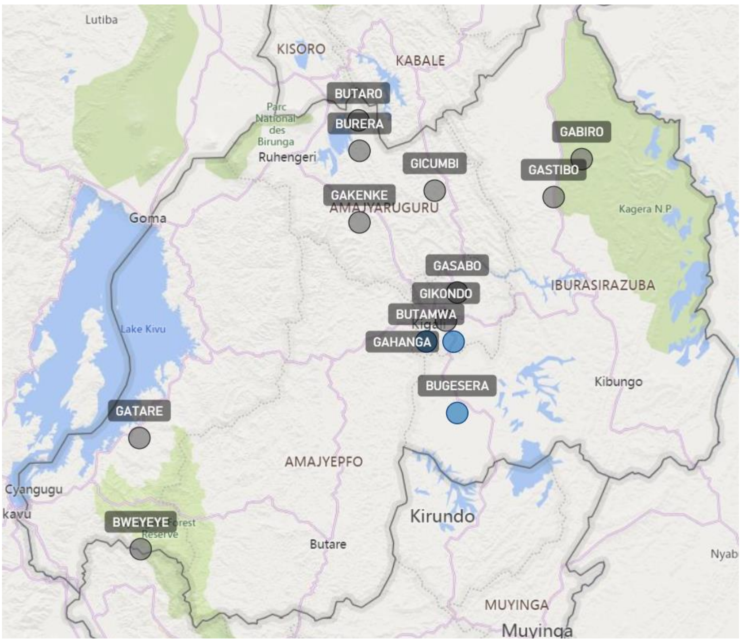

Figure 64: Delivery cities positioned both within (blue) and outside (grey) the candidate Bugesera VW catchment area

11.4.6 Constraint Set

The configuration of EO objects and links described above would not constrain the optimization engine such that any meaningful results would be generated. While the use of transport costs modelled on the inventory-to-sales link would ensure the algorithm would not fulfil demand from any VW that would require the vehicle to be diverted outside the VW's catchment area, the optimizer would still find a way to fulfil all demand without incurring the excessive costs associated with such secondary legs. The market reach of the VW network would thereby maximize the value of objective function.

Although this, in itself, is not undesirable, the mechanism by which the optimization engine would achieve the complete fulfilment of demand using VWs would produce results that are not useful in terms of the purpose of the network optimization model and the larger hybrid mathematical model of which it is a component. The candidate VW cities modelled on the inventory object and the demand node cities modelled on the sales object are derived from the same list of Rwandan cities. A value of zero was assigned to the cost per unit on each inventory-to-sales link record for which the candidate VW city and delivery city overlap. This meant that all orders in all demand nodes could be fulfilled by VWs by directing the truckloads to each demand node's corresponding VW without incurring any of the transport costs associated with diversions. The optimization results would therefore show that management should establish a VW in each of the 57 candidate cities. This does not answer the question intended to be asked to the model, namely where should management establish VWs if the number of VWs used by the CIMERWA logistics office were increased.

Equation 3 illustrates how the optimization model might be constrained in terms of how many VWs might be activated. This constraint was incorporated to the EO network optimization model using the attribute and constraint set concepts.

A "flow: out" attribute was created for each candidate VW and selected as the attribute 1 value for each corresponding record on the inventory object (see Figure 65). These attributes thereby acted as separate counters for each unit of material (i.e. each truckload) that exited the inventory object per record (i.e. candidate VW city).

Cimerwa_VW_Network_1.0 [2 Attributes - 1. Attribute Definitions] - Table

	Facility	Attribute	On/ Off?	Tag 1	Tag 2	Attribute Type	Totaller Type	Object Class Applied to	Use as Default for Objects?	Constraint Type
1	All	BUGESERA VW	on			Flow: Out	Units	Inventory	off	Hard
2	All	BURERA VWH	on			Flow: Out	Units	Inventory	off	Hard
3	All	BUTAMWA VW	on			Flow: Out	Units	Inventory	off	Hard
4	All	BUTARO VWH	on			Flow: Out	Units	Inventory	off	Hard
5	All	BWEYEYE VWH	on			Flow: Out	Units	Inventory	off	Hard
6	All	GABIRO VWH	on			Flow: Out	Units	Inventory	off	Hard
7	All	GAHANGA VW	on			Flow: Out	Units	Inventory	off	Hard
8	All	GAKENKE VWH	on			Flow: Out	Units	Inventory	off	Hard
9	All	GASABO VWH	on			Flow: Out	Units	Inventory	off	Hard
10	All	GASTIBO VWH	on			Flow: Out	Units	Inventory	off	Hard
11	All	GATARE VWH	on			Flow: Out	Units	Inventory	off	Hard
12	All	GATSIBO VWH	on			Flow: Out	Units	Inventory	off	Hard
13	All	GICUMBI VWH	on			Flow: Out	Units	Inventory	off	Hard
14	All	GIKONDO VWH	on			Flow: Out	Units	Inventory	off	Hard

Figure 65: EO attribute definitions table of the CIMERWA VW network optimization model

The abovementioned attributes were assigned to a single constraint set. Two critical parameters were configured on this constraint set:

- A minimum activity per element value of one. This ensured that any record on the inventory object would be considered as an active element by the constraint set at any stage of the optimization process if its associated attribute reflected a value of one or more. A candidate VW through which any truckloads of cement flowed during the modelled time period was therefore considered an activated VW and was counted by the constraint set that utilized the number of active elements.
- A minimum number of active elements per period value of zero. This ensured that the model could elect to not activate any VWs within the CIMERWA distribution network. Although this was not expected to occur, this increased the solution space in which the optimization algorithm could navigate.
- A minimum number of active elements per period value corresponding to the number of VWs of the scenario being optimized. This was the only parameter value that was changed between separate runs of the EO optimization engine. As this value defined the upper limit of active elements on the constraint set, it controlled the number attribute vales that could assume a value of one or more. This in turn controlled the number or records on the inventory object that could register activity, which translated to the number VWs activated by the model.

Cimerwa_VW_Network_1.0 [3 Constraint Sets - 1. Constraint Set Definitions] - Table

	Facility	Constraint Set	On/ Off?	Constraint Set Type	Report Type	Bias/ Element	Min Activity/ Element	Min Active Set Elements/ Period	Max Active Set Elements/ Period
1	All	VWH	on	All Periods		-0.0001	1.0000	0.0000	1.0000

Cimerwa_VW_Network_1.0 [3 Constraint Sets - 1. Constraint Set Definitions] - Table

	Facility	Constraint Set	On/ Off?	Constraint Set Type	Report Type	Bias/ Element	Min Activity/ Element	Min Active Set Elements/ Period	Max Active Set Elements/ Period
1	All	VWH	on	All Periods		-0.0001	1.0000	0.0000	5.0000

Figure 66: EO constraint set definitions table of the CIMERWA VW network optimization model for optimization of a network with one VW (top) and five VWs (bottom)

11.5 Appendix 5: Operation Simulation Model Input Quantities

The input quantities of a Monte Carlo simulation model include external parameters that must defined using data that is sourced, cleansed and prepared. It follows that some of these quantities are discussed in section 3.3. The management of this data is therefore not discussed in this section, although some reference is made to the described assumptions and techniques that influenced the condition of these input quantities and how this condition influenced the operation simulation model.

11.5.1 Daily Delivery Volumes

One such external data set was the transactional TMS consolidated ad hoc report, which provided the historical patterns that governed the generation of random variates that drove the probabilistic nature of the model. The way this data was aggregated to describe the demand patterns directly influenced how the random variates could be generated by the model.

It follows that this influenced the level to which the VW operation could be modelled, and eight key modelling decisions were made when historical demand was defined using the TMS transactional data. Historical demand was defined in terms of the number of fulfilled (1) orders (2) planned (3) daily (4) for bagged (5) cement of each strength grade (6) for delivery (7) to each city of demand (8) during the analysis timeframe.

1. Some orders that were placed for delivered cement might not have been fulfilled by CIMERWA transportation. This could have been due the customer cancelling the order for delivery before vehicle arrived at the ship-to address. If the vehicle had already been dispatched, it would have been diverted to another unallocated order visible on the TMS. Another cause could have been a temporary shortage of the ordered product (see analysis assumption 14) or the customer deciding to collect the cement with his/her own vehicle after the order was placed, both scenarios of which could have led to the original order being cancelled and replaced at a later time. The original order in all scenarios described above would have represented demand that was ultimately not fulfilled by trucks planned by the CIMERWA logistics office and was therefore excluded from the historical demand used to describe the demand patterns.
2. The number of orders, rather that the number of tons or bags ordered, is the simplest unit of measurement for CIMERWA's demand. The detailed reasons for this modelling decision are identical to those that led to the unit of material on the network optimization being modelled as a truckload of cement and are not therefore discussed in this section. As analysis assumption 11 extends across both components of the hybrid mathematical model, the selection of this unit of measurement is acceptable for both models contained within the hybrid model. Furthermore, the same modelling considerations regarding unit conversions discussed in the description of the

purchase object in Appendix 4 apply to the operation simulation model and, as such, the same unit of measurement was chosen for describing demand patterns derived from the historical data for the simulation model.

3. The TMS transactional data included multiple date fields that described the lifecycle of each order for delivered cement from a logistics perspective (e.g. order origination date, load created date, planned, actual and original planned pick-up and drop-off dates, etc.). The logistics office first obtains visibility of the requirement to delivery cement using the TMS between one and 10 minutes after the order is created on CIMERWA's ERP, SAP, due to EDI between the two systems. At this time, only the order origination date (i.e. the date and time at which the order was entered on SAP) is captured on the TMS order. The order is actioned daily shortly after the order entry cut-off time, at which time the load created date (i.e. the date and time at which the delivery of the order was planned) is generated. The remaining date values are populated during the planning and execution process. It follows that the date on which demand is registered was best described by the order origination date. However, as the operation simulation model logic was centered on planning decisions, that the date on which the demand was first actioned represented the most relevant date to these decisions. For example, if several orders were entered on SAP for a new customer on 2 January, their order origination dates would reflect as such on the TMS transactional data. However, if the deliveries were placed on hold by the accounts receivable department due to a credit issue, this value would not be an accurate reflection of the date on which the planning decisions regarding the orders were made. If the credit issues were resolved on 9 January, the deliveries would have only then have been planned then and thereby stamp the loads with a load created date of 9 January. The input data should associate this demand with the later date.
4. The chosen duration of the standard time bins used for defining demand had to be small enough to model the VW planning rhythm simulated by the logistics office, as well as the implications of decisions made by this team and the random variates generated by the model. The logistics office operates on a "plan today for tomorrow" basis, which establishes and maintains a daily cycle of assessing the demand for delivered cement, transportation capacity and carrier rates and allocating orders to carriers who, in turn, allocate their orders to vehicles and drivers. This supported the daily modelling of the operation, as opposed to defining the stages of the model in terms of weeks or months. Furthermore, transit times of trucks to VW cities are defined in terms of days of travel and no standard service level (SLA) lead time for any city in which demand resided during the analysis periods exceeds three days. This would prevent the model from distinguishing between near and far VWs if the bins were of a week or longer and the incorporation of the lag between the dispatch of trucks to VWs and the arrival of trucks at customers within the VWs catchment areas into the logic would not have been possible. The practice of daily planning of the collective demand after a

cut-off time also prevented the modelling of demand patterns on any level lower than that of a day (e.g. hourly or per minute) from adding any value to the simulation. Analysis assumption 5 also renders intra-day modelling meaningless. The historical demand was therefore aggregated into daily time buckets.

