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Distributed Autonomous Systems in Construction

Simulation-Based Hybrid Optimisation Model in Construction Logistics

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Abstract

The distributed autonomous system (DAS) approach is expected to improve the construction industry's productivity by automating the construction logistics process. A research gap has been identified regarding the lack of research efforts on informing the potential of Construction Logistics Operation (CLO) automation with DAS and its revolutionary impacts on the industry from different aspects. This study explores the potential of an urban consolidation centre (UCC) with an automated intelligent planning system in connecting seamlessly among disassociated parties to reduce freight traffic, delivery wait time, distribution cost, and environmental impacts. A simulation-based hybrid model created using Agent-Based Modelling (ABM), Discrete Event Modelling (DEM) and System Dynamic Modelling (SDM) is used to conceptualise the difference under the context of vehicle routing problem (VRP) between the CLO with UCC implementation and the direct CLO composed of several dissociated parties. The model is designed considering different disruptive event effects like traffic levels and critical weather to the vehicle behaviour. Vehicles' speeds have been modelled with stochasticity to simulate real-life speed fluctuation. The speed limit constraints have also been simulated according to different traffic levels and critical weather conditions which to the best of the authors' knowledge never have been done before by other researchers. Two case studies on real-life construction projects have been conducted to verify the hypothesis made on the benefits of proposed UCC implementation. The results demonstrate that the UCC scheme reduces both deliveries wait time and distribution cost but increases the carbon emissions contributed by material distribution. The outcomes were then investigated and the reasonings behind them were explained in detail. Finally, the paper summarised some limitations of the methodology and proposed several recommendations for future work.

Keywords: Distributed Autonomous System, Construction Logistics, Vehicle Routing Problem, Hybrid Modelling Technique, Agent-Based Modelling (ABM), Discrete Event Simulation (DES), System Dynamic Modelling (SDM)

Contents

Chapter 1: Introduction **11**

1.1 Project Objective 11

1.2 Main Contribution to Knowledge of Work 11

1.3 Overview 12

Chapter 2: Literature Review 12

2.1 Distributed Autonomous System in Construction 12

2.2 On-Site Construction Automation 13

2.3 Modular Construction 13

2.4 Construction Logistics Operation (CLO) 14

2.5 Urban Integrated Construction Logistics Distribution 15

2.6 Vehicle Routing Problem (VRP) 16

2.6 Research Gap 19

Chapter 3: Methods 19

3.1 Literature Review Research Methodology 19

3.1.1 Planning Stage 20

3.1.2 Operating Stage 21

3.1.3 Analytical Stage 21

3.2 Options to address the problem 22

3.3 Rationale 23

3.4 System Description 24

3.5 Outline of the hybrid model framework 26

Chapter 4: Construction Logistics Vehicle Routing Modelling 27

4.1 Modelling of Vehicle Routing 28

4.2 Modelling of Delivery System Dynamic 31

4.3 Modelling of Material Delivery Schedule 34

4.4 Modelling of Measuring Metrics 37

Chapter 5: Result, Discussion & Validation 44

5.1 Prologis Park Hemel Hempstead 44

5.1.1 With UCC 45

5.1.2 Direct 46

5.1.3 Comparative Analysis 47

5.2 Bishop Square 50

5.2.1 With UCC 51

5.2.2 Direct 52

5.2.3 Comparative Analysis 52

5.3 Similarities and differences between projects 54
5.4 Discussions 55
5.5 Sensitivity Analysis 56
Chapter 6: Conclusion, Limitations and Future Work 57
Chapter 7: References/ Bibliography 60

LIST OF FIGURES

Figure 1: Three-Step Approach to Conduct Systemic Literature Reviews 20
Figure 2: Classification of Simulation Techniques 23
Figure 3: Supplier Chain System with & without Urban Consolidation Centre (UCC) 24
Figure 4: Systemic Framework for developing the Multi Objectives Optimisation model in Vehicle Routing Problem (VRP)... 26
Figure 5: Snapshot of Bishop Square and Suppliers in Modelling Environment....................... 29
Figure 6: (Truck & Semitrailer) vehicle state chart 30
Figure 7: Process flow chart of the hybrid model (suppliers & UCC)....................................... 32
Figure 8: Process flowchart of the hybrid model (construction sites & UCC) 32
Figure 9: System Dynamics blocks that simulate the inventory system 33
Figure 10: Process flowchart of the hybrid model (Direct)... 33
Figure 11: Stocking Schedule from Suppliers to UCC modelled as multi-agents 34
Figure 12: Stocking Parameters in Hybrid Model... 35
Figure 13: Delivery Schedule from UCC to construction site modelled as multi-agents 35
Figure 14: Delivery Parameters in Hybrid Model... 36
Figure 15: Delivery Schedule from Suppliers to Construction Site modelled as multi-agents... 36
Figure 16: Delivery Parameters in Hybrid Model (Direct) 37
Figure 17: Time measuring function from UCC to the construction site.................................. 38
Figure 18: Time measuring function from supplier to UCC 38
Figure 19: (a) Time Stacked Histogram (b) Time Stacked Graph 39
Figure 20: Time measuring function from suppliers to the construction site............................ 39
Figure 21: (a) Time Stacked Histogram (b) Time Stacked Graph 39
Figure 22:Activity-Based Costing Technique.. 40
Figure 23:Activity-Based Costing Technique adopted in Model.. 41
Figure 24: Event Function and Cost Computed to calculate the associated Cost of Delivery Event 41
Figure 25: a) Transport Delivery Cost Evaluated in Time Chart (minutes) (b) Multi-activity and Total Delivery Cost Evaluated in Time Chart (minutes).. 42
Figure 26: Event Function and Codes Computed Carbon Emission produced on Delivery Event 43
Figure 27: Total Carbon Emission Evaluated in Time Chart (minutes).................................... 44
Figure 28: Delivery Cost (£) between the implementation of with and without UCC.............. 48
Figure 29: Carbon Emission (kgCO2e) between the implementation of with and without UCC49

Figure 30: Carbon Emission for each time interval (kgCO2e) between the implementation of with and without UCC 50
Figure 31: Delivery Cost (£) between the implementation of with and without UCC................ 53
Figure 32: Carbon Emission (kgCO2e) between the implementation of with and without UCC 53
Figure 33: Carbon Emission for each time interval (kgCO2e) between the implementation of with and without UCC 54

LIST OF TABLES

Table 1: Summary of Review Papers about Vehicle Routing Literature 18
Table 2: Keyword Search Strategy... 21
Table 3: Speed distribution of vehicles during traffic and weather disruptions.......................... 31
Table 4: Block Description (Process Modelling Library) in DEM 31
Table 5: Loading & Unloading Time Delayed in Triangular Distribution (Min, Max, Mode)... 31
Table 6: Limitation and Assumption of the Stocking Parameters... 35
Table 7: Limitations and Assumptions made of the Delivery Parameters 36
Table 8: Limitation and Assumption made of the Delivery Parameters (Direct)........................ 37
Table 9: Parameter and Values adopted for Cost Calculation Function 42
Table 10: Parameter and Values adopted for Carbon Emission Function.................................. 43
Table 11: Summary of model outputs (UCC) 45
Table 12: Parameters adopted and outputs obtained for optimisation of Prologis Hemel Hempstead... 46
Table 13: Summary of model outputs (without UCC) 47
Table 14: Comparison of delivery wait time between UCC and without UCC 47
Table 15: Summary of model outputs (UCC) 51
Table 16: Parameters adopted and outputs obtained for optimisation of Bishop Square............ 51
Table 17: Summary of model outputs (without UCC) 52
Table 18: Summary of Optimisation Output without Consolidation Centre............................... 52
Table 19: Results of sensitivity analysis on model parameters.. 57

LIST OF ALGORITHMS

Pseudocode 1: Proposed framework algorithm (UCC vs Direct) 28
Pseudocode 2: Vehicle Speed Algorithm for different traffic levels 30

LIST OF ACRONYMS

ABC	Activity Based Costing
ABM	Agent Based Modelling
BIM	Building Information Modelling
CIVIC	Construction in Vicinities, Innovative & Co-creation
CLO	Construction Logistics Operation
CSC	Construction Supply Chain
DAS	Distributed Autonomous System
DEM	Discrete Event Modelling
ETO	Engineer-To-Order
EV	Electric Vehicle
FLP	Facility Location Problem
GIS	Geographic Information System
GPS	Global Positioning System
HGV	Heavy Goods Vehicle
IABC	Improved Artificial Bee Colony
LRP	Location Routing Problem
MAS	Multi Agent Systems
SCM	Supply Chain Management
SDM	System Dynamics Modelling
SLR	Systemic Literature Reviews
SVR	Support Vector Regression (SVR)
TSACS	Two-Stage Ant Colony System
UCC	Urban Consolidation Centre
V&V	Validation & Verification
VRP	Vehicle Routing Problem

Chapter 1: Introduction

1.1 Project Objective

The increased usage and evolution of the distributed autonomous system (DAS) approach in the construction industry will fundamentally increase construction productivity. Increasingly, DAS will be used to design and construct infrastructure, which challenges our insight into how infrastructure is erected and constructed. Explorations in DAS are inextricably tied to the availability of the programmed algorithm and the network used. As DAS becomes more pervasive, it unifies the design and construction activities by improving the design capabilities impact, necessitating designers and contractors to work closer together. The impact points include improved material deposition, computational aid design, machine learning, and robot manipulation. The recent research trend in DAS focused more on distributed (ground and aerial) robots that work with highly processed, specialised building materials or prefabrication technologies for modular construction; less attention is paid to construction logistics operations (CLO) that necessitate wide-area connectivity and integrated information exchange between autonomous systems. Recognising the benefits of connectivity in CLO, particularly in providing automated communication between supplier and construction site, this paper intends to conceptualise the future of automation by investigating the difference between having implemented a smart urban consolidation centre (UCC) as opposed to the current direct CLO composed by several dissociated parties under the context of vehicle routing problem (VRP) and evaluate its impact in terms of delivery wait time, cost and carbon emission to verify the low energy consumption and high operational efficiency hypothesis made on UCC. This is achieved by developing a hybrid model in simulating the system behaviour of a highly integrated logistics flow with UCC acting as the brain, controlling and planning the resources smartly.