5. Although the distinction between cement package type was ignored for the network optimization model, the simulation model component of the hybrid model was required to model the operation to a greater level of accuracy. Analysis assumption 3 states that fulfilment of demand for bulk cement via an expanded VW operation is infeasible. Historical demand for bulk cement was therefore deemed irrelevant to the operation simulation and was therefore excluded from the historical demand used to describe demand patterns. It could therefore be said that the benefit of aggregating data by disregarding the package type on an order was not deemed to outweigh the loss of detail in the case of the simulation model as it was for the network optimization model.
6. Similar to the package type consideration mentioned above as point (5), the distinction between order cement strength grades was also required for the operation simulation model, even though this was disregarded for the network optimization model. However, the strength grade classification order was not used to exclude any data from the demand patterns. It was instead used to support the development of two sets of demand patterns, one for 32.5N strength cement and one for 42.5N strength. This supported logic that addressed analysis assumption 1, which related to the diversion of trucks carrying 42.5N cement to customers that had ordered 32.5N cement.
7. Analysis assumption 6 states that the VW operation cannot be used to fulfil demand for collected cement. Historical demand for collected cement was therefore deemed irrelevant to the operation simulation and only the demand patterns for bagged cement were described.
8. The city in which demand resided, not the individual customer or customer's ship-to address, was chosen as the demand node for the network optimization model. As management assumption 11 and analysis assumption 13 apply to both components of the hybrid mathematical model, the same modelling considerations regarding demand aggregation discussed in terms of the sales object configuration in section 3.4.1.2 applied to the operation simulation model. The same definition of the node of demand was therefore used for describing demand patterns derived from the historical data for the simulation model. For a historical VW load, the destination city of the VW sales order fulfilled by the diversion was taken as the demand node, although the load created date in this case may refer to a date prior to the placement of the order.

A Microsoft Excel spreadsheet pivot table was used to extract these quantities from the TMS transactional data. These quantities were considered pre-validated, as they stemmed from a cleansed, prepared and validated dataset (see section 3.3). The individual aggregated values were validated, however, by comparing the sum of the values on the pivot table to the sum of the orders on the master spreadsheet. These sums were found to be equal[42]. Some visual representation of these values (see Figure 67) was also used to detect outliers and thereby validate the aggregated values.

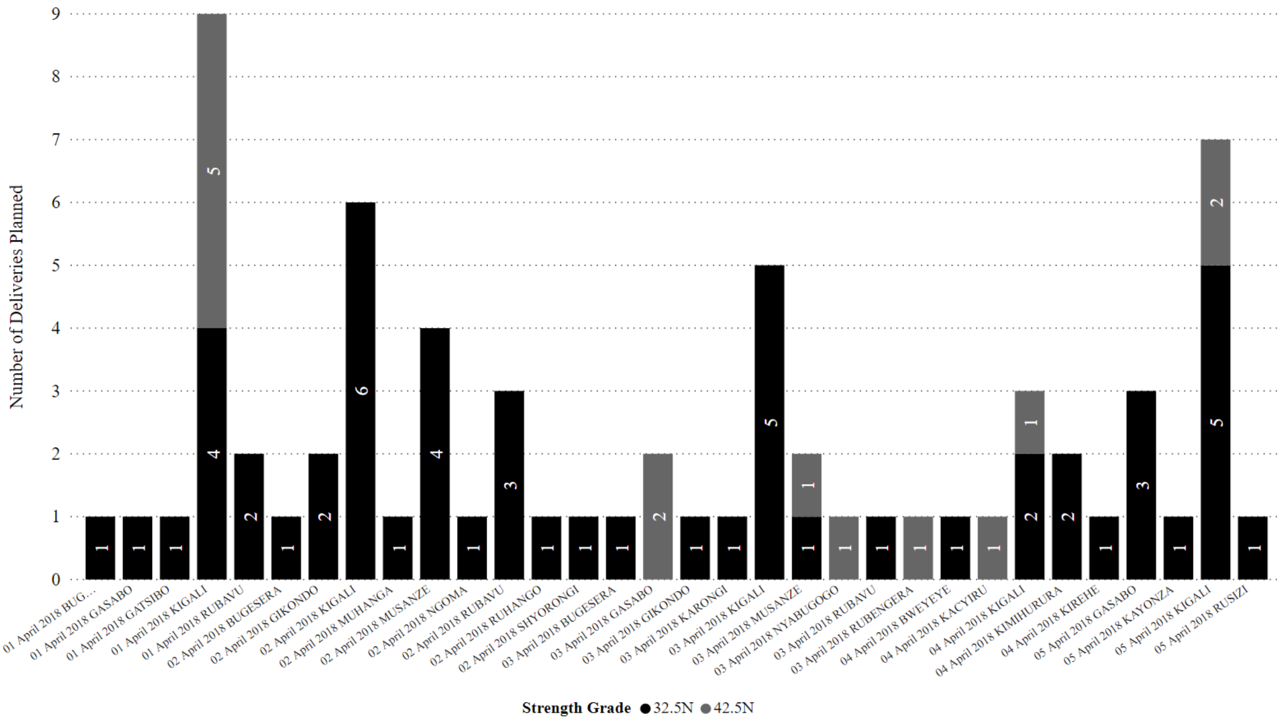

Figure 67: Deliveries planned by the logistics office for a random sample of five days

The demand patterns were prepared for the operation simulation model in the form described above and used as Excel formulae parameters such that the random variates generated by the model followed the distribution of the daily number of orders of each strength grade of delivered cement per demand node. A Monte Carlo model is often instructed how to convert pseudo random numbers to random variates using the Excel inverse formulae with parameters that define the probability distribution the random variates are supposed to replicate. The distribution type (e.g. normal, exponential, etc.) and its summary statistics are chosen such that the historical demand pattern is described as accurately as possible. For example, if the historical number of sales per day of 32.5N bagged cement for delivery at a demand node followed a normal distribution shape with a mean of five and a standard deviation of two, the Excel formulae =NORM.INV(RAND(),5,2) could have been used to generate random variates that emulate historical data. A large enough sample of data generated by this formula would exhibit a mean of five and a standard deviation of two.

[42] Orders for bulk cement were filtered from both the pivot table and the master transactional data spreadsheet for the comparison.

The use of such a method to inform the CIMERWA VW operation Monte Carlo model was anticipated to be problematic for two reasons, which are described below.

The first reason was that the statistical distribution that best fits each delivery city's historical daily sales orders per strength grade would have to be determined individually, as not all these datasets follow the same distribution. The city for which with the highest number of orders for delivered cement were planned, Kigali[43], provides a pertinent example of a difference in distribution types that would have to be detected and modelled differently. Figure 68 and Figure 69 show the statistical distributions of the frequency with which each daily number of orders was placed during the year analysed for 32.5N and 42.5N strength cement respectively. The distribution of the 32.N daily sales numbers could be described as following a right-skewed normal distribution, while the 42.5N dataset appears to follow an exponential distribution.

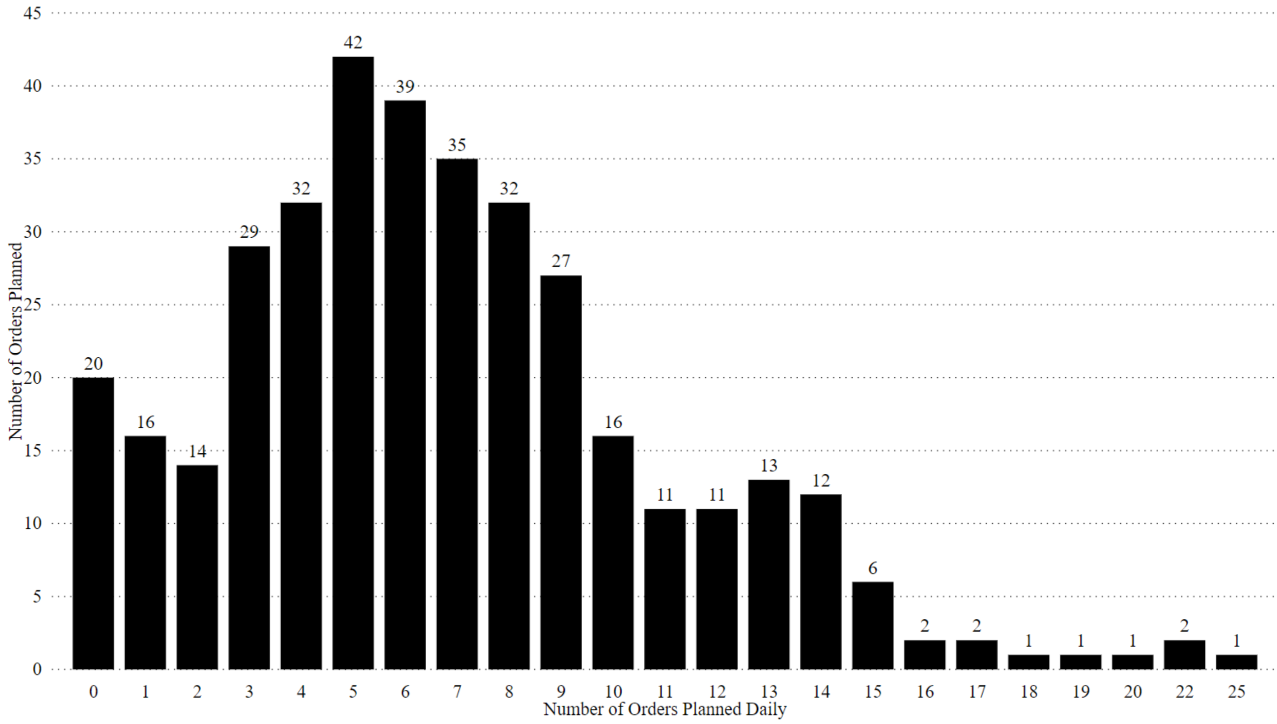

Figure 68: Daily deliveries of 32.N strength cement to Kigali

[43]2932 of the 7928 (36.98%) bagged cement delivered reflected on the cleansed and prepared transactional were for delivery to Kigali.

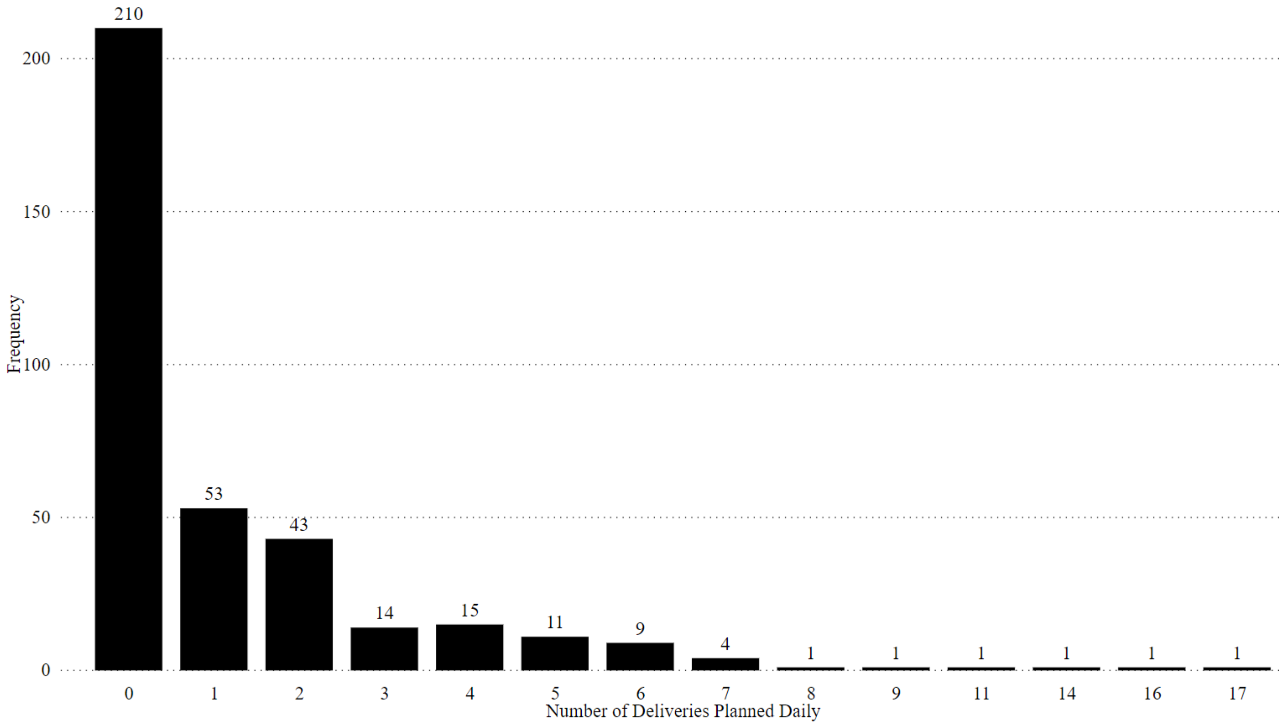

Figure 69: Daily deliveries of 42.N strength cement to Kigali

The presence of 57 discrete delivery cities in the transactional dataset and two different cement strength grades gave rise to 114 unique datasets for which the best distribution fit would have had to be determined. Doing so visually would have been a restrictively onerous process for the modeller. While existing statistical software tools such as Minitab that can perform this function computationally, the 114 sets of results would require some manual validation and interpretation. These tools usually calculate three measures, namely the Anderson-Darling statistic (AD), the p-value and the LRT P, which indicate the goodness of fit of multiple distributions to a dataset. The best fit is usually determined by the simultaneous human consideration of the set of the three measures' values calculated for each distribution, aided by probability plots generated by the tool [35]. Performing this analysis for 114 datasets would have been infeasibly time-consuming.

The second anticipated problem associated with using statistical distributions to model the historical demand patterns was the small sales volumes of each cement grade recorded for many of the delivery cities. Meaningful visual identifications of the underlying distributions represented by Figure 68 and Figure 69 were possible due to the large daily sales volumes registered in CIMERWA's most active centre of demand. Analysis of the historical annual sales volumes per delivery cities, however, showed that two or fewer orders are registered in the first quartile cities (see Figure 70). Probability distributions could not be derived from such small datasets.

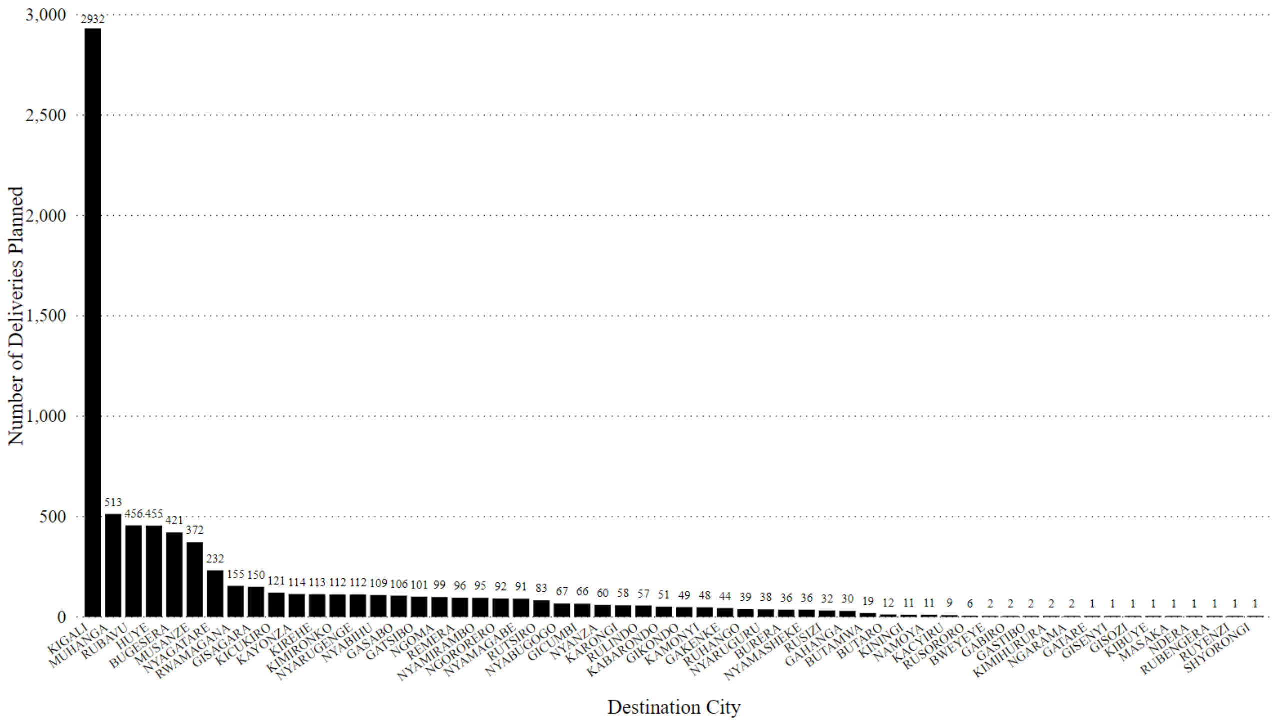

Figure 70: Deliveries planned by the CIMERWA logistics office per delivery city

While the sample size for each of the 57 delivery cities was 363, one observation per working day of the year (see business assumption 15), for the abovementioned first quartile nodes, 361 or 362 of the values would be zero, with the remaining values either being one or two. This limited number of outcomes made the nature of the daily sales distribution less continuous and more discrete in nature. This favoured modelling of the probability distribution on a value-by-value basis.

A limitation of Excel in terms of its suite of available inverse distribution formulae further complicated the modelling low sales volumes using statistical distributions. For example, the Bweyeye only received two truckloads of cement during the analysis period, each planned on a different date. The most likely distribution to best fit this demand pattern would be a geometric distribution. However, there is no inverse geometric formula available on Excel [36]. As such, the probability distribution would be best defined using a value of as 0.9945 for the probability of zero sales being registered on a given date (i.e. using 361 as the number of the total 363 days on which the condition of making zero sales was met) and the probability of one sale being registered as 0.0055 (i.e. using two as the number of days this condition was met).

This would have represented the introduction of a second broad method of defining the probability distributions that would govern the Monte Carlo model's generation of the sales volumes random variates for the, which would have required the modeller's discretion in terms of the applicability of each method to by applied to each of the 114 datasets.

To ensure the simplicity and repeatability of the research, only one method was used to define the random Excel formulae for generating the daily planned deliveries random variates for each delivery city. The method described above for determining the probability of each number of sales orders being planned for delivery in Bweyeye was selected and extended for each city and each cement strength grade.

The probability of *k* orders being planned for delivery to demand node *x* on a randomly selected day of the CIMERWA's logistics office's operation was defined as the quotient of the historical number of observations of k orders planned for delivery to *x* and the total number of operational days analysed. The latter was 363 due to two days on which the sales and logistics offices do not work (see business assumption 15). The value for k was drawn from a set of integers increasing from one up to and including 25 by increments of one. The upper boundary of this set was chosen to reflect the maximum number of deliveries planned on one day during the year of analysis, which was recorded on 29 March 2019 for delivery of 32.5N cement to Kigali.

Equation 4: Probability distribution of the number of daily deliveries planned per demand node

$$P\left(X = k_p\right) = \frac{x_{k,p}}{363} \qquad (4)$$

for k number of deliveries planned daily (k= 1,2,… ,56 ,57) for strength grade p

where

- $P\ (X = k_p)$ is the probability that k orders for cement strength *p* will be planned for delivery to delivery city *x*
- x_{kp} is the historical number of observations of k deliveries of cement strength grade p to delivery city *x* planned on a day

The Monte Carlo simulation Excel spreadsheet used the pivot table values of daily numbers of deliveries planned to specify the 114 required probability distributions. A cumulative probability value was also calculated as this value would be used by the model during a subsequent step. Actual data is given in Table 6 for two examples' probability distributions to illustrate the concept, namely the planning activity for 32.5N strength cement deliveries to Burera and 42.5N strength cement deliveries to Ngoma.

Table 6: Probability distributions for numbers of daily deliveries of different cement strengths planned to different cities

Delivery City (x)	**Strength Grade (N/mm^2) (p)**	**Number of Deliveries (k)**	**Number of Historical Observations**	**Probability of k Deliveries Planned $P\left(X = k_p\right)$**	**Cumulative Probability $\sum_{k=1}^{k} P\left(X = k_p\right)$**
Burera	32.5	0	343	0.9397	0.9397
Burera	32.5	1	15	0.0411	0.9808
Burera	32.5	2	5	0.0137	0.9945
Burera	32.5	3	2	0.0055	1
Ngoma	42.5	0	347	0.9560	0.9560
Ngoma	42.5	1	10	0.0274	0.9835
Ngoma	42.5	2	5	0.0137	0.9972
Ngoma	42.5	3	0	0	0.9972
Ngoma	42.5	4	1	0.0027	1

The cumulative probability values were used in conjunction with the pseudo random number Excel formula to produce numbers of daily deliveries that followed statistical distributions that matched the probability distributions observed in the historical transactional data. A pseudo random decimal number between zero and one was first generated using the =RAND() Excel expression for every cement grade and delivery city for every day of the year simulated. 41 610 pseudo random numbers[44] were therefore generated for each simulated year of operation.

Each pseudo random number was used as an input to a nested if-statement that translated the random number into an integer value according to the corresponding probability distribution derived from the historical data (i.e. a random variate). The if-statements sequentially compared the pseudo random number to the cumulative probability associated with each number of daily deliveries. Equation 5 and Equation 6 below give the Excel expression used for converting pseudo random numbers between zero and one to the random variates that replicate daily numbers of 32.5N strength cement deliveries to Burera and 42.5N

[44] Two cement strength grades multiplied by 57 demand nodes multiplied by 365 days.

deliveries to Ngoma respectively. Note that the values used for the nested inequalities in these formulae correspond to the cumulative probability values calculated for these scenarios shown Table 2[45].

Equation 5: If-statement for generating random variates for daily deliveries according to the Burera 32.5N probability distribution

=IF(x<0.9397, 0, IF(x<0.9808, 1, IF(x< 0.9945, 2, 3))) (5)

where

- x is a pseudo random decimal number, $x \in [0; 1]$

Equation 6: If-statement for generating random variates of daily deliveries according to the Ngoma 42.5N probability distribution

=IF(x<0.9560, 0, IF(x<0.9835, 1, IF(x<0.9972, 2, IF(x<0.9972, 3, 4))) (6)

where

- x is a pseudo random decimal number, $x \in [0; 1]$

This method of converting pseudo random numbers into random variates resulted in a pair of numbers for each combination of strength grade, demand node and day of operation, consisting of a pseudo random number and a number of orders planned for delivery. The latter was the value inserted to the model logic and, due to it being a function of the former, was the primary source of variation for the Monte Carlo simulation model.

Table 7 includes the pairs of pseudo random numbers and random variates for demand for 32.N strength cement in three different delivery cities, namely Kicukiro, Kigali and Kimihurura, for a period of one week. Although the pseudo random numbers for each city appear to be evenly distributed between zero and one, the number of deliveries calculated for delivery to Kigali is significantly higher during this week than to the other two cities. This is due differences in the cities' cumulative probability values that are inserted to the if-statement that translates the random numbers into random variates. Demand for delivered cement in cities according to their historical demand is thereby simulated.

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45 Values are presented rounded to four decimal places. The if-statements on the Excel spreadsheet directly referenced the cells on which these values were initially calculate, therefore rounded numbers were not used for these comparisons by the model itself.

Table 7: Pseudo random number and random variate pairs for a sample week of simulated planned deliveries

Date	32.N Strength Cement Planned Deliveries					
	=rand( )	No. Deliveries	=rand( )	No. Deliveries	=rand( )	No. Deliveries
2018/04/01	0.1109825	0	0.9085519	14	0.4697414	0
2018/04/02	0.9865831	2	0.7693076	10	0.7372476	0
2018/04/03	0.5908778	0	0.9870146	21	0.2869915	0
2018/04/04	0.1837686	0	0.7815450	11	0.2891551	0
2018/04/05	0.3864678	3	0.5291404	8	0.1369582	0
2018/04/06	0.4707415	0	0.2769032	4	0.9001858	0
2018/04/07	0.3216932	0	0.7644030	10	0.0278406	0

11.5.2 Virtual Warehouse Catchment Areas

While the model logic required the simulation of city-level demand for delivered cement to determine the implications of simulated planning decisions made by the logistics office, the simulation of the decisions themselves did not require this level of granularity in the demand. A key benefit of the VW concept as used by CIMERWA is that it aggregates predicted and actual demand according to geographic areas within which distances, from a planning and costing perspective, are immaterial. This aggregation increases the predictability of demand and therefore reduces the risk of the logistics office pre-emptively dispatching trucks towards their epicentres (i.e. the VW city) and having the trucks stand in these cities awaiting demand.

These areas are referred to as VW catchment areas throughout this document and represent the set of cities of demand to which trucks en route to or stationed at a VW can be diverted without incurring additional transport charges. From a cost performance perspective, the logistics office can view a catchment area as a single demand node to and within which vehicles can move to fulfil demand. It was therefore necessary to incorporate these catchment areas into the Monte Carlo simulation model as input quantities, as these would instruct the model logic in terms of how to aggregate the random variate values for the numbers of deliveries planned per city and cement strength grade.