1.2 Main Contribution to Knowledge of Work

The contribution of this dissertation is three-fold. Firstly, the development of a hybrid model incorporating Agent-Based Modelling (ABM), Discrete Event Modelling (DEM), and System Dynamic Modelling (SDM) in simulating the CLO with UCC implementation under the DAS approach is novel. Secondly, accounting for the stochasticity of vehicle speeds, different types of vehicle fleets, and the effects of disruptive events like the traffic level and critical weather occurrence on vehicle behaviour when modelling the vehicle routing and fleet dispatching operations is new. Finally, the evaluation and optimisation of the model performance in terms of delivery wait time, delivery cost, and carbon emission coupled with the qualitative and quantitative analysis of the model results provide the practitioners or researchers with a better understanding of the impacts of UCC implementation.

1.3 Overview

The dissertation is organised as follows. Chapter 2 provides a literature review of the key research areas on DAS in construction and relevant works dealing with CLO and VRP. Chapter 3 illustrates the methodologies follow in the literature review and the rationale behind the applied concept of multi-objective simulation through hybridising ABM, DEM, and SDM. Chapter 4 presents and explains the methodologies used in the hybrid modelling and performance metrics used to evaluate the model. Chapter 5 discusses the model results and depicts a summary of integrated analysis and interpretations of research findings, then closes off the chapter with model validation. Model limitations, work reflections, recommended future works and conclusions are discussed in Chapter 6. References and appendices are included in Chapters 7 and 8 to provide supplemental information such as algorithms formulated for this study and detailed information on the analysed results.

Chapter 2: Literature Review

2.1 Distributed Autonomous System in Construction

The DAS approach is better explained in two separate components: autonomous and distributed systems. An autonomous system was described as machine intelligence that can adjust its decision-making process and subsequent behaviour without human interaction to unanticipated events during operation (P. Watson David, 2005). Similarly, a distributed system is a computing environment with a function achieved by intensive communication and interaction among multiple components distributed over different locations or devices. Combining the concept above, a DAS can be described as a collection of human-free intelligent machines with decision-making and reasoning abilities cooperating through communication to achieve one predefined common objective. Its application is broad and diverse depending on the defined objective, penetrating different industries at different rates.

Melenbrink et al. (2020) suggested that there is an existing gap between the academic and industry research, where industry experts have focused more on robotic and intelligent automation during the on-site construction stage, particularly on three main groups of activities, site preparation, substructure construction and the building of superstructure, exploring its potential in automating highly risky, labour-intensive and time-consuming construction activities. Furthermore, the global trend of offsite prefabrication related studies has been followed intensively by academic researchers predominantly due to environmental concerns. After thoughtful consideration, this paper will navigate the off-site construction research area for one main reason. The authors believe that insufficient industrial experience and exposure will prevent them from critically analysing the on-site construction issue, affecting the quality of the research outcome. In contrast, the off-site construction study is a data-driven problem where much information could be obtained through the internet and investigated computationally. More importantly, the need for a revolution in the construction industry is critical, and the authors are keen to contribute to this changing momentum.

2.2 On-Site Construction Automation

Within the research area of site preparation, Jud et al. (2021) performed several studies on developing an autonomous walking excavator for autonomous trench digging, assembly of dry-stone walls, forestry work, and its complementary planning tasks. Schmidt and Berns (2013) developed a control algorithm for connecting and operating the autonomous bucket excavator Thor without the need for human assistance. In terms of substructure research efforts, Zhou et al. (2020) utilised two powerful optimization algorithms, artificial neural network, and genetic programming, to create predictive models for the tunnel boring machine to increase its time and cost efficiency in tunnel excavation. Spenneberg and Kirchner (2010) presented a control algorithm for automating the shotcreting process in tunnelling and its established concrete layer quality by adjusting in real-time the trajectory of the shotcreting.

In the case of superstructure building, there was quite a significant effort invested in this area. Chu and Chua (2019) present a concurrent processing vertical climbing robot design that automatically tightens steel structures' nuts and bolts. Melenbrik et al. (2021) investigated the potential of incorporating local force measurements using force sensors on structural members as a guiding signal for a team of independent climbing robots in building a cantilever. Usevitch et al. (2020) introduced the design of a truss-climbing robot with a reconfigurable planning algorithm to construct reconfigurable structures.

Besides, some researchers focused on the less noticeable but critical side of the construction industry. Teizer et al. (2010) presented a paper on developing an autonomous pro-active real-time construction worker and equipment operator proximity safety alert system using RF tagged technologies to reduce construction fatality. Wareham (2019) designed a robotics system in handling the repairing and maintenance work in distributed construction activities. Therefore, it is observable that the research capital invested in the sub-structure is lacking, and site preparation is overly concentrating on earthwork-related activities, not to mention the post-construction activities such as repairing and maintenance.

2.3 Modular Construction

Off-site construction is defined as the completion or prefabrication of structural elements and modules beforehand in a factory environment where building components are manufactured before being transported to an on-site location where the components will be installed (Jin *et al.*, 2018). Similarly, modular building is a form of offsite construction where prefabricated components that are transported on-site are assembled using a crane (Caldarelli *et al.*, 2022). Hussein et al. (2021) found that academic researchers are more inclined to investigate the field of modular construction in an interdisciplinary approach due to the construction industry's multifaceted and overlapping nature, with approximately 33% of articles related to it. Research studies related to production line problems contributed up to 28% of all the literature, followed by 19% on on-site construction, then 13% on design and planning perspective and around 7% of studies are discovered to be related to CLO (Hussein *et al.*, 2021). In addition, feasible solutions incorporating different methodologies like optimisation, simulation, and building information modelling (BIM) have been proposed by researchers to solve the respective problems related to modular construction. However, most researchers (35%) prefer to attempt the solution with an integrated approach predominantly owing to its complexity, implementing more than one method in formulating the solution. Also, modular construction has its own set of challenges particularly when construction sites are located in a metropolitan area as the structural components left from a manufacturer are generally huge, require more caution when transporting across highways, and are assembled on-site (Rogers and Bottaci, 1997). In this context, traffic congestion can cause significant delays in the on-site assembly plan. In a separate thread, urban construction sites typically have limited storage capacity, necessitating a temporary warehouse in the suburbs, adding another degree of complication to the construction supply chain and transportation (Azhar, Lukkad and Ahmad, 2013). Thus, CLO will be the problem domain of this research to solve the recent emerging difficulties mentioned earlier.

2.4 Construction Logistics Operation (CLO)

CLO is concerned with the transportation of materials from offsite to on-site. The literature on construction logistics is relatively scarce compared to the on-site construction stage, as most construction activities were performed on-site back in the day. However, with more construction activities being shifted offsite nowadays, it is important to examine and prioritise the interlinking stage between the offsite prefabrication and the on-site construction stages. Until today, most problems found in the logistics stage could be roughly categorised into logistics management and route planning. Jaśkowski et al. (2018) developed a mixed-integer linear programming economic order quantity model to respond to the supply and demand variation in a dynamic construction environment for better logistics management. Ahn, Han and Al-Hussein (2020) focused solely on the cost incurred during the transportation phase by estimating transportation costs using spatial and temporal data collected through GPS devices; the collected cost datasets were used to train a Support Vector Regression (SVR) learning model for future cost prediction. Yi, Wang and Zhang (2020) proposed a mathematical programming model to utilise trucks' capacity to reduce delivery trips and the overall inventory and distribution cost.

Regarding routing problems, Li et al. (2020) incorporated an Improved Artificial Bee Colony (IABC) algorithm in solving the time window constrained VRP to optimise the prefabricated system delivery time. Despite the increasing research on CLO, the existing research does not account for the likelihood of unexpected risks and other factors such as weather conditions, traffic level, vehicle breakdown, and other adverse events in their studies. Most proposed solutions are focused on improving inventory management, decision-making process, demand prediction, and information sharing. There is an evident scarcity of studies targeting construction VRP. The lack of concrete formulation of VRP with considerations of delivery wait time and sustainability impact must be addressed to enhance the performance of the overall CLO.

2.5 Urban Integrated Construction Logistics Distribution

UCC) is a transport initiative intended to reduce truck journeys into urban areas. UCC is a logistics hub close to the region from which it consolidated deliveries that provide service within the area. UCC typically handle final mile delivery, whereby carrier conveys their delivery to the UCC. The UCC received the parcel, consolidated cargo from the carrier, and distributed them accordingly with the smallest possible frequency and routing distance. Location Routing Problem (LRP) is generally embedded within the UCC problem as it involves all facets of decision levels needed in the supply chain, which are strategic decision making regarding the UCC location, tactical decision making regarding the customer allocation concerning UCC availability and finally the operational decision making regarding the assigning of optimal delivery routes between UCC and customers (Nataraj *et al.*, 2019). LRP is also commonly being regarded as an integration of Facility Location Problem (FLP) and VRP where the former focuses more on strategic decision making and later focuses more on operational decision making. Nataraj et al. (2019) analysed the implementation of UCC with different degrees of cooperation levels from companies and evaluated its overall impacts on cost savings and CO_2 reduction. On a greater scale, multiple UCCs can form a multi-echelon distribution network for maintaining cost and inventory management across multi-level supply chains (Cuda, Guastaroba and Speranza, 2015). In the complex multi-channel supply chains system, flexibility within the network is the most crucial aspect ever.