These catchment areas were optimally determined for different numbers of VWs used by the network optimization model. The used of these results to aggregate simulated demand on the Monte Carlo model represented the completion of the link between the two components of the hybrid mathematical model (see Figure 6).

The optimal networks for one to five VWs were determined and a total of six different VW cities were activated by the optimization algorithm for the five scenarios. These would be the only catchment areas to which the logistics office would direct VW vehicles and therefore only these sets of cities were prepared and inputted to the Monte Carlo model (see Table 8). Similarly, only the SLA transit times for the legs from the CIMERWA production plant in Muganza to each of these VW cities were determined using the TMS transit time profile and prepared as a set input data for the model logic to use to simulate the delay between the dispatch of vehicles from the factory and their arrival at VWs.

Table 8: VW cities inputted to the operation simulation model per scenario

VW City	**Activated for Scenario**					**Province**	**Transit Time (d)**
	1 VW	2 VWs	3 VWs	4 VWs	5 VWs		
Butamwa	Yes	No	No	No	No	Kigali	2
Huye	Yes	Yes	No	No	No	Southern	1
Kamonyi	No	Yes	Yes	Yes	Yes	Southern	2
Kicukiro	No	No	Yes	Yes	Yes	Kigali	2
Burera	No	No	No	Yes	Yes	Northern	3
Rubavu	No	No	No	No	Yes	Northern	3

Table 4 shows one deviation from the TMS transit time profile that was made to recognize the substantial difference between distances from the CIMERWA production plant to two VW cities situated the Southern Province of Rwanda. Huye is 77.1 kilometres[46] from the production plant, while Kamonyi is 123.9 kilometres (see Figure 71). Kicukiro resides in the Kigali Province and is situated 147.2 kilometres from Muganza. A leg travelled from Muganza to a VW in Kamonyi is therefore more comparable to a leg to Kicukiro (i.e. 84% of the distance Kicukiro) to that Huye (160% of the distance to Huye), even though these cities lie in difference provinces. It was decided that the standard time to Kigali Province was a better benchmark than the Southern Province, as it is represented a more dense area of demand. The transit time to Kamonyi was therefore kept at two days and the Huye transit time reduced to one day.

[46] Comparative distances are given as the straight-line distance used as an input to the network optimization model

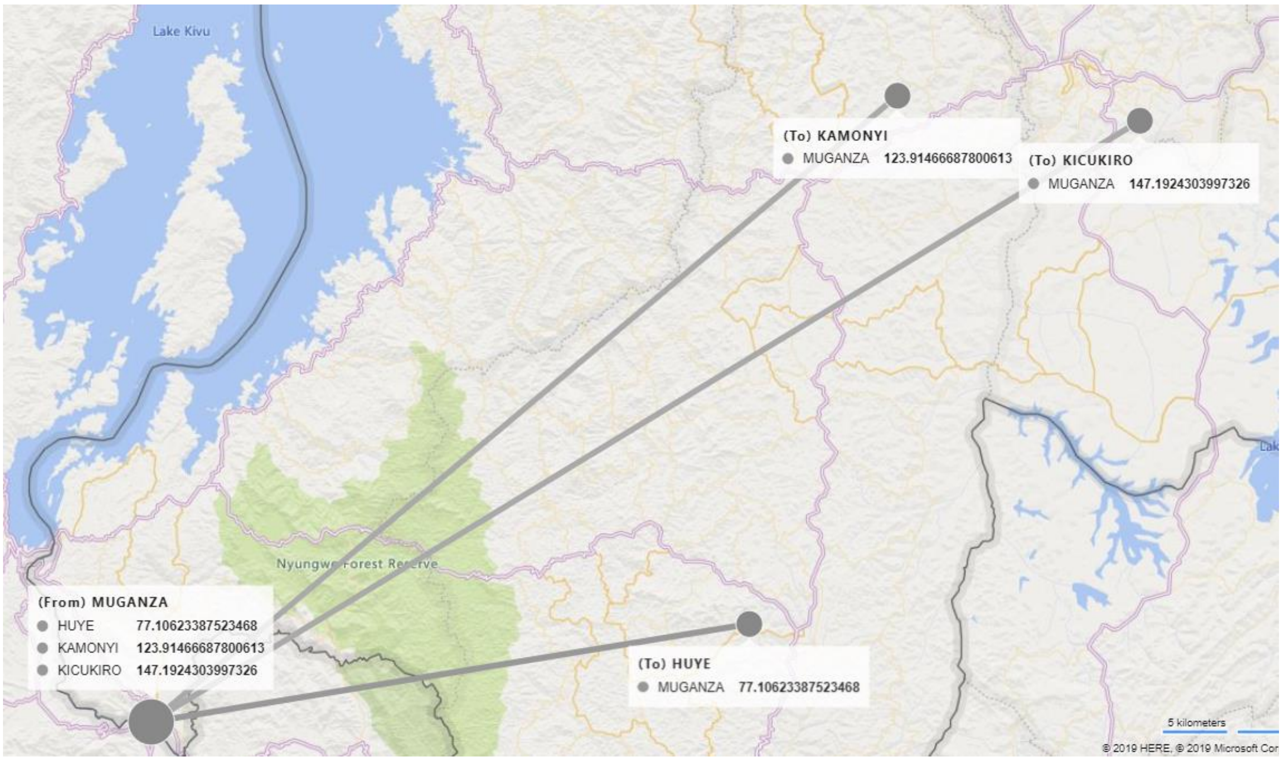

Figure 71: Positions of the VWs in Huye, Kamonyi and Kicukiro relative to the production plant in Muganza

The modelled transit times were validated using two methods. The transit times for Butamwa, Huye and Rubavu were validated by comparison to historical transit time averages (see Table 9).

Table 9: Comparison of modelled transit times to historical transit times

VW City	Modelled Transit Time (d)	Average Historical Transit Time (d)	Validation Method
Butamwa	2	1.20	Historical data comparison
Huye	1	0.63	Historical data comparison
Kamonyi	2	0.78	Visual analysis
Kicukiro	2	0.89	Visual analysis
Burera	3	1.43	Visual analysis
Rubavu	3	2.05	Historical data comparison

Visual analysis of the historical transit time distributions was used to validate the remaining modelled transit times. For example, the average historical transit time to Burera was 1.43 days, which suggested that a transit time of two days should have been modelled. However, analysis of the histogram for this data (see Figure 72) showed that 48% of the trips were recorded as having taken less than one day to complete. When the distance from the production plant to this city was considered, these times were deemed the result of data entry errors. 73% of the remaining trips required three days to complete and the modelled transit time was therefore accepted as valid.

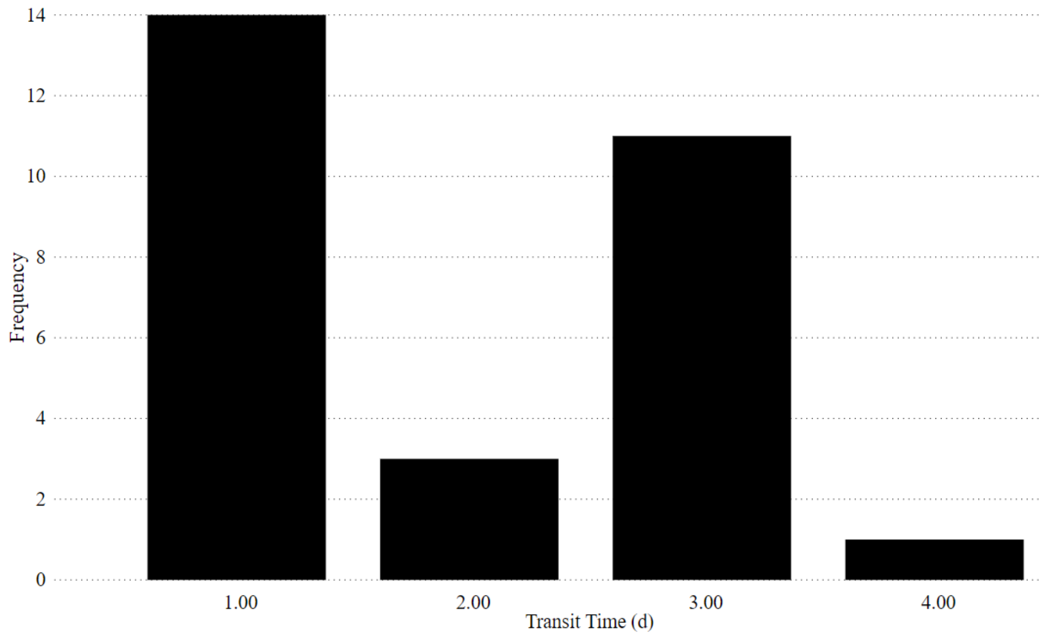

Figure 72: Transit times from Muganza to Burera

11.5.3 Forecasted Daily Delivery Volumes per Catchment

Expansion of the CIMERWA VW operation would require some formalisation of the methodology used to determine how many vehicles to dispatch to each VW. Such a methodology would require some form of a prediction in terms of the number of orders for delivery to be received in the immediate future as an input.

A fully inclusive collaborative planning, forecasting and replenishment (CPFR) would coordinate mathematically driven forecasts and marketing events [3] and therefore be likely to provide a robust and successful means of estimating the demand in each VW’s catchment. However, the simulation of this process would require the modelling of ad hoc major construction projects arising at differing locations across Rwanda and sales promotions. The complexity associated with isolating such events from the historical transactional data such that these events could be realistically simulated was inhibitive. CPFR is also a highly manual process which would be problematic to program.

Similarly, if the time of year was not considered when the historical demand patterns were used to govern the generation of the random variates for the daily deliveries planned (see analysis assumption 9), seasonality or trends in the historical data were averaged out and any forecasting methods that accounted for these would be redundant. Therefore, as discussed in section 3.1, a simple moving average forecasting method was deemed sufficient for providing the model logic with a prediction for the number of deliveries expected per VW catchment to be planned the following day.

Equation 7: Calculation of next-day forecast

$$M_{x,p,t} = \frac{\sum_{t=1}^{t-1} Z_{x,p,t}}{t-1} \qquad (7)$$

where

- $M_{x,p,t}$ is the forecasted number of orders for strength grade p for delivery within at VW x's catchment to be planned on day t
- $Z_{x,p,t}$ is number of actual simulated orders for strength grade p for delivery within at VW x's catchment to be planned on day t

The model logic had to differentiate between orders placed for delivery of 32.5N strength cement and 42.5N strength, as analysis assumption 1 implies that the ability of a truck to be diverted to a customer was dependent on the strength grade of the cement on the vehicle and the grade ordered. Moving average forecasts were therefore modelled for each VW catchment for each strength grade of cement.

The forecasted number of deliveries for the following day was calculated using the average for all subsequent days. This assumed that more recent demand activity was equally meaningful an indicator of future demand as observations experienced further back in the past [3] (see analysis assumption 9). Actual data is given in Table 10 below for the moving average calculation to illustrate the concept, namely the forecast of daily numbers of planned deliveries of 32.5N strength cement to cities within the Butamwa VW's catchment area.

Table 10: Moving average forecasts for numbers of daily deliveries of 35.5N strength grade cement to the Butamwa VW catchment

Date	Moving Average Calculation $\left(\frac{Total\ Deliveries\ to\ Date}{Number\ of\ Obervations}\right)$	Forecasted Number of Deliveries for Planning	Actual Number of Deliveries for Planning
2018/04/01	-	-	9
2018/04/02	$\frac{9}{1}$	9.000	18
2018/04/03	$\frac{27}{2}$	13.500	11
2018/04/04	$\frac{38}{3}$	12.667	7
2018/04/05	$\frac{45}{4}$	11.250	14
2018/04/06	$\frac{59}{5}$	11.800	20
2018/04/07	$\frac{81}{6}$	13.167	11

11.6 Appendix 6: Operation Simulation Model Decision Logic

The boundaries of the model logic component of a Monte Carlo simulation model are subject to some interpretation. The state of the system is determined by the input quantities and output quantities of each stage, all of which are generated using some defined logic. This logic is explained in these components' respective sections of the document and should not be confused with the model logic simulated that the human decisions that is discussed in this section.

For the CIMERWA operation simulation model, the model logic refers to the heuristics governing the decisions being made by the role-players (i.e. the CIMERWA logistics office) within the simulated environment (i.e. the CIMERWA distribution network) at each stage (i.e. day of operation) given the state (i.e. the number of vehicles and orders for delivery in each city) of the system. This section is named "Model Decision Logic" to increase the clarity of this distinction and thereby deviates from the framework presented in Figure 12.