Allen et al. (2012) conducted a literature review on the use of UCC over 114 UCC schemes in 17 countries. One of the best-known UCC implementations is the one in London conducted by Browne, Allen and Leonardi (2011). The paper concluded a reduction of total travel distance and CO2 emissions by 20% and 54% respectively through a trial run on freight traffic under the context of UCC. Similar results have also been obtained by the study done by Giampoldaki et al. (2021), meanwhile, he suggested a future research direction in exploring business models to integrate the operations between construction based UCC and conventional UCC. Marcucci and

Danielis (2007) also conducted a stated-preference study to estimate the potential demand for UCC in the city of Fano, Italy, and determined the key factors affecting its feasibility.

UCC aside, some other solutions for logistics distribution improvement are proposed as well. Cheng et al. (2016) and Ehmke, Campbell and Thomas (2016) are some of the most recent works on this issue that focus on using crowds for logistics services. Crowd logistics – alternatively termed collaborative logistics, is presented as a concept that uses excess capacity on premeditated trips scheduled to make deliveries, maximising logistics efficiency and reducing congestion and emissions. The timely delivery of materials to construction sites in the appropriate quantity, desired quality, and at a reasonable cost is crucial. It can significantly impact the project's productivity, cost, and duration (Crainic, Ricciardi and Storchi, 2009).

2.6 Vehicle Routing Problem (VRP)

VRP is a research area investigated broadly in the research study. VRP can be defined as finding the optimal set of routes or travel sequences for vehicles to satisfy the requirements of the clients where it could be as delivery time, cost, distance (Dündar, Ömürgönülşen and Soysal, 2021). VRP is a widely known difficult problem to solve (NP-Hard) due to its exponentially expanding nature in potential solutions and the increase in delivery events. Importantly, research disciplines that support the convergence of research topics are starting to define development in VRP towards developing algorithms and traffic management, thereby allowing significant increases in supply chain productivity. Eksioglu, Vural and Reisman, (2009), Golden, Raghavan and Wasil (2008), and Tan and Yeh (2021) provide an in-depth, comprehensive review of the VRP throughout the research history. The majority of VRP has been considered in two main constraints: time window rate and heterogeneous with a recent emergence of electric vehicle variant owing to the increasing awareness of environmental protection. The study generally focuses on a single objective of either cost, distance, or emission rate rather than multiple objectives. Cattaruzza et al. (2017) highlighted a few overviews that provide insight into the current issue of VRP. The first issue embeds time-dependent trip times, illustrating peak traffic congestion in cities (Van Woensel et al., 2008). Access constraints are also one of the VRP variants whereby Heavy Goods Vehicle (HGV) trucks can only move within the city during specific time intervals. The third variant discussed is the carbon emission routing problem, whereby Bektaş, Demir and Laporte (2016) tried to reduce carbon emissions within certain constraints. Solution wise for VRP, exact method, heuristics, and meta-heuristics are commonly used. For instance, Çimen and Soysal (2017) formulated the time-dependent capacitated VRP as a Markovian Decision Process and solved it using Approximate Dynamic Programming to achieve the goals of minimal cost and carbon emissions. Besides, scholars have proposed many solutions to tackle the VRP with a sustainable approach. Koç and Karaoglan (2016) intended to minimise carbon emission by limiting vehicles' driving range (a grid of boundaries set up with a depot located in the centre of the location configuration) during goods distribution. Another common variant of VRP is with the extra condition of multi-depot; Zhang et al. (2020) proposed a Two-Stage Ant Colony System (TSACS) algorithm to find the global optimal to minimise the total carbon emission. Li et al. (2021) uses the improved K-means algorithm to obtain the solution for the same problem but achieve the highest possible customer satisfaction. Weerakkody (2021) performed a systematic literature review on solution approaches for VRP with shipment consolidation and found that metaheuristic algorithms work the best in solving complex models with large target nodes. *Table 1* provides a summary of additional literature papers about VRP in the past.

Table 1: Summary of Review Papers about Vehicle Routing Literature

Author/Year	Scope	Objective	Eco		Social			Env			MT	HM	DT		Factor Considered										Results
			C	P	T	R	O	G	E	W			r	h	a	b	c	d	e	f	g	h	i	j	
(Martins et al., 2021)	Coordination of production and supply chain	Min: Veh and Cost	√		√							BR-VRD		√	√			√				√		√	The proposed model able to optimise the delivery by minimisation 10% of the service time to the last mile delivery.
(Cai et al., 2021)	Connected Autonomous Vehicles	Min: CO2						√				PSO	√		√	√				√			√		The proposed low-carbon VRP able to optimise CAV routing with reduce carbon emission.
(Zhang et al., 2015)	Sustainable Urban VRP	Min: CO2 and Fuel	√		√			√				TS	√		√						√		√	√	The numerical experiments of low carbon routing problem reveal that exist a trade-off relationships among fuel consumption, vehicle operational cost and carbon emission.
(Wang et al., 2019)	Sustainable Urban VRP	Min: CO2 and Fuel	√		√			√				TS	√		√						√		√		The proposed algorithm able to effectively reduce the carbon emission and fuel consumption in compared to traditional VRP.
(Shahvari & Logendran, 2017)	City Logistics	Min: Dist and Cost	√	√	√							TS	√		√	√	√	√						√	Metaheuristic algorithm based on tabu search is developed on solving batching and scheduling phases.
(Wang and Odoni, 2016)	Last Mile Logistics	Min: Dist and Time	√		√						Sim	C&W-SWA	√		√	√	√			√					Vehicle usage rate increased in most of the scenarios considered as number of passengers surged. Nevertheless, the proposed simulation able to optimise the VRP as the passengers decreased.
(Masson et al., 2017)	Urban Logistics	Min: Veh and Cost	√								MIP	LS		√	√										The research findings concluded that mixed transportation (transport passengers and product goods) through buses was possible.
(Wang et al., 2018d)	Collaborative Logistics	Min: Cost	√								MIP	GA-PSO	√		√			√			√			√	The proposed integrate production and distribution (VRP) phases able to reduce distribution cost by up to 12%.
(Li et al., 2018)	2E-VRP	Min: Cost, Time and CO2	√		√			√			MIP		√		√	√	√	√	√	√	√		√	√	The proposed model able to optimise the delivery and lead to saving of 2.5% of fuel consumption; nevertheless lead to a cost increase of 10.8%.
(Yu and Lam, 2018)	Smart City - EVRP	Min: Time and Dist		√	√			√			MIP			√	√	√	√								The proposed model would be positively contributed to autonomous distributed system by automating the coordination of vehicles and operational cost in smart city.
(Friedrich and Elbert, 2022)	City Logistics -VRPTF	Min: Dist and Cost	√		√					√		ALNS-LS	√		√		√							√	The VRP algorithm provide a managerial insights on decision to hire transhipment facility (consolidation centre).
(Cortes and Suzuki, 2020)	VRPSD	Min: Cost	√	√	√						MIP	TSSA			√	√	√	√						√	The proposed VRPC model through implementation of mid-route shipment consolidation for logistics companies led to 10% saving in cost and efficiency of last-mile delivery.
(Suzuki, 2016)	PRP	Min:Dist, Fuel and Payload	√					√			MIP	LS		√	√					√	√				The proposed model able to provide a 0.5% reduction of fuel consumption in compared to model developed by Xiao et al. (2012).
(Hu et al., 2018)	Urban VRP	Min: Time and Fuel		√	√			√				LS	√		√					√	√				The research findings concluded that transportation time can be effectively reduced by up to 20% followed by a 10% reduction of fuel consumption.
(Simoni et al., 2018)	Urban VRP and Logistics	Analysis of CC- Cost and CO2	√	√						√	MIP	C&W-GA-PSO	√		√	√		√						√	By implementation of urban consolidation centre and electric vehicles might reduce CO2 emission up to 40% and total distribution cost up to 20%.

Scope (VRP: Vehicle Routing Problem, VRPTF: VRP with Transhipment Facilities, VRPSD: VRP Shipment Consolidation). Objective (Veh :Number of Vehicle, Dist: Distance). Eco: Economic (C: Cost, P: Profit). Social (T: Time, R: Risk, O: Other). Env: Environmental (G: GEG Emission, E: Electric Car, W: Waste). MT: Model Type (SIM: Simulation, MIP: Mix Integer Programming). HM: Heuristics Model (BR-VRD: Biased-Randomised Variable Neighbourhood Descent metaheuristic, PSO: Particle Swarm Optimisation, TS: Tabu Search, LS: Local Search, C&W: Clark & Wright, SWA: Sweep Algorithms, GA: Genetic Algorithm, ALNS: Adaptive Large Neighbourhood Search, TSSA: Two Stage Simulated Annealing Algorithm). DT: Data Type (r: real data, h: hypothetical data). Factor Considered (a: Distance, b: No of Vehicle, c: Travel Time, d: Vehicle Capacity, e: Labour Wage, f: Speed, g: Fuel Consumption Function, h: Service Level, i: Greenhouse Gas Emissions, j: Vehicle Distribution Costs).