The operation simulation model modelled only one type of decision made by the CIMERWA logistics office, that being how many vehicles to pre-emptively dispatch each day to each activated VW city. This decision was modelled to be informed by the following three key variables:

- The forecasted daily delivery volumes per catchment, which was an input quantity for each current stage of the simulation.
- The number of vehicles that stood overnight at the VW city, which was an output quantity of the previous stage of the simulation.
- The planning method, which was set for the entire run of the simulation model and only changed when a different scenario was tested. The planning method was inputted to the model as a combination of four different variables, the values of which were selected according to the scenario being simulated. These variables were:
    - The strength grade of cement loaded and dispatched on VW vehicles. Analysis assumption 1 implies that a VW truck carrying 42.5N strength cement can be diverted to fulfil an order for 32.5N, although the converse is not true. It follows that the selection of 42.5N cement for VW trucks is a more risk averse practice than 32.5N cement, as the trucks can service a larger pool of demand using the former cement than the later[47].
    - The forecast consolidation method. If 42.5N strength cement was dispatched on VW vehicles, the logistics office had to either use the forecasted value for only the number of

[47] As 42.5N strength cement is more expensive to produce, the practice to selling 42.5N cement to satisfy demand for 32.5N represents an erosion of margin made by CIMERWA.

32.5N cement deliveries for planning, or a consolidated value that was the sum of the forecasted values for the 32.5N and 42.5N strength cement deliveries. The former method would return a lower value than the latter and could be described as the use of 42.5N strength cement to satisfy demand for 32.5N strength cement, while using orders for 42.N strength cement as a buffer to protect CIMERWA against demurrage.

- The factor of safety, represented as a decimal value between zero and one, multiplied by the estimated required trucks per catchment to give the actual number of vehicles dispatched to the catchment area's corresponding activated VW.
- The downward adjustment value, represented as an integer number, subtracted from the required trucks per catchment to give the actual number of vehicles dispatched to the catchment's corresponding activated VW.

Step 1: Estimated Trucks Required to Dispatch

The forecasted daily delivery volumes per catchment for the current time period and the number of vehicles standing overnight at the VW city for the previous period were inputted to the model logic to determine how many trucks should be dispatched to each activated VW city. This quantity was calculated as the difference of the two input values (see Equation 8).

Equation 8: Calculation of estimated trucks required to dispatch

$$C_{x,p,t} = A_{x,p,t} - B_{x,p,t-1} \tag{8}$$

where

- $C_{x,p,t}$ is the estimated number of vehicles required to dispatch on day t to VW x carrying cement of strength grade p
- $A_{x,p,t,q}$ is the number of forecasted deliveries to VW x carrying cement that can be fulfilled using strength grade p for planning on day t using forecasting method q
- $B_{x,p,t-1}$ is the number of available vehicles carrying cement of strength grade p not diverted to deliver to demand nodes within VW x's catchment area on day $t-1$

As the moving average method of forecasting the deliveries to VWs gave rise to decimal numbers, the calculated values of required number of trucks to dispatch were also often found to be decimal values. As less-than-truckload volumes were not to simulated by the model (this follows analysis assumption 11), the calculated values were rounded down to simulate the dispatch of an entire truckload.

This number, however, assumed complete accuracy of the forecast and its direct use to dispatch trucks would introduce a high degree of risk of demurrage. Should a forecasted value have overstated the demand for delivered cement in the catchment, cement would arrive at the VW without a feasible order to which it could be diverted and demurrage charges would have resulted. Table 11 includes data for an example of the application of this method of determining the number of vehicles to dispatch to a VW using actual simulated data[48]. The sum of the final column shows, for the given set of orders generated by the model, the use the unmitigated values for the actual number of required trucks to dispatch resulted in 20 trucks arriving at the VW city without orders to fulfil within a single week of operation.

Table 11: Calculation of estimated trucks required for dispatch to the Butamwa VW to deliver 35.5N strength grade cement

Date (t)	**Trucks Standing at VW (B_{t-1})**	**Forecasted Deliveries to VW (A_t)**	**Required Number of Trucks to Dispatch (C_t)**	**Trucks Standing Overnight (B_t)**
2018/04/01	-	0	0	0
2018/04/02	0	13.000	13	0
2018/04/03	0	14.500	14	4
2018/04/04	4	12.667	8	3
2018/04/05	3	13.250	10	0
2018/04/06	0	13.600	13	8
2018/04/07	8	11.667	3	5

Step 2: Actual Trucks Dispatched

The primary and supporting objectives of the project recognize that the model should allow for daily systematic increase or decrease of the estimated number of required vehicles to an actual number of trucks to dispatch to each VW. The manner in which this adjustment is performed is a function of appetite for risk, which can be adjusted. This degree of speculation used when numbering the trucks to dispatch is highlighted explicitly stated in the primary objective as a required input to the model.

It follows that the output of step 1 would be interpreted and converted to an actual number of trucks to dispatch according to some logic, the parameters of which would define the degree of risk accepted by the

[48] The method by which the number of trucks standing overnight was determined is described in section 3.4.2.3 and values associated with this calculation are therefore omitted from illustrative tables in this section.

CIMERWA logistics office when pre-emptively directing trucks to areas of anticipated demand. The method by which this conversion was achieved is referred to as the planning method. The planning method was defined as a sequential application of a factor and quantum to the estimated required number of vehicles dispatched to each VW. Both calculations are encapsulated by Equation 9, which indicates the sequence of these successive calculations using brackets.

Equation 9: Calculation of actual trucks dispatched

$$D_{x,p,t} = (C_{x,p,t} \times F) - Q \quad (9)$$

where

- $D_{x,p,t}$ is the number of vehicles dispatched to VW x carrying cement of strength grade p on day t
- $C_{x,p,t}$ is the estimated number of vehicles required to dispatch on day t to VW x carrying cement of strength grade p
- F is the factor of safety[49] applied to the estimated number of vehicles required to dispatch, $x \in (0; 1]$
- Q is the downward adjustment value, $x \in Z$

Similar to the use of moving average forecasting method to calculated the estimated number of required trucks, the use of a decimal factor of safety resulted in the formula presented on Equation 9 oftentimes returning decimal numbers of trucks to be dispatched. The calculated value was therefore rounded down to simulate the dispatch of an entire truckload and thereby adhere to analysis assumption 11.

Some further manipulation of this calculation's results was needed due to the downward adjustment value's introduction of the possibility of negative values, which would represent negative numbers of trucks being dispatched. This would give rise to negative numbers of VW trucks arriving at VWs, which would register negative numbers of order fulfilled and/or reduce the number of trucks standing at the VW, which would not be the reality that such a scenario would produce.

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[49] A term *factor of safety* is most commonly associated with civil engineering and 'the load carrying capacity of a system beyond what the system actually supports' (White 2018) [40]. It is therefore usually chosen as a value greater than one. It could therefore be argued that the value multiplied by the estimated required trucks to give the actual dispatched trucks, when viewed through this lens, could be better described as the inverse of the factor of safety. The term *factor of safety* was retained for ease of use.

Logic was therefore built into the planning method such that negative numbers of trucks would not be dispatched. The VW was first checked for standing trucks. The number of trucks standing at the VW was subsequently used by the following rule:

1. If a truck was found to already be standing at the VW, the model logic would prescribe that zero trucks would be dispatched to the VW.
2. If no trucks were found to be at the VW, the model logic would prescribe that one truck would be dispatched to the VW.

The branching of this logic based on the number of existing vehicles at the VW was primarily incorporated to accommodate VWs with catchments with relatively low volumes of sales for delivery. If the moving average forecast value converged to a value lower than the downward adjustment value, a negative number of dispatched trucks would be calculated for every time period simulated. If these values were always adjusted to zero, no vehicles would ever be dispatched to the VW. The downward adjustment factor would therefore have the effect of deactivating the VW, which was not its intended purpose. Modelling that a single vehicle was still dispatched to such a low volume VW catchment when it was empty of trucks ensured that the VW was utilized even when a conservative planning method was simulated.

Table 8 includes data for an example planning method applied to actual simulated data to illustrate the application of Equation 9 and the programmed manipulation of each calculated value to account for decimal and negative values.

Table 8: Planning method adjustments made to the daily estimated required vehicles for 35.5N strength grade cement deliveries to the Butamwa VW

Date	**Required Number of Trucks to Dispatch (C_t)**	**Planning Method Factor of Safety (F)**	**Partially Adjusted Forecast (C_t x F)**	**Downward Adjustment Value (Q)**	**Fully Adjusted Forecast (C_t x F – Q)**	**Dispatched Vehicles (D_t)**
2018/04/01	0	0.5	0	4	-4	0
2018/04/02	13	0.5	6.5	4	2.5	2
2018/04/03	14	0.5	7	4	3	3
2018/04/04	8	0.5	4	4	0	0
2018/04/05	10	0.5	5	4	1	1
2018/04/06	13	0.5	6.5	4	2.5	2
2018/04/07	3	0.5	1.5	4	-2.5	0

Figure 73 summarizes the full model decision logic sequence of steps. Note that the input quantities and output quantities are classified in terms of their function relative to the logic that models the decision-making aspect of the operation.

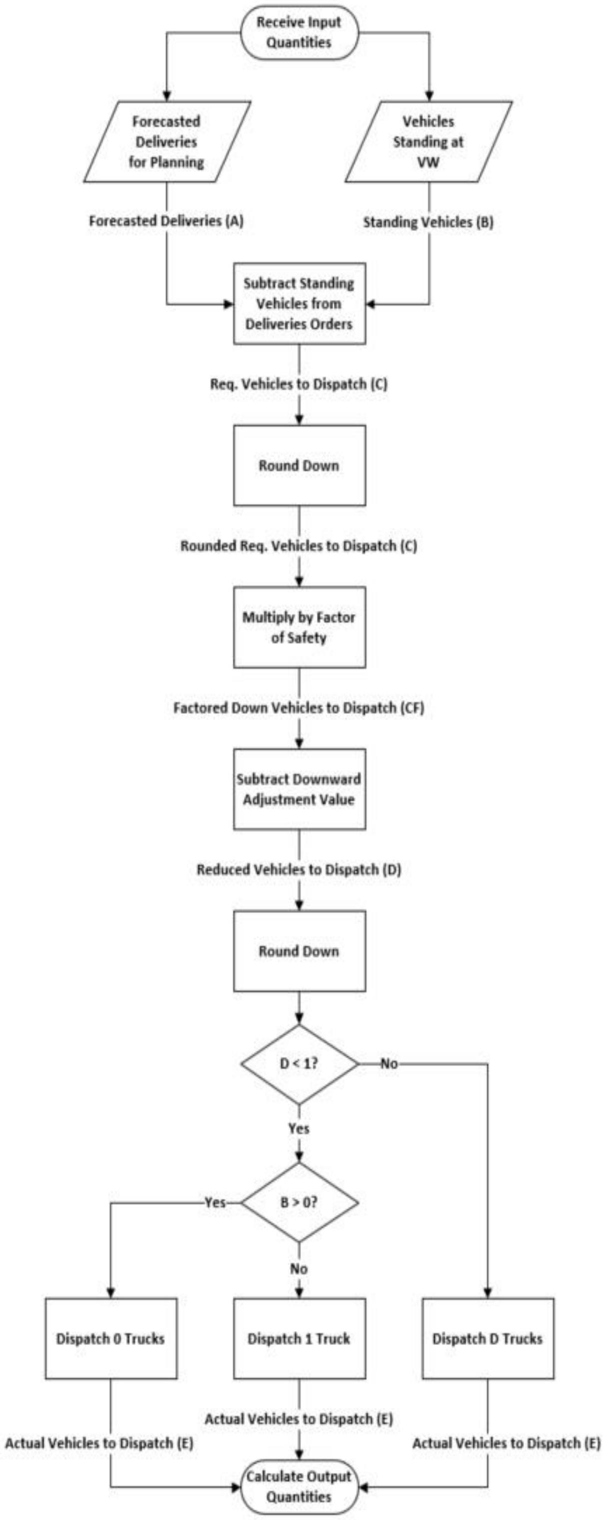

Figure 73: Model decision logic flow chart

11.7 Appendix 7: Operation Simulation Model Output Quantities

The effect of the output of each time period's modelled decision logic had to be determined according to defined rules such that:

1. The data for measurement of system's performance metrics of interest could be collected.
2. The state of the system could be updated to reflect the effect of the simulated decisions made for the current time period and used as an input to the model logic for the next time period of the simulation.