2.6 Research Gap

To the best of the authors 'knowledge, the existing research has a scarcity of research focused on the logistics facet of the construction industry. Although many related studies attempt to address the problems found in the logistics function, there are limited studies targeting specifically the integrated logistics distribution in the construction industry as most of it has done on other industries like e-commerce and food industries with different fundamental characteristics. The research gaps found are: (i) Existing studies did not demonstrate sufficient research efforts on the potential of CLO automation with DAS and its revolutionary impacts on the industry in terms of delivery efficiency, cost, and sustainability; (ii) The literature still lacks concrete and comprehensive consideration on potential risks such as traffic level and weather condition when formulating their VRP solutions that designed specifically for construction industry accounting its material characteristics, vehicle characteristic, and scale of transported goods; (iii) There is a lack of an optimisation-based simulation approach in providing unique interpretation and visualisation into VRP in serving construction site in contrast to conventional mathematical formulation approach by a majority of the scholars.

Recognising the research gaps found, the main contribution of this study intends to achieve are: (i) develop a hybrid optimisation-based simulation approach on the VRP with a UCC implementation considering different traffic levels, vehicle characteristics, and material characteristics in the construction logistics; (ii) conceptualise the future of automation through investigating the difference of having implemented a smart UCC as opposed to the current direct system composed by several dissociated parties; (iii) provide a quantitative and qualitative evaluation on the impacts of the model from a socio-economic and sustainable standpoint.

Chapter 3: Methods

3.1 Literature Review Research Methodology

A literature search strategy was created to depict the past and existing literature on distributed autonomous systems in construction and narrow down the distributed autonomous system to develop an optimisation model for solving construction logistics VRP. In performing our systemic literature review (SLR), we used the generic three-step data collection and analysis approach. This generic systemic literature review involved a planning, operating, and analytical stage, as shown in *Figure 1*.

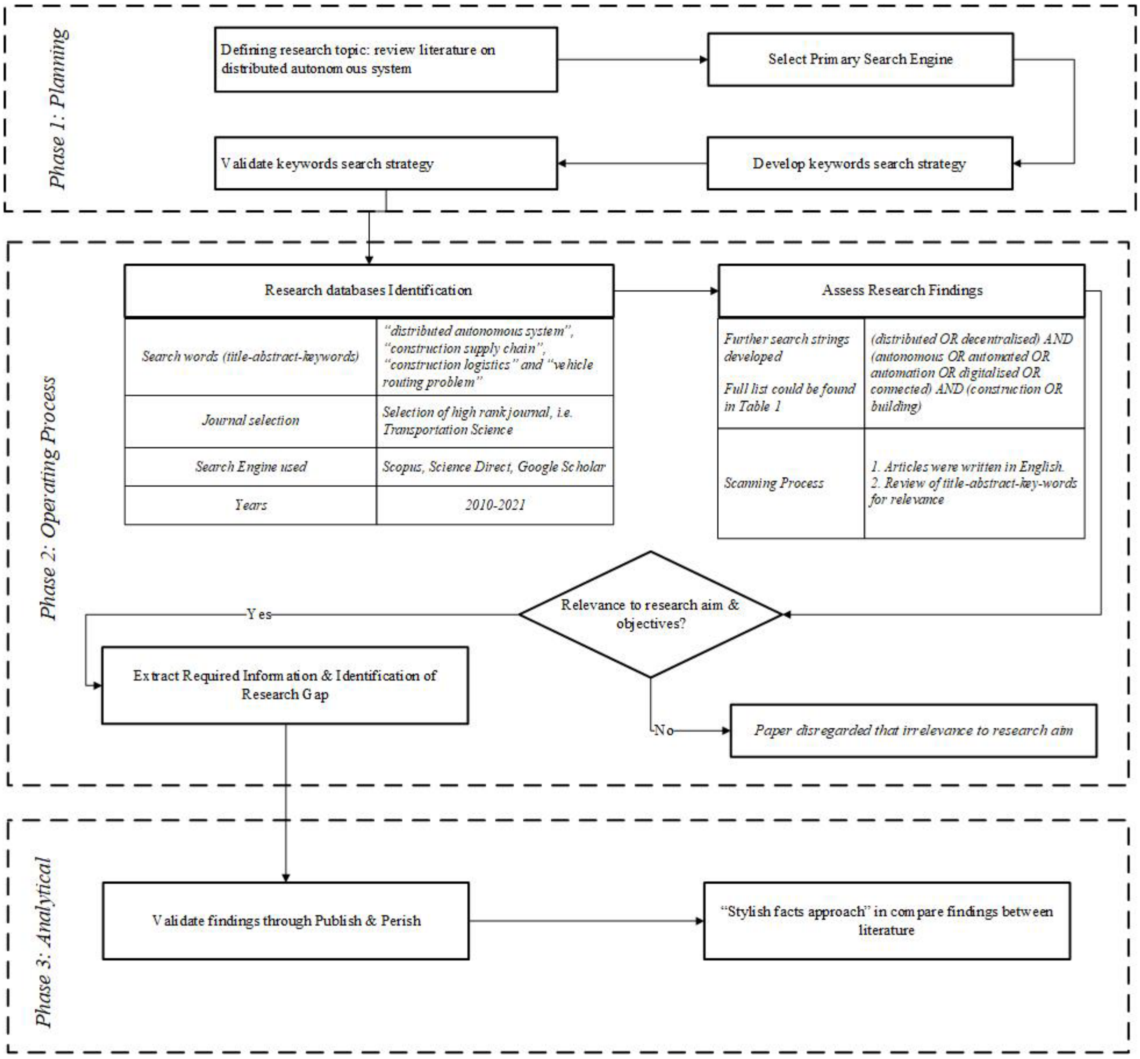


Figure 1: Three-Step Approach to Conduct Systemic Literature Reviews.

3.1.1 Planning Stage

Our thesis aimed to understand the relationship between DAS and proximities of distributed systems in construction supply chains (CSCs). Particular emphasis on the DAS related to CSCs and VRPs. Scopus database is selected as our primary search engine to identify the research gap. We extend our search strategy to include publications from Google Scholar, Science Direct, and Transportation Science to identify relevant information regarding our research topic. To define our research's conceptual boundaries, we specify the key terms such as "distributed autonomous system" and "construction supply chain" or "construction logistics" and "vehicle routing problem" in publications and articles that are related to engineering and computer science.

String	Search Strategy, and Search Inclusion Criteria
1	(Distributed OR decentralised) AND (autonomous OR automated OR automation OR digitalised OR connected) AND (construction OR building)
2	(Modular OR prefabricated OR offsite)
3	(Sustainable OR smart) AND (construction OR building) AND (logistics OR distribution OR transportation) AND (system OR model OR planning)
4	(Vehicle OR truck OR freight) AND (routing OR navigation) AND (construction OR building)
5	(Impact OR affect) AND (traffic level OR material characteristic OR vehicle characteristic OR weather condition) AND (logistics distribution OR consolidation centre)

Table 2: Keyword Search Strategy.

3.1.2 Operating Stage

The keyword search strategy is illustrated in *Table 2*, it demonstrates the series of keywords used to identify the research gap and applied using the Scopus database. We also reviewed relevant conference contributions, such as the winter simulation conference on simulating complex distributed service systems. This method relies on keyword search based on the search engine and ensures that relevant content is extracted from relevant publications. However, not all journal articles found were related to the area of interest. Hence, the criteria outlined below help us conclude the relevant literature to include:

1. The articles were written in the English language.
2. The articles are based on Industry 4.0 methodology and research focussed on algorithms related to CSCs and VRP.
3. The articles focused on DAS and keywords outlined in *Table 2*.

Our sample is rigorous as it involved an extensive manual exclusion of articles to eliminate the articles that did not match the criteria described above and dissertations and books, leaving only scientific peer-reviewed journal articles available from the online database. There are two reasons for exclusively reviewing scientifically reviewed journal articles: 1) there are sufficient journal articles available that provide more in-depth research with more rigorous frameworks compared to non-peered scientific review journal articles and 2) manual review of other documents did not offer much value on our research; hence, their exclusion makes our review more reliable.

3.1.3 Analytical Stage

To validate the reliability of our articles, we incorporated the research software, Publish or Perish in eliminating duplicates across the databases and sorted the literature on the importance sequence of citation per year, total citation, and publication year to ensure the most reliable and relevant paper is selected for further review. We also devoted special attention to assessing by manual comparing factual data for agreement. We did not simply take the journey's quality rating or influence level for granted. Instead, we implemented quality assessment criteria to review papers by adopting a qualitative research method known as "stylised facts" to structure and evaluate the earlier research topic. By incorporating knowledge built on literature review and identifying recurring topics, this strategy allowed us to identify more lines of evidence inside the research topic. In this way, we were able to appraise study findings while also placing them in context with the findings of other studies. The most dependable findings are those that reoccur and are confirmed over time. Interrater dependability and stylised facts worked together to provide us with objective foundations to develop our arguments about the current state of knowledge.

3.2 Options to address the problem

The ultimate goal of this study is to test and verify the hypothesis made on UCC towards VRP in CLO, which is that the implementation of UCC will improve the delivery efficiency, and reduce delivery cost and carbon emissions. As mentioned previously under the VRP literature review section, various algorithms are commonly used to study the VRP. However, each solution has its advantages and disadvantages over one another. For instance, exact methods are typically efficient and establish bound solutions but are only appropriate for small-scale. It is getting harder to obtain optimal solutions as the problem scale-up infinitely where the complexity of mathematical formulation increases drastically and does not reflect the real-world consideration. Due to insufficient understanding of UCC's operation and business model, the modelling paradigm is a common practice to investigate the behaviour of UCCs and gain new insights. A unique modelling practice for UCCs or complex supply chains is to represent the complex CLO as VRP and evaluate the performance of direct and UCC-based CLO.