In terms of the CIMERWA operation simulation, function (1) above primarily refers to the number of instances of demurrage charges being incurred as a result of VW use, as this was the focus of the primary objective of the project. Some of the positive effects of the expansion of the VW model were also quantified per time period. The extent of modeller discretion and simplifying assumptions required to reflect the positive outcomes in financial terms, however, meant that combining these with the incurred demurrage charges into a single objective function value for optimization by trial and error was not possible. Nonetheless, these KPIs were recorded throughout each run of the simulation model such that this data could be considered simultaneously with the risk of demurrage and the advantages and disadvantages of each simulated scenario discussed by management.

Function (2) above refers to the number of trucks in each VW city for which a delivery was not secured and, as such, parked overnight in the city. While these values were registered as instances of demurrage and were therefore for consideration after the simulation was run, they was also required by the model logic that simulated the estimation of the number of required trucks to dispatch daily (see Equation 8).

It can therefore be seen that the logic that serves function (1) and function (2) overlap. Each calculation is therefore presented in terms of the execution sequence rather than some form of classification in terms of the nature or purpose of the calculation. This set of steps receives the number of trucks actually dispatched to each VW from the model decision logic and the number of orders for delivery of each strength grade of cement from the input quantity logic as an input. The way in which these steps processed this input data is described below.

Step 1: Vehicles Arrived at VWs

Orders placed for delivery within a VW's catchment area cannot be fulfilled by a vehicle that is still en route to the VW. The dispatch and arrival of vehicles to and at each VW were therefore modelled as separate concepts. The number of vehicles that were simulated to arrive at a VW was the same as the number dispatched, but the time periods at which they arrived was calculated to correspond with the modelled transit times from the production plant to the VW. This simulated a lag between the dispatch and arrival of vehicles, which had a material impact on the ability of the forecasting planning method to respond to sudden occurrences of VWs standing overnight at VW cities.

No variation in transit times was modelled (see analysis assumption 3).

Equation 10: Calculation of actual trucks arrived

$$F_{x,p,t} = E_{x,p,t-l_x} \tag{10}$$

where

- $F_{x,p,t}$ is the number of vehicles arrived at VW x carrying cement of strength grade p on day t
- $E_{x,p,t-l_x}$ is number of vehicles dispatched to VW x carrying cement of strength grade p on day $t - l_x$
- l_x is the modelled transit time for the leg from the production plan to VW x, $l_x \in Z$

Step 2: Vehicles Present at VWs

The number of vehicles at a VW city available for the delivery of orders was a function of both the number of trucks that arrived at the VW that day and the number of trucks that were already at the VW due to failure to secure orders for their cement and their parking overnight. It was therefore necessary to sum these values to provide the model with a consolidated view of the demand for delivered cement that could be satisfied by VW trucks for the time period simulated. This aggregation was supported by business assumption 19 as it allowed the distinction between the newly arrived vehicles and the standing vehicles to be ignored.

Equation 11: Calculation of actual trucks present

$$G_{x,p,t} = F_{x,p,t} + B_{x,p,t-1} \tag{11}$$

where

- $G_{x,p,t}$ is the number of vehicles available to deliver cement of strength grade p to demand nodes within at VW x's catchment area on day t
- $F_{x,p,t}$ is the number of vehicles arrived at VW x carrying cement of strength grade p on day t
- $B_{x,p,t-1}$ is the number of vehicles in VW x carrying cement of strength grade p that did not fulfil a sales order on day $t - 1$

Step 3: Orders Fulfilled by VW Vehicles

While the generation of numbers of orders for delivery of each cement strength grade was necessary to furnish the moving forecast calculation used by the model logic with data (see Equation 7), its primary role was to determine the number of orders in each VWs catchment area to which available trucks could be diverted. Analysis assumption 7 provided the basis of the rule defined by Equation 12 below, which calculated the number of orders fulfilled by pre-emptively dispatched vehicles as the minimum of the number of orders planned for delivery and the number of trucks available to execute such deliveries.

Equation 12: Calculation of actual VW diversions

$$H_{x,p,t} = \begin{cases} G_{x,p,t}, & G_{x,p,t} < J_{x,p,t} \\ J_{x,p,t}, & G_{x,p,t} \geq J_{x,p,t} \end{cases} \qquad (12)$$

where

- $H_{x,p,t}$ is the number of vehicles diverted to deliver cement of strength grade p to delivery cities within VW x's catchment area on day t
- $G_{x,p,t}$ is the number of vehicles available to deliver cement of strength grade p to delivery cities within at VW x's catchment area carrying on day t
- $J_{x,p,t}$ is the number of orders of cement that can be fulfilled using cement of strength grade p planned for delivery to VW x on day t

The variable p is defined somewhat differently for the value $J_{x,p,t}$ (see Equation 12) when compared to its definition for other variables in this formula. This is due to the eligibility of a truck for fulfilment of an order not being exclusively reliant on a like-for-like match of the strength grade of cement on the VW truck to the type of cement ordered for each delivery. The rule for the determination of eligibility of the truck's cement followed analysis assumption 1. If the order is for 32.5N strength cement, the stock on the vehicle could be used to fulfil the order. If the order is for 42.5N strength cement, the stock on the vehicle could only be used to fulfil the order if it is of 42.5N strength.

Step 4: Orders Fulfilled by VW Vehicles using Overlapped Demand

Catchment areas were selected by the optimization model algorithm such that the objective function value was maximized. Transport costs calculated using straight-line distances (see Equation 1) were used to incentivize the model to activate VWs such that anticipated transport distances were minimized if the sales volumes that resided in two different VWs catchment areas were the same or similar. These transport costs and, by extension, inter-city distances therefore acted as tie breakers for VW activation decisions made by the model.

Distances between delivery cities also acted as tie breakers when a city could have been assigned to two or more different activated VWs. These situations arose when the catchment areas of two selected VWs overlapped. Although the assignment of delivery cities located within overlapping catchments to single VWs was useful from a forecasting and planning perspective[50], the logistics office's ability to divert a truck to an address within the truck's reach was not to be inhibited by the assignment of the overlapped city to another VW.

Provision for this complexity was required of the operation simulation model due to the overlap of the Kamonyi and Kicukiro catchment areas introduced by the network optimization model's selection of these two cities as VW locations when three or more VWs were to be used (see Figure 74). While each VW could reach some cities that the other could not (e.g. Bugesera resided in Kicukiro's catchment area, but was out of reach of the Kamonyi VW), thus justifying the activation of both VWs, some cities could be serviced by vehicles en route to or parked at either VW. In such cases, the optimization model assigned the demand node to the nearer of the two VWs.

For example, Shyorongi is closer to Kamonyi than Kicukiro and was therefore assigned to the Kamonyi VW[51]. As such, all forecasted demand for Shyrongi contributed to the decision logic for dispatching trucks to Kamonyi, not Kicukiro. However, a vehicle standing at Kicukiro was not modelled to stand overnight and incur demurrage costs if there was unsatisfied demand in Shyorongi.

[50] Directing trucks to a delivery city's assigned VW to satisfy its forecasted demand reduced transport cost, even though the truck's ability to satisfy this demand from another VW within reach of the city would be equal.

[51] The straight-line distance from Shyorongi to Kamonyi was found to be 18.7 kilometres, while the distance from Shyorongi to Kicukiro was 24.7 kilometres.

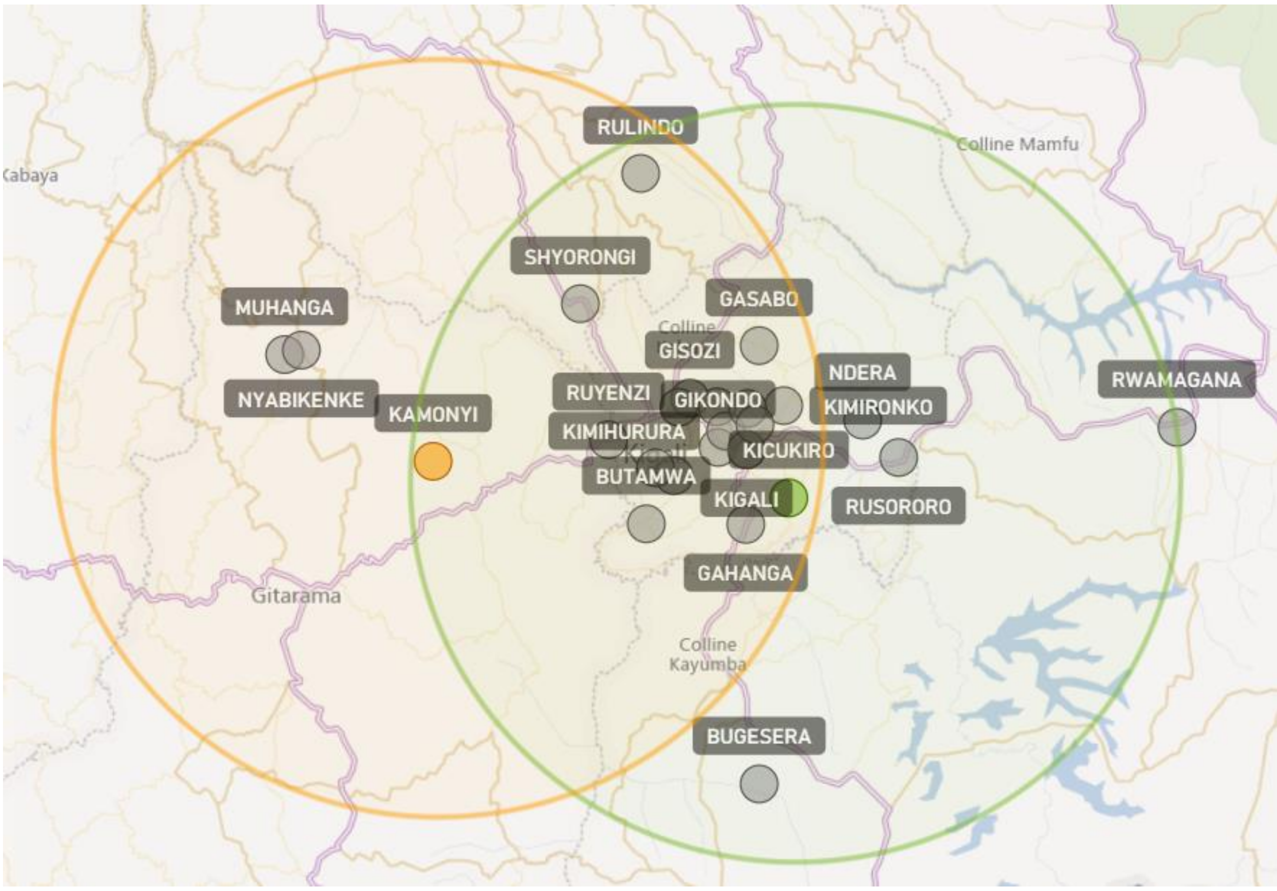

Figure 74: Overlapping catchment areas of the Kamonyi VW (orange) and the Kicukiro VW (green)

A second diversion step was introduced to the model to accommodate the fulfilment of demand that resided within this overlapping area for all scenarios using networks optimized for three or more VWs. Due to the extent of branching required to define the rules to govern the model's diversion of vehicles in such circumstances, the logic is represented using a flow chart only (see Figure 75).

Figure 75: Overlapping order diversion logic flow chart

The logic represented by Figure 75 was incorporated as an intermediate step that updated the values of $H_{x,p,t}$ and $J_{x,p,t}$ calculated during step 3 (see Equation 12). All subsequent calculations that utilized these values as inputs therefore incorporated the diversion of vehicles overlapped delivery cities assigned to other VWs.

Step 5: Lead Time Saved by VW Vehicles

The number of deliveries executed by VW vehicles calculated in step 4 was used primarily to drive the calculation of the number of instances of incurred demurrage (see step 6), which was the key output quantity of the operation simulation model and indeed the hybrid mathematical model of which it formed part. However, the model also simultaneously measured some of the non-financial benefits of VW expansion. One such measure was the reduction in the number of days spent by a customer waiting for the order due to the presence of a VW truck. While the calculation of such auxiliary measures is discussed as a step executed at the end of the output quantity process (i.e. step 7), this particular auxiliary value of interest is discussed as its own step below.