Moreover, simulations can consider the system's behaviour, including disruptions and dynamic properties with descriptive results. Taniguchi et al. (2014) stated that the most appropriate method for studying the behaviour and interactions between numerous agents in the complex supply chain environment is ABM. Also, a recent trend suggests combining ABM with DES to characterise agents with utility functions based on stated preference data. Marcucci et al. (2017) simulated stakeholders' interactions in urban freight transportation through the real-world dynamic nature of the supply chain. Therefore, instead of formulating the VRP as a mathematical program, it is here formulated as a hybrid simulation model that combines the pros and cons of both methods as it reflects the real-world dynamic nature of CLO. In this paper, we will incorporate a hybrid optimisation-based modelling technique that incorporates ABM, DES and SDM to simulate the vehicle routing and truck dispatching problem under the UCC concept to verify the proposed hypothesis.

3.3 Rationale

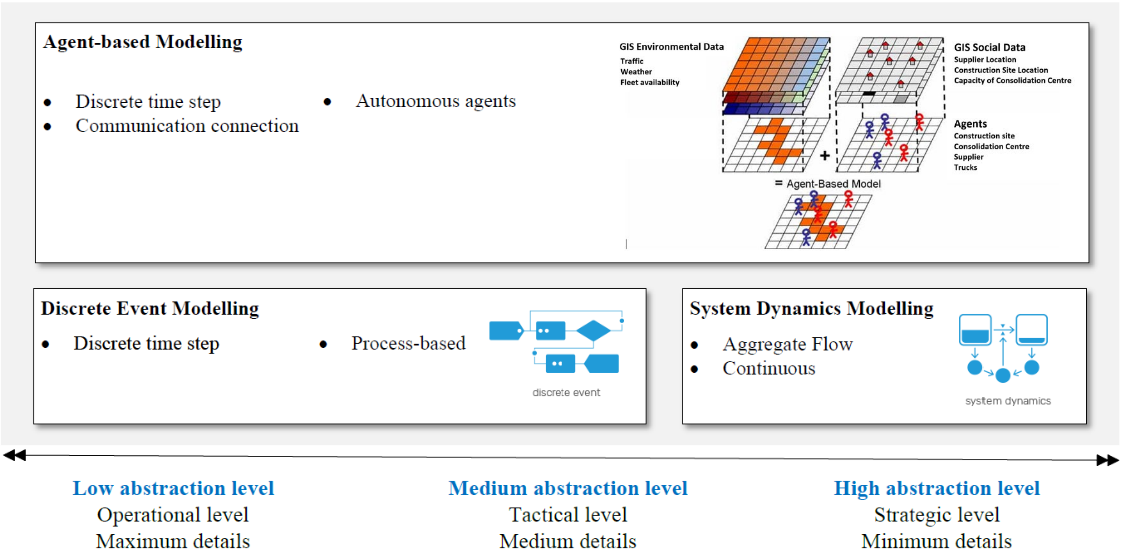


Figure 2: Classification of Simulation Techniques.

This section will elaborate in detail on the reasonings behind using a simulation-based approach in attempting to verify the hypothesis. Simulation application in the supply chain has been an important approach for decades. It provided the path for monitoring reality by encapsulating the system behaviours or disciplines of a real-world system into a computer programme (Abar *et al.*, 2017). Various simulation techniques have been created in recent decades to replicate real-world problems in different aspects and disciplines, and each of them has its advantages and disadvantages. The most prevalent modelling techniques have been summarised in *Figure 2*. ABM technique has been characterised as an emerging technological innovation in which a group of distributed agents communicate with each other and accomplish the model developer's predefined objectives (Li, Rombaut and Vanhaverbeke, 2021). An intelligent distributed agent modelling is composed of two essential characteristics: (1) a collection of autonomous agents that can process decision making within a static and dynamic environment and (2) agents with self-coordination ability without manual communication connection. The DEM operated mostly in quantitative analysis for solving process-related issues based on the micro to meso abstraction level. On the other hand, the SDM approaches are widely used in strategic problem identification, operating at the highest abstraction level. However, due to the complex environment of CLO, a stand-alone simulation technique is ineffective compared to a hybrid of techniques. Brailsford et al. (2019) commented on the recent emerging practice of hybrid simulation and stated that there is a need for hybrid simulation supply chain operation as modern supply chain management involved multiple management problems and has become increasingly complicated. Therefore, a hybrid simulation may tackle a wide range of management issues more efficiently, flexibly, and effectively by integrating the abovementioned modelling techniques. Hybrid simulation is still in its early stages in operational usage despite the advantages. There is a lack of guidelines on designing a hybrid simulation, especially in the CLO field.

By incorporating the advantages of each simulation method, we can evaluate the supply chain system performance quantitatively under different disruptions (i.e., weather and traffic congestion). In addition, the model will serve as a basis for decision-making tools for the future, based on analysed quantitative (i.e., carbon emission, cost allocation, and truck fleet resource utilisation) results.

3.4 System Description

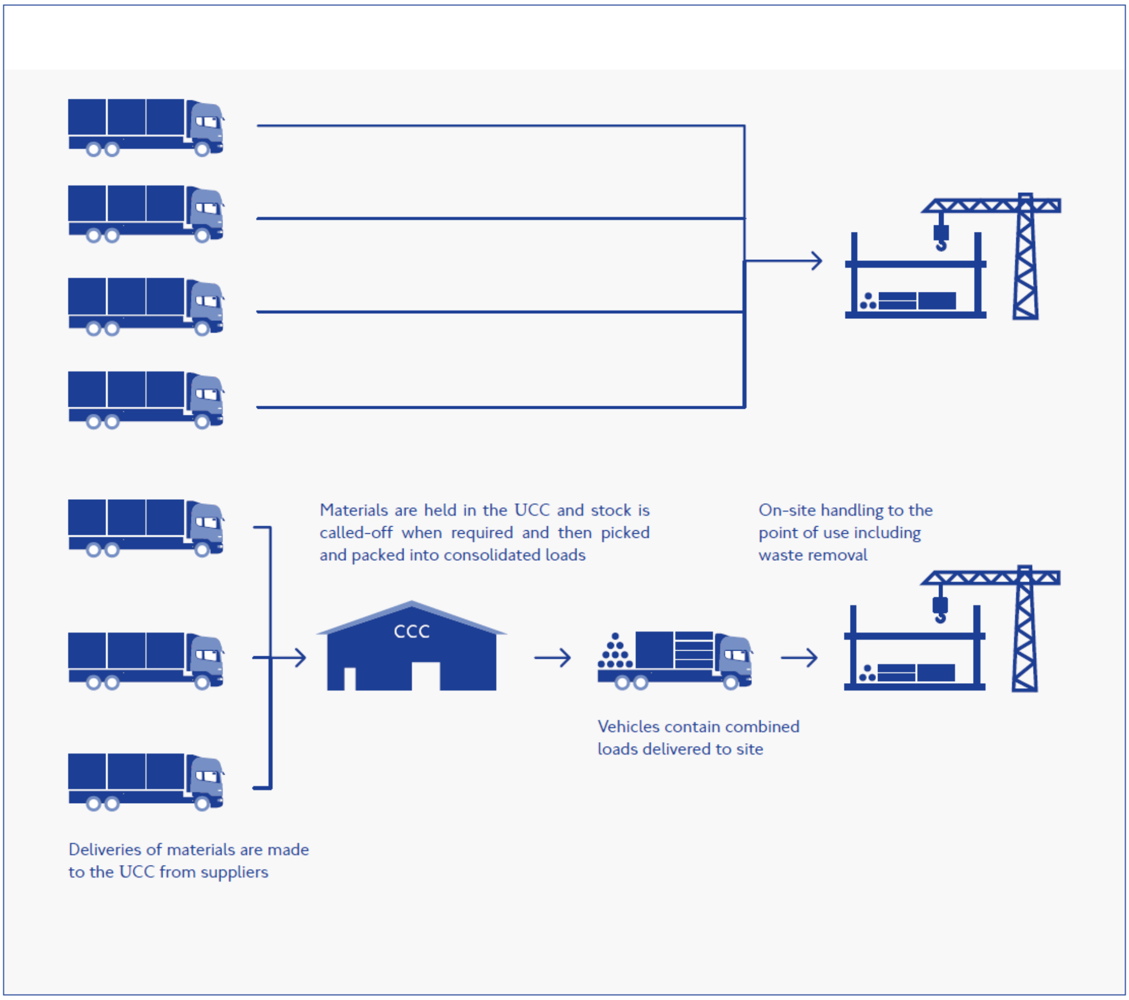


Figure 3: Supplier Chain System with & without Urban Consolidation Centre (UCC).

As shown in *Figure 3*, we proposed a CSC in which construction materials from the manufacturer are temporarily stored at the UCC and later transported by the UCC carrier fleet to the respective construction site. The supply chain system consists of three parts: supplier, UCC, and construction site. In the context of the CSCs, the carrier's delivery operations to suppliers and constructions are both operated by the UCC.

The UCC implementation is often applied for more sustainable means of urban freight transport. In principle, UCC can decrease the number of vehicles entering a city and reduce the carbon emission to achieve the transition toward zero-emission, which would decrease congestion, pollution, and distribution cost. Therefore, in this study, we aimed to quantify the impacts of the utilisation of UCC by using a hybrid model. To represent a real-life supply chain, we consider both traffic level and weather conditions. Those factors affected the overall performance of the supply chain the most and are involved in the model to examine their impacts on the system design. As traffic levels and weather conditions differ according to geographical locations; hence, in this study, we limit the implementation of UCC in central London. The construction materials often vary in size and nature; for instance, some materials need to be kept dry, such as insulation materials, while others might be bulky or awkward shapes, requiring a flatbed vehicle to transport to a dedicated location. However, it is assumed in this study that construction materials would not be affected by vehicle type, and most of the materials considered in the case may be moved by any vehicle type and are storable in UCC.

3.5 Outline of the hybrid model framework

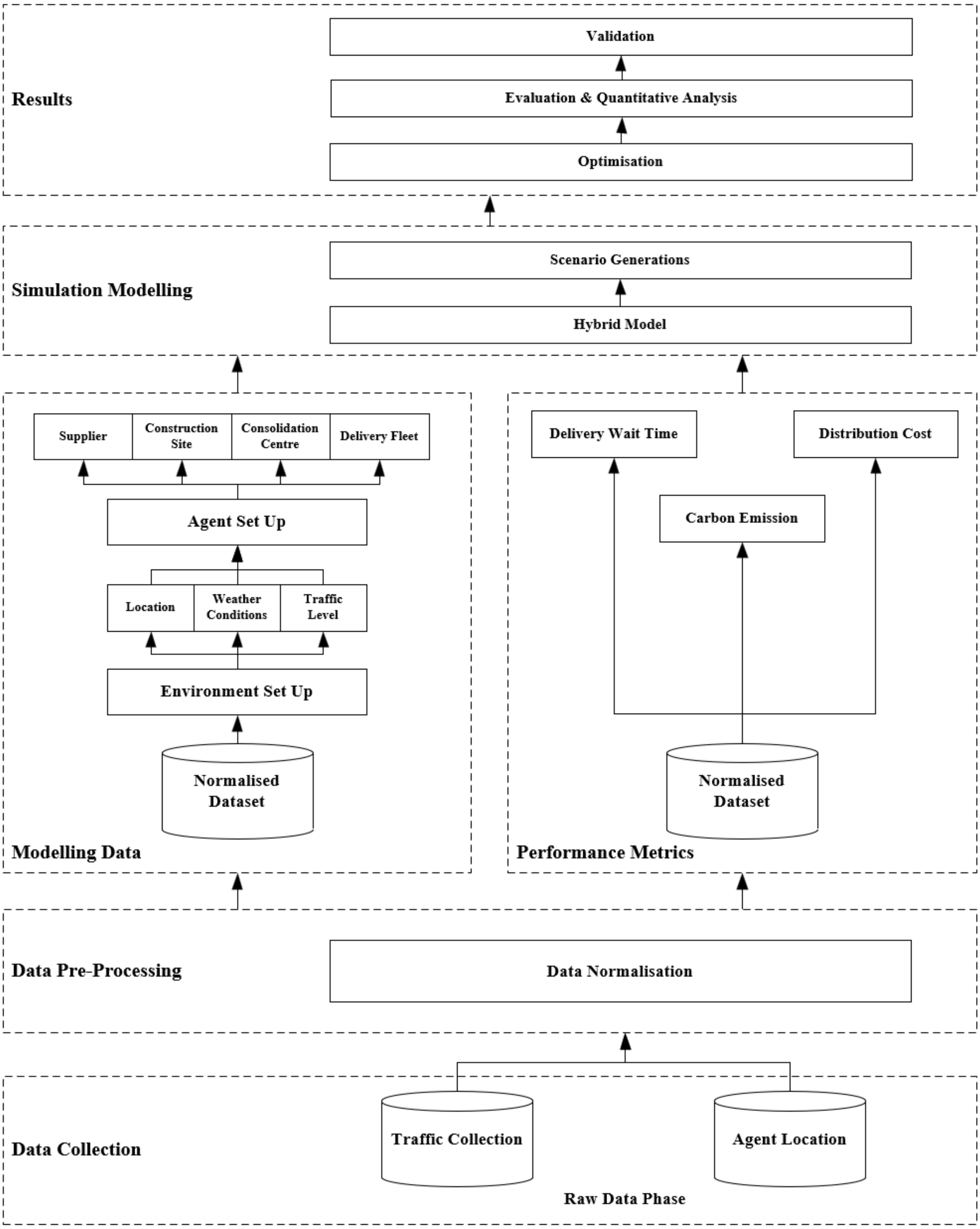


Figure 4: Systemic Framework for developing the Multi Objectives Optimisation model in Vehicle Routing Problem (VRP).

Figure 4 presents the framework of the designed hybrid model. To explain: this model simulates the UCC implementation of a CSC on a scheduled basis. Generally, the hybrid model consists of three main phases: simulation, optimisation, and validation. Data analysis and collection are required at the initial stage to develop the simulation for the CLO. It involved setting up the simulation environment by identifying the key data inputs like geographical location and delivery time. As discussed in Section 3.4, a CSC that involved a UCC required transport from both supplier and construction site. Delivery fleets are agents necessitated to fulfil the scheduled delivery of the supply chain system between the construction site and supplier.

Three decision-making performance metrics are developed to evaluate the competency of the UCC in comparison to the scenarios without UCC. The three decision-making metrics are (1) delivery wait time, (2) distribution cost, and (3) carbon emission. After the agents and performance metrics of the CSC system are set up from the hybrid model, the model will simulate the vehicle routing according to pre-set schedule and instructions. Afterwards, the simulation process continued with different scenario considerations – without UCC to quantify the difference between them.

Chapter 4: Construction Logistics Vehicle Routing Modelling

Considering the complexity of CLO, the vehicle routing hybrid modelling is composed of three main components, which are DES, SDM, and ABM, for a more in-depth investigation at both the department and overall system level. The three-echelons model is made up of many agent-based and discrete-event components. Agents are defined in the top layer to represent various departments within the hybrid model. The freight movement of the logistics is modelled using the agent-based method as it allows behaviour and reaction to be specified using a state chart. Similarly, suppliers and construction sites are modelled as individual agents representing each delivery event from the supplier to the construction site. In the second tier, we construct DEM components to model the diverse interactions and process-related issues of the internal environment of the UCC. Performance metrics are modelled at the lowest hierarchy in this hybrid model. Agents under the same agent type have similar processes and behaviours while operating independently. With this multi-method approach, the model can represent even closer to the real system.

The system in this work contained not only process-related issues in the UCC but also captured the independent behaviour of the autonomous agents and the interactions among them. For instance, the UCC processed the order and demand independently, as reflected by the changes in inventory level alongside the arrival and departure of materials. The DEM has unrivalled advantages in process-centric behaviour and can be utilised to simulate the operation process in UCC. Also, considering the need for communications between different agents, ABM is particularly useful in handling complex interactions and autonomous behaviours. The integration of ABM and DEM simulation approaches is highly suitable for decentralised or distributed VRPs as they enable the simulation of segmented smaller tasks. P*seudocode 1* below will describe in detail the algorithm of the hybrid model.

```
Algorithm 1 Proposed Framework Algorithm
Require: Information
  DeliveryEvent, N ← n
  DeliveryTime, T ← t
  SupplierLocation, I ← i
  ConsolidationCentreLocation, D ← d
  ConstructionSiteLocation, J ← j
  for N = 1, 2, 3.....n do
    Extract relevant data from set T, I, D, J
    if T = t then
      Prepare the delivery fleet
      Check for the corresponding delivery scenario
      if n is under the UCC scheme then
        Search for the nearest route
        Truck moves from i to d before scheduled delivery time, t - a
        Semitrailer moves from d to j at scheduled delivery time, t
        Update inventory level
        Measure delivery wait time
        Measure distribution fixed and variable cost
        Measure carbon emission
        Compute truck and semitrailer utilisation rate
      else if n is under the direct scheme then
        Search for the nearest route
        Truck moves from i to j at scheduled delivery time, t
        Measure delivery wait time
        Measure distribution fixed and variable cost
        Measure carbon emission
        Compute truck utilisation rate
      end if
    else if T is not t then
      Pass
    end if
  end for
```

Pseudocode 1: Proposed framework algorithm (UCC vs Direct).

4.1 Modelling of Vehicle Routing

A total number of five main agents with different behaviour and characteristics have been created: UCC, construction site, manufacturer, truck, and semitrailer. The location of the UCC is being selected from a list of currently operating UCC service providers from open sources where the complete list is provided in the appendix.

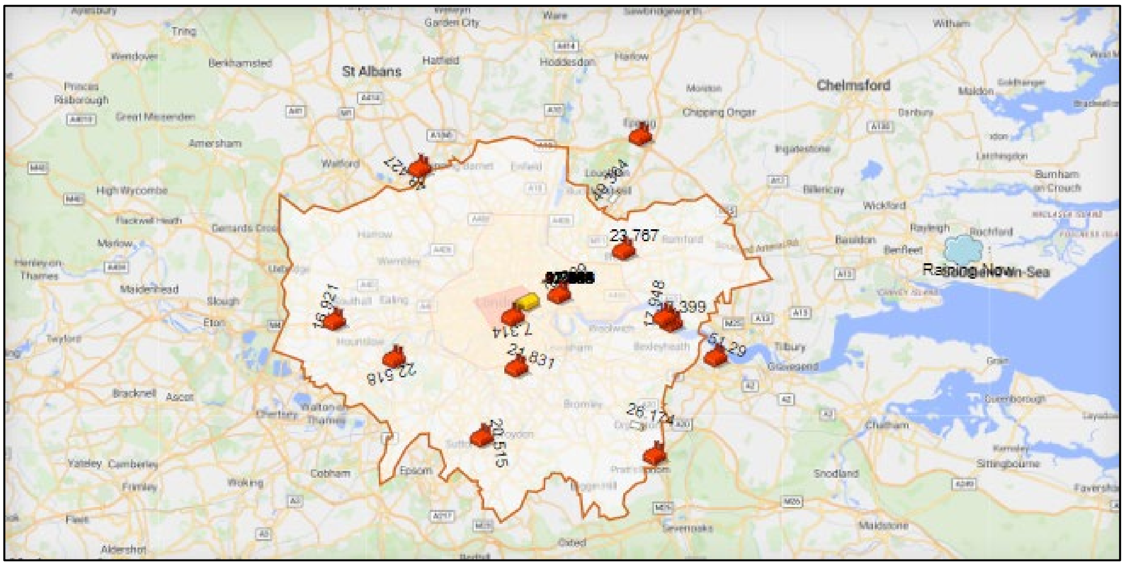


Figure 5: Snapshot of Bishop Square and Suppliers in Modelling Environment.

The behaviour of the population of trucks and semitrailers is defined within a state chart with three main stages, which are the free flow traffic state, changing traffic flow state, and critical weather state. Each state has been assigned different allowable normal distributed speed windows according to its respective area and traffic levels. Each truck and semitrailer agent are being designed to evaluate its current location and traffic level every second and change its speed accordingly to simulate the effect of real-life vehicle speed-changing stochastic processes as described in *Pseudocode 2*. *Figure 5* refers to a snapshot of the model when it is running while *Figure 6* demonstrates the state chart's configuration for the truck and semitrailer behaviour. It can be observed from the snapshot that the speed changes of the vehicle are shown above the vehicle icon and the GIS map has been colour-coded, corresponding to different traffic levels and speed distribution. The vehicle's trajectory follows a normal distribution curve in different traffic levels and disruptive events:

$$v(x) \sim N(\sigma^2, \mu)$$

Hence, $E(v(x)) = \mu$ and, var $(v(x)) = \sigma$

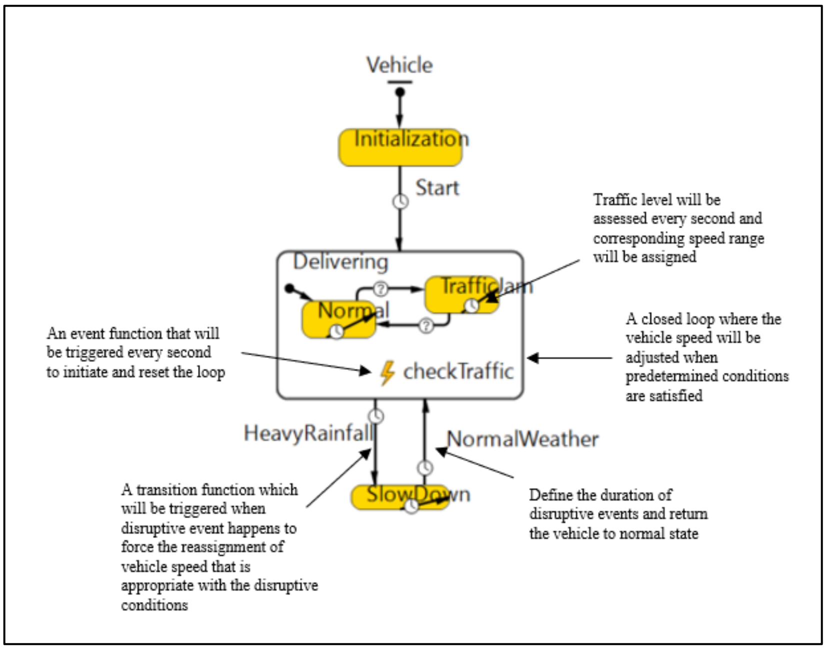


Figure 6: (Truck & Semitrailer) vehicle state chart.

```
Algorithm 2 Vehicle Speed Algorithm
Require: Information
  Deliveryfleet, K ← k
  for K = 1,2,3.....k do
     if Critical weather event is not being triggered then
        while k is moving do
           Check for the corresponding real time coordinate
           if k is within the central london zone then
              Vehicle speed is being normally distributed with mean 8 MPH
  and
              standard deviation 1 MPH
           else if k is within the inner london zone then
              Vehicle speed is being normally distributed with mean 12 MPH
  and
              standard deviation 2 MPH
           else if k is within the outer london zone then
              Vehicle speed is being normally distributed with mean 20 MPH
  and
              standard deviation 4 MPH
           else if k is within the smooth zone then
              Vehicle speed is being normally distributed with mean 50 MPH
  and
              standard deviation 5 MPH
           end if
        end while
        k stop moving
     else if Critical weather event is being triggered then
        while k is moving do
           Check for the corresponding real time coordinate
           if k is within the central london zone then
              Vehicle speed is being normally distributed with mean 5 MPH
  and
              standard deviation 0.5 MPH
           else if k is within the inner london zone then
              Vehicle speed is being normally distributed with mean 8 MPH
  and
              standard deviation 1 MPH
           else if k is within the outer london zone then
              Vehicle speed is being normally distributed with mean 15 MPH
  and
              standard deviation 2 MPH
           else if k is within the smooth zone then
              Vehicle speed is being normally distributed with mean 45 MPH
  and
              standard deviation 4 MPH
           end if
        end while
        k stop moving
     end if
  end for
```

Pseudocode 2: Vehicle Speed Algorithm for different traffic levels.

Traffic & Critical Weather (CW) Zones	Speed Distribution
Central London	normal (1, 8)
Inner London	normal (2, 12)
Outer London	normal (4, 20)
Outside London	normal (5, 50)
Central London (CW)	normal (0.5, 5)
Inner London (CW)	normal (1, 8)
Outer London (CW)	normal (2, 15)
Outside London (CW)	normal (4, 45)

Table 3: Speed distribution of vehicles according to different traffic levels and weather disruptions.

4.2 Modelling of Delivery System Dynamic

Two delivery systems are defined to simulate the delivery systems, one with the UCC and one without the UCC. A process flowchart is typically composed of a series of connected blocks each with different operations and complemented by a set of resource units. The set of block functions used in our model is described in *Table 4* and *Table 5* shows the parameter values used in this simulation.

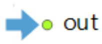
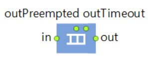
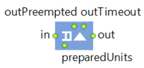
Block Name	Block	Description of the block
Enter		Connecting the external vehicle routing system to the internal process flow
Queue		Storing the incoming orders from suppliers to be accepted by the next operation of the process flow chart
Seize		Seizing a given number of resource units from the defined resource pool
Delay		Delaying the operation for a given amount of time to achieve the effect of certain operations like loading or unloading materials
Release		Releasing the given number of resource units previously seized by the seize pool and allowing them to return to a predetermined place
Exit		Taking the incoming agents out of the process flow and ending the flow
Resource Task Start		Resource preparation process (truck or semitrailer preparation)
Move To		Moving the agent to a new location
Resource Task End		Resource ending process (truck or semitrailer wrap-up process)

Table 4: Block Description (Process Modelling Library) in DEM.

Blocks	Parameter Values (hrs)
Unloading - delay	Triangular (0.5, 0.75, 1)
Loading - delay	Triangular (0.5, 0.75, 1)

Table 5: Loading & Unloading Time Delayed in Triangular Distribution (Min, Max, Mode).

UCC

Two process flowcharts have been defined to simulate the operation logic of the UCC. One process flowchart is being created to mimic the material delivery from suppliers to the UCC before the actual scheduled delivery time for warehousing purposes, while the other process flowchart is being used to describe the material delivery from the UCC to the construction site upon the actual scheduled delivery time. It is also worth noting that the delivery from suppliers to UCC will be conducted using truck fleets with higher fuel consumption rates whereas the delivery from the consolidation centre to the construction site will be carried out with a lower fuel consumption rate semitrailer to reflect the restriction on vehicle size in certain zones.

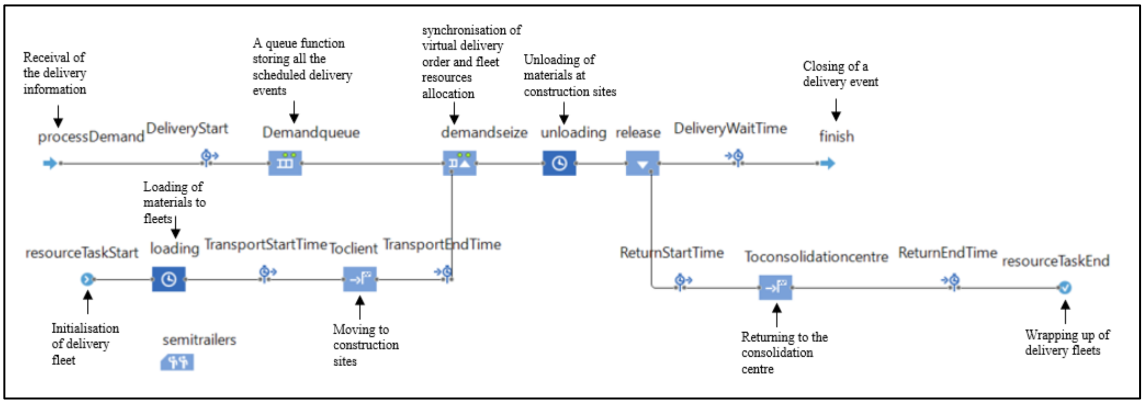


Figure 7: Process flow chart of the hybrid model (suppliers & UCC).

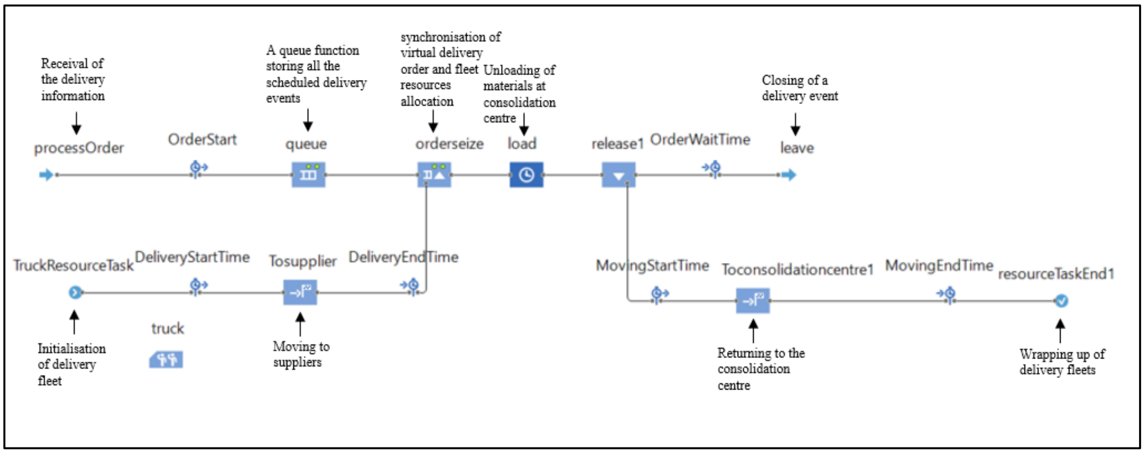


Figure 8: Process flowchart of the hybrid model (construction sites & UCC).

Figures 7 and 8 above showcase graphically the process flowchart of the UCC. The materials will be delivered from suppliers to the UCC in advance before the actual delivery time. Once the model time reaches the scheduled delivery time of a particular delivery account, the system will start processing the delivery information like the manufacturers ‘locations, the total material weight to be delivered and the construction site's location before initiating the transaction.

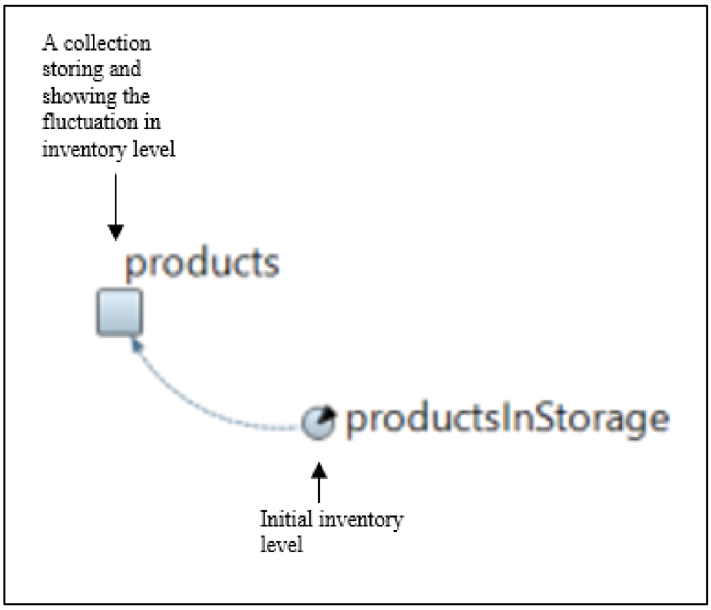


Figure 9: System Dynamics blocks that simulate the inventory system.

Nonetheless, the system dynamics library of Anylogic simulation platform is being deployed to simulate the mechanism of the inventory system within the UCC as it allows the changes in inventory level to be visualised easily. Generally, the material weights of each delivery event to the UCC will be recorded in the "products" collection like *Figure 9*, indicating an increase in the inventory level, then decrease again when the materials are being transferred to the construction site.

Direct

The materials will be delivered to construction sites straight away from suppliers, requiring a different process flow underlying the delivery system. *Figure 10* will illustrate the logic behind the delivery system without the UCC.

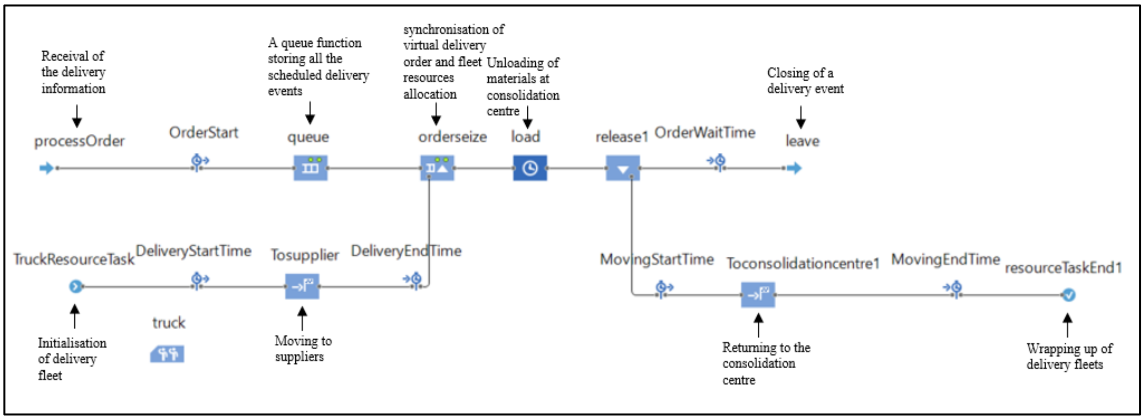


Figure 10: Process flowchart of the hybrid model (Direct).

Overall, the main difference between the delivery system with and without UCC is the delivery sequence where the former delivers materials to an intermediate storing point before delivering to the construction sites as opposed to the latter case where the delivery events are being completed directly between suppliers and construction sites.

4.3 Modelling of Material Delivery Schedule

In this hybrid model, each delivery event from supplier to construction is simulated and defined as an agent with a set of information like location, material amount, departure time, etc. There are two approaches for modelling delivery schedules, UCC and direct schemes. Moreover, certain assumptions have been made in this case due to the limitation of the dataset available to simplify the complexity of the model itself.

UCC

The delivery schedules with the UCC are divided into two phases which are the first warehousing phase, where materials will be transported to the UCC before the actual delivery time during non-peak hours to minimise the peak hours traffic congestion and the second delivery phase, where materials will be delivered directly to the construction site from UCC minimising the delivery wait time. In addition, the logistics fleets will be managed by the UCC to reduce the total number of fleets and optimise vehicle utilisation rate. *Figures 12 & 14* demonstrate the modelling of the material delivery schedule with the UCC. *Tables 6 & 7* depict the limitations we faced on the collected dataset and our assumptions to overcome them.

First Phase: Warehousing (from suppliers to UCC)

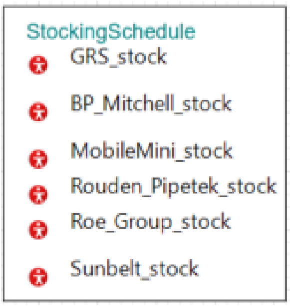


Figure 11: Stocking Schedule from Suppliers to UCC modelled as multi-agents.

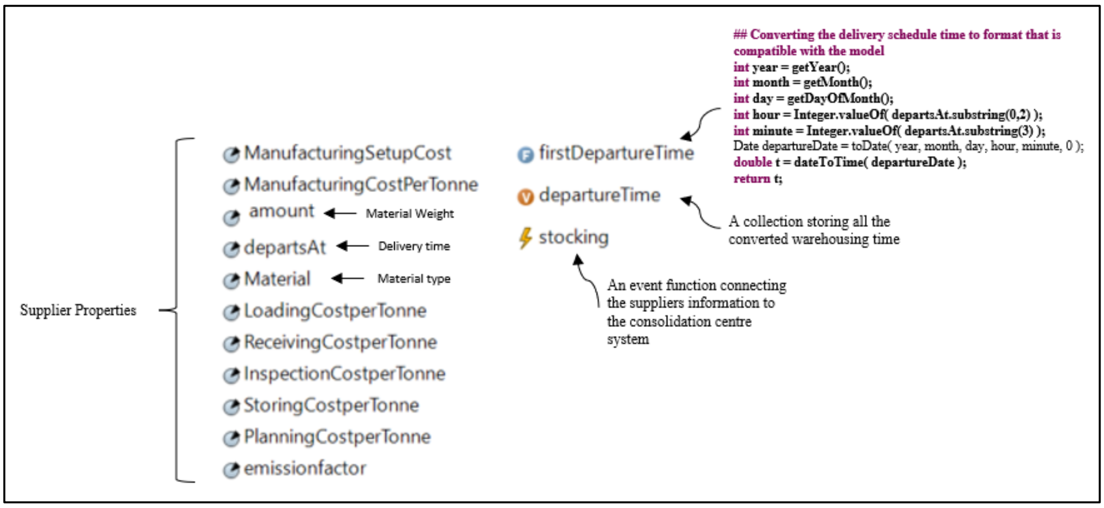


Figure 12: Stocking Parameters in Hybrid Model.

Parameter	Limitation	Assumption
Manufacturing setup cost	insufficient information	assuming a £50 initial setup cost for all delivery event
Manufacturing cost per tonne	insufficient information	assuming a £10 manufacturing cost per tonne for all supplier
Material amount	insufficient information	material weights are estimated using the delivery vehicle types and its s with a normal distribution of utilisation rate
Departs At	No indication on whether it is the departure time or arrival time	assuming it is the departure time
Loading cost per tonne	insufficient information	assuming £2 per tonne
Receiving cost per tonne	insufficient