Management assumption 2 prevented the use of an unutilized VW truck to satisfy an existing order for which there was already an assigned vehicle en route from the plant carrying the customer's invoice. Each order fulfilled by a VW truck diversion could therefore be assumed as a new order (i.e. less than one day old). It follows that each successful VW truck diversion represented a saving in customer waiting time for the delivery of the cement. This lead time reduction was equal to the modelled transit time of the leg from the factory to the customer[52] that would have otherwise been incurred had the truck not been available to respond to the order from a VW, plus the additional day that would have been required to accommodate for the CIMERWA logistics office's planning rhythm of only sourcing vehicles to load the following day.

Equation 13: Calculation of total lead time saved due to VW truck diversions

$$K_{x,p,t} = H_{x,p,t} \times l_x + 1 \tag{13}$$

where

- $K_{x,p,t}$ is the number of days' delivery lead time saved by fulfilling orders for cement of strength grade p in VW x's catchment area on day t using VW vehicles
- $H_{x,p,t}$ is the number of vehicles diverted to deliver cement of strength grade p to demand nodes within at VW x's catchment area on day t
- l_x is the modelled transit time for the leg from the production plan to VW x, $l_x \in Z$

Step 6: Un-Diverted VW Vehicles

The project's primary objective can be interpreted such that the key output of the simulation of the VW operation is the risk of demurrage associated with each degree of its expansion. Management assumption

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[52] The delivery via diversion is assumed to be completed on the same day as the placement of the order. This assumption is justified by the combination of both business assumption 7 and analysis assumption 5.

14 implies that the number of demurrage charges received by CIMERWA per day is equal to the number of vehicles that remain un-diverted and remain overnight in the VW network. The risk of demurrage was therefore measured as the calculated instances of vehicles available at VW cities but remained un-diverted until the following day summed over the year of operation that was simulated.

Equation 14: Calculation of un-diverted VW vehicles

$$B_{x,p,t} = \begin{cases} 0, & G_{x,p,t} \leq J_{x,p,t} \\ G_{x,p,t} - J_{x,p,t}, & G_{x,p,t} > J_{x,p,t} \end{cases} \tag{14}$$

where

- $B_{x,p,t}$ is the number of available vehicles not diverted to deliver cement of strength grade p to demand nodes within VW x's catchment area on day t
- $G_{x,p,t}$ is the number of vehicles available to deliver cement of strength grade p to demand nodes within VW x's catchment area on day t
- $J_{x,p,t}$ is the number of orders of cement that can be fulfilled using cement of strength grade p planned for delivery to VW x on day t, including orders for overlapped areas for unfulfilled by trucks at their assigned VWs

Being the KPI that constituted the key output of interest, the numbers of un-diverted vehicles per VW and cement grade were used to provide insight into system dynamics that influenced the results. Examination of the raw data that was generated per time period of the simulated year of operation, however, would have been onerous and important patterns would have almost certainly been overlooked. Summary statistics were therefore calculated to aid the further understanding of the relationships that affected the performance of the VW operation as well as the sensitivities of the model to the quality of different input datasets and the validity of assumptions that manifested as modelling decisions regarding data preparation and programmed logic [3].

These statistics were generated by summing the values for $B_{x,p,t}$ (see Equation 14) along the x, p and t dimensions. These aggregations were subsequently expressed as ratios or percentages of selected input data quantities. These summary performance metrics are presented in Table 12. Example results generated by an actual run of the simulation model are included for illustrative purposes.

Table 12: Demurrage risk metrics

Description	Calculation[53]	Example
Total Number of Demurrage Charges	$\sum_{x=1}^{V}\sum_{p=1}^{2}\sum_{t=1}^{365} B_{x,p,t}$ where V is number of VWs in the network	A total of 205 days was spent by trucks awaiting orders at the all VWs during the year
Total Number of Demurrage Charges per VW	$\sum_{p=1}^{2}\sum_{t=1}^{365} B_{x,p,t}$	A total of 78 days (38% of the total) was spent by trucks awaiting orders at the Butamwa VW during the year
Ratio of Total Number of Demurrage Charges to Total VW Vehicles Dispatched	$\frac{\sum_{x=1}^{V}\sum_{p=1}^{2}\sum_{t=1}^{365} B_{x,p,t}}{\sum_{x=1}^{57}\sum_{p=1}^{2}\sum_{t=1}^{365} E_{x,p,t}}$	Total number of demurrage charges divided by the total number of vehicles dispatched to VWs was 0.13
Ratio of Total Demurrage Charges to Total VW Vehicles Dispatched per VW	$\frac{\sum_{p=1}^{2}\sum_{t=1}^{365} B_{x,p,t}}{\sum_{p=1}^{2}\sum_{t=1}^{365} E_{x,p,t}}$	Total demurrage charges incurred at the Butamwa VW divided by the total number of vehicles dispatched to the Butamwa VW was 0.06

The numbers of un-diverted VW vehicles calculated for each VW and cement grade not only incremented the demurrage charge totaller variable that supported the summary statistics assessing the performance of the system at the end of the simulation, but were also used was an input to the model decision and output quantity logic (see Equation 8 and Equation 11). This feedback loop was represented by the link between the "Subtract Diverted Trucks from Available Vehicles" and "Receive Input Quantities" processes on the output quantity model logic flow chart (see Figure 76).

Step 7: Auxiliary Metrics

While the number of demurrage charges (i.e. number of days VW vehicles parked in VW cities overnight) was the KPI under investigation, the operation simulation model generated other values of interest per time period. Summation of these values along selected dimensions provided insight into the relationships between these system KPIs, the risk of demurrage and the degree of VW operation expansion.

The analysis of these metrics supported did not directly support the primary objective of the project. However, it assisted in developing a deeper understanding of the system dynamics that influenced the

[53] Symbols are inherited from those used in model decision and output quantity logic equations.

number of un-diverted trucks. These auxiliary system summary statistics thereby enhanced the discussion regarding the results of the hybrid mathematical model and therefore indirectly contributed to the understanding of relationship between the expansion of the VW operation and risk of incurring demurrage.

This data also addressed, to a limited degree, a question that, although not included in the scope of the project, would be asked by management in tandem with the question regarding risk of demurrage. A real-world investigation that quantifies the risk of implementing a new or modified system would be somewhat incomplete without some analysis of the benefits of the change. The operation simulation model provided data to support this analysis without any rework. The logic that was already developed for the study of demurrage risk was therefore leveraged and metrics were developed to quantify the positive effects of the expanded VW operations.

The lead days saved per time period discussed in step 5 above was one such metric. The definition of summary statistics driven off this calculation and others are included in Table 13. Like Table 12, data from an actual run of the simulation model is included.

Table 13: Auxiliary system performance metrics

Description	Calculation[54]	Example
Total Deliveries by VW Vehicles	$\sum_{x=1}^{V}\sum_{p=1}^{2}\sum_{t=1}^{365} H_{x,p,t}$ where V is number of VWs in the network	A total of 1553 orders for delivered cement were fulfilled via the VW network
Total Deliveries by VW Vehicles per VW	$\sum_{p=1}^{2}\sum_{t=1}^{365} H_{x,p,t}$	A total of 1297 orders for delivered cement were fulfilled via the Butamwa VW
Percentage of Total Orders Fulfilled by VW Vehicles	$\frac{\sum_{x=1}^{V}\sum_{p=1}^{2}\sum_{t=1}^{365} H_{x,p,t}}{\sum_{t=1}^{365} Z_{x,p,t}}$	22.85% of orders for delivered cement were fulfilled via the VW network
Percentage of Total Orders within a VW's Reach Fulfilled by VW Vehicles per VW	$\frac{\sum_{p=1}^{2}\sum_{t=1}^{365} H_{x,p,t}}{\sum_{p=1}^{2}\sum_{t=1}^{365} Z_{x,p,t}}$	29.05% of orders within reach of the Butamwa VW were fulfilled via the Butamwa VW
Total Lead Time Days Saved	$\sum_{x=1}^{V}\sum_{p=1}^{2}\sum_{t=1}^{365} K_{x,p,t}$	The total days waited by customers for delivered cement was reduced by 5041 using the VW network
Lead Time Days Saved per VW	$\sum_{p=1}^{2}\sum_{t=1}^{365} K_{x,p,t}$	The total days waited by customers for delivered cement was reduced by 3966 using the Butamwa VW
Ratio of Lead Time Days Saved to Demurrage Charges	$\frac{\sum_{x=1}^{V}\sum_{p=1}^{2}\sum_{t=1}^{365} K_{x,p,t}}{\sum_{x=1}^{57}\sum_{p=1}^{2}\sum_{t=1}^{365} B_{x,p,t}}$	Total lead time days saved divided by the number days spent by trucks awaiting orders was 8.15
Ratio of Lead Time Days Saved to Demurrage Charges per VW	$\frac{\sum_{p=1}^{2}\sum_{t=1}^{365} K_{x,p,t}}{\sum_{p=1}^{2}\sum_{t=1}^{365} B_{x,p,t}}$	Total lead time days saved by trucks dispatched to the Butamwa VW divided by the number days spent by trucks awaiting orders at the Butamwa VW was 54.05

Figure 76 summarizes the sequence of steps that constitute the model output quantity logic.

[54] Symbols are inherited from those used in model decision and output quantity logic equations.

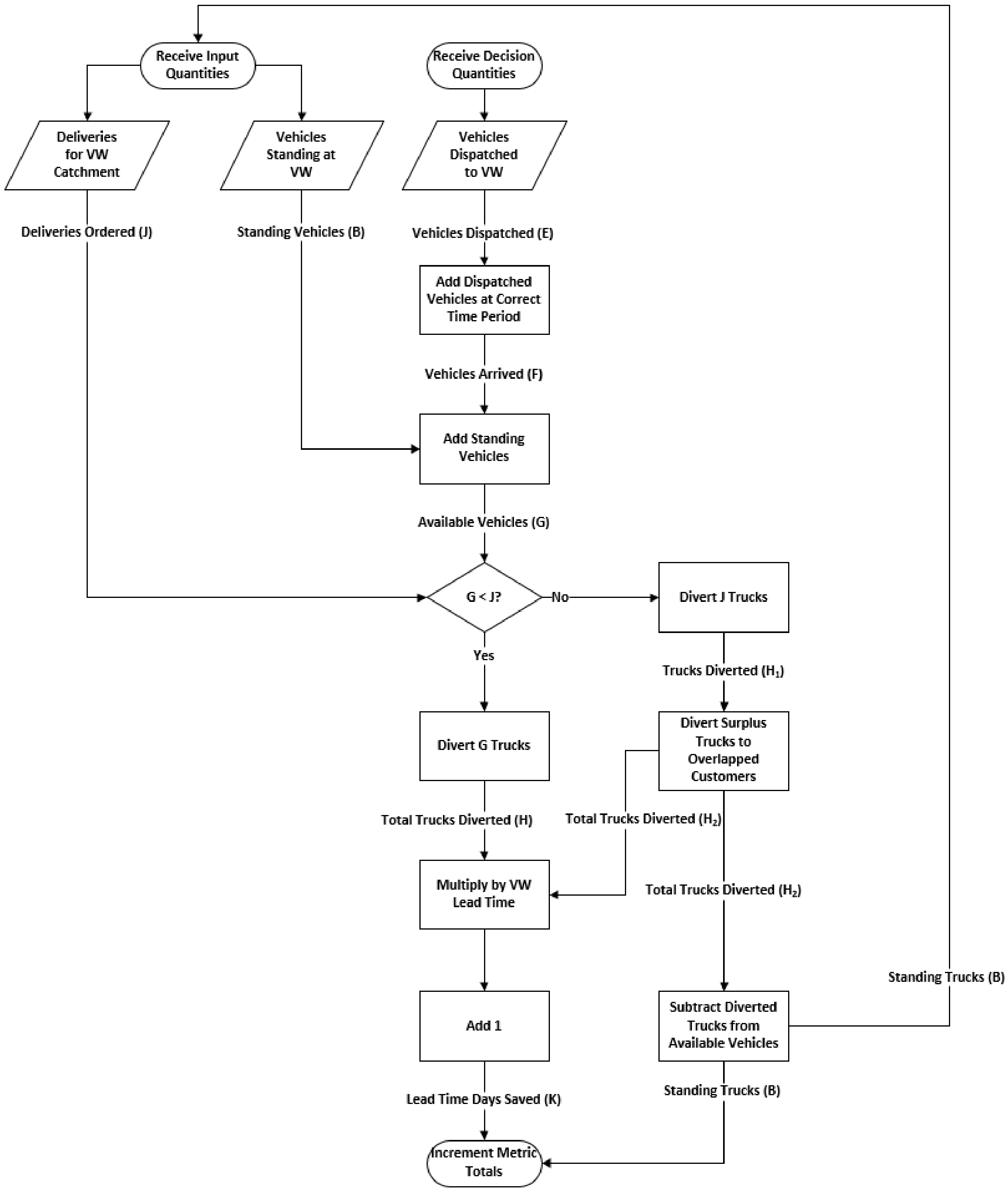

Figure 76: Model output quantity logic flow chart

11.8 Appendix 8: Operation Simulation Optimization Run Methodology

A methodology was required to guide the adjustment of the Monte Carlo simulation model between runs of the model such that the necessary data could be collected. The runs had to be conducted such that the effect of expansion of the VW model along a number of dimensions could be measured.

11.8.1 Expansion Along the Number of VWs

One such dimension of possible expansion was the number of VWs used in the distribution network. An Excel what-if analysis data table was used to run the Monte Carlo to simulate 100 different years of operation for each VW configuration generated by the network optimization model. The lead time days saved, the number of cases of demurrage and auxiliary metrics for each simulated year of operation was recorded such that the average, minimum, maximum, lower- and upper-quartiles for each metric could be calculated for each VW network and box-and-whisker charts generated.

11.8.2 Expansion Along the Planning Method

Full analysis of VW expansion, however, would involve testing each optimal VW network under different conditions to account for the second dimension along which the operation could be expanded. For each number of VWs, the 100 years of operation were simulated using different planning methods to replicate the use of the VWs by the logistics office with varying levels of speculation. This degree of speculation, however, could be simulated by adjusting three different input parameter values, namely the strength grade of cement dispatched to VWs and the factor of safety and downward adjustment values (see Appendix 6).

This resulted in multiple methods by which so-called conservative, moderate or aggressive planning methods could be simulated. For example, the use of a factor of safety value of 0.1 and a downward adjustment value of zero could be described as conservative, while such a conservative methodology could also be simulated using a factor of safety value of 1 and a downward adjustment value of five. Each would produce a different effect on the system behaviour.

Testing each VW network using as few as five different factors of safety and five different downward adjustment values would result in 25 different sets of results per network. Repeating each of these combinations for the two different strengths of cement that could be loaded on pre-emptively dispatched trucks would increase this number of tests to 50 per network.

If 42.5N strength cement was selected for a simulation run, the model decision logic had to use one of two possible different forecasts as the input to the required trucks calculation (see Equation 8). Either the consolidated forecast for both cement grades or the forecasted value for only the number of 32.5N orders placed for delivery could be used. The former would result in more trucks being dispatched and therefore was considered a more aggressive selection. This choice of forecast effectively resulted in three different strength grade options per run of the simulation model, namely 32.5N cement, 42.5N cement off a 32.5N cement forecast and 42.5N cement off a combined 32.5N and 42.5N cement forecast.

These three aspects of the planning methods resulted in an extreme proliferation of scenarios to be tested for a full analysis. The five VW networks, three cement strength scenarios, five factors of safety and five downward adjustment values gave rise to 375 different possible scenarios (see Figure 77). This relatively large number of scenarios meant the generation of data would be infeasibly onerous step five of the modelling process was executed with a focus on exploring the solution space. This step would have also resulted in a cumbersome quantity of output data that would be difficult to effectively visualize in two-dimensional space for management while failing to add significant value to the analysis.

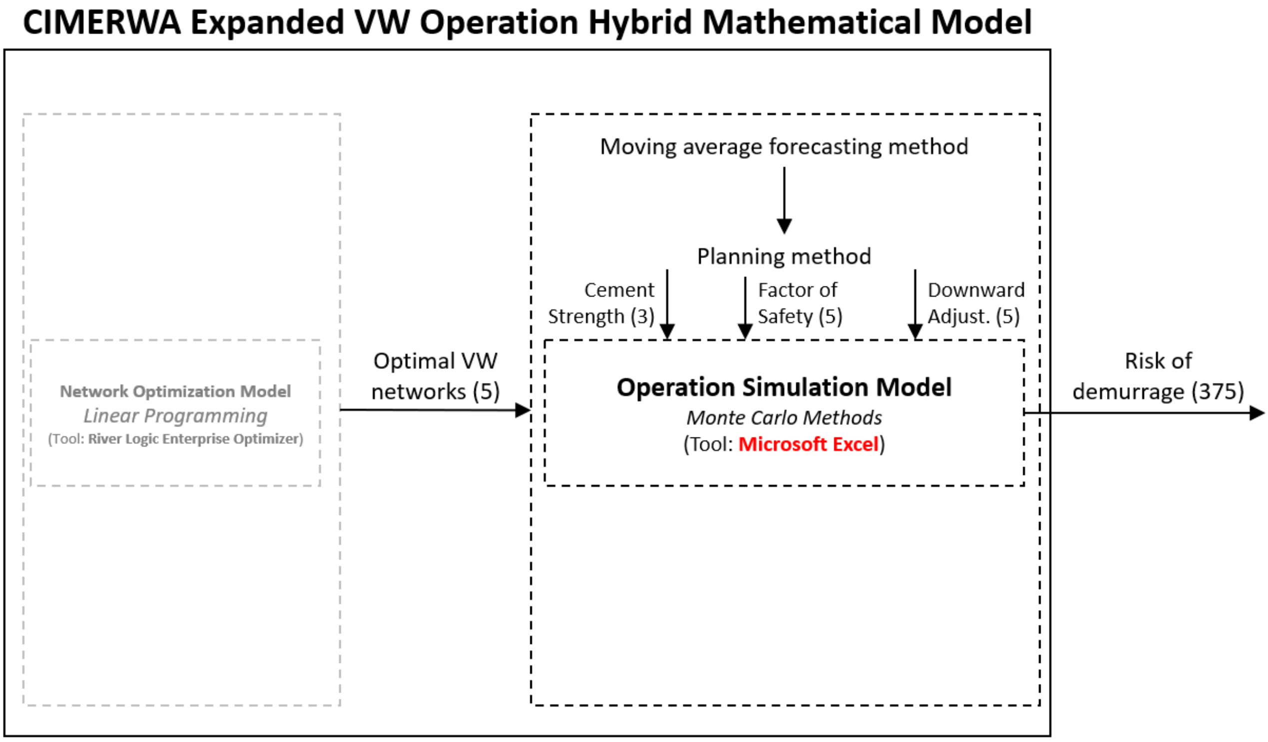

Figure 77: Input parameters to the operation simulation model (number of alternative values in brackets)

It was therefore decided to run the operation simulation model with a focus on investigating relationships between each the planning method parameter and the performance of the system the VW operation for each optimal VW network. Each relationship was investigated using a default value for each of the remaining two parameters. Default values were chosen to reflect the simplest value to implement (see Table 14).

Table 14: Default planning method parameters

Planning Method Parameter	Default Value
Forecast factor of safety	1
Downward adjustment value	0
Cement strength dispatched	32.5N

For example, the use of the optimal one-VW network was first tested using a cement strength of 32.5N and a factor of safety value of one, while the downward adjustment value was incremented between each run. The exercise was then repeated for the remaining VW networks. This data could be effectively represented on a two-dimensional visualisation by plotting using the downward adjustment values as the independent variable and the system performance metric, such as number of demurrage charges, as the dependent variable, with each number of VWs represented as a different series of box-and-whisker plots on this same set of axes.

This reduced the number of abovementioned combinations from 125 to 15 and therefore reduced the total scenarios tested from 375 to 75.

This graphic and the analysis thereof was deemed sufficient for the purposes of demonstrating an analysis of the relationship using the method. This graph was therefore not generated or analysed for other cement strength grades or downward adjustment values. The impact that adjustments to these parameter values would have on risk of demurrage would be analysed as other distinct investigations while locking the other parameter values, including the factor of safety. The insights generated by the investigation of these relationships would provide CIMERWA management with the quick method of ruling out determining planning parameter value ranges for secondary analysis, which would provide results when different non-default values for planning method parameters are used. This, analysis and subsequent iterations, however, was out of the scope of the primary objective.

11.8.3 Starting Conditions

The simulation model was run with zero vehicles en route or stationed at VWs. The moving average forecast for numbers of deliveries ordered for each VW's catchment was also initially configured with a value of zero.

During model verification, it was discovered that the sensitivity of the moving average forecast to the variable demand in each delivery city in first weeks of each simulated years resulted in the model, in some cases, unduly simulating the logistics office dispatching quantities of cement to VWs that far exceeded the annual average demand in those catchment areas. This resulted in relatively large numbers of demurrage charges that would have been prevented in the real system by some manual intervention by the logistics office.

Two possible methods were identified to rectify this issue:

1. The moving average forecast could have been redesigned. A dummy year of demand would first be simulated by generating a full set of random variate values. This data would then be used as an input to forecast during actual simulated year of operation. The moving average forecast values for day two of the simulated year would therefore reflect the average for a full year plus one day instead of only the first day of the year. The forecast would therefore be significantly less nervous during the early stages of the simulated year.
2. The model could be allowed to run without modification to the design of any of the logic, but the model would be allowed to stabilize before data was collected for analysis. By only considering the number of vehicles dispatched to each VW, the number of deliveries satisfied by VW trucks, the number of vehicles standing overnight in VW cities, etc. from day eight of the simulated year of operation onwards, the effects of the early forecast nervousness on the results of the simulations would be mitigated. Figure 78 shows the moving average forecast values for the number of 32.5N cement strength deliveries of an example actual run of the simulation model. A factor of safety value of one and downward adjustment value of zero were used. The system performance data would only reflect the operation's performance from the eighth day of operation onwards, represented by the vertical line, to give the moving forecasts time to stabilize.

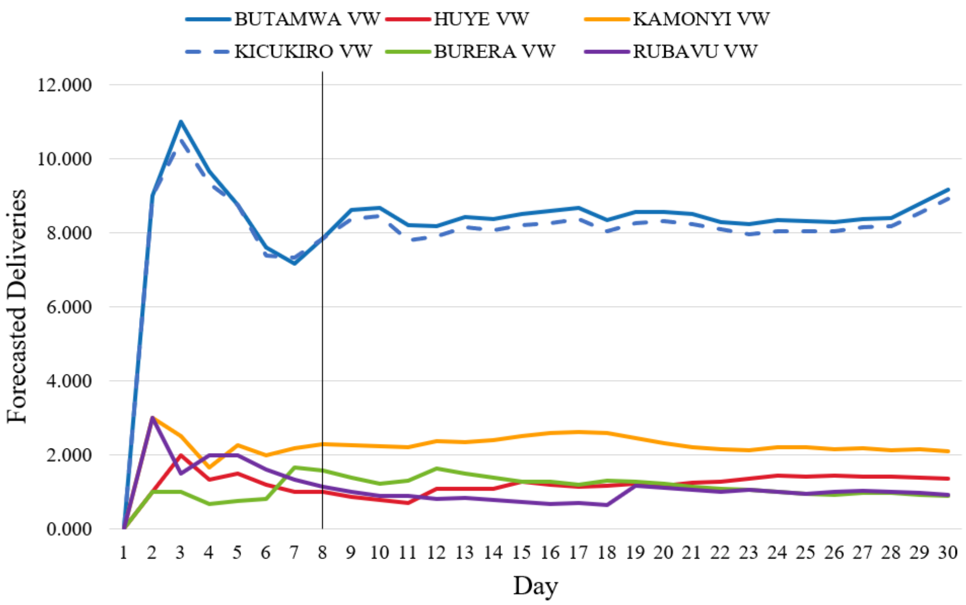

Figure 78: Moving average forecast values per VW as a function of day of year

The strain that option (1) above would have on the simulation computer and, by extension, model run time by requiring two sets of random variate values was the determining factor of the selection of solution to forecast nervousness. Option (2) would not require any additional calculations to be made by the model and was therefore selected as the solution. All simulation model results therefore reflect the performance of a 51 week year of operation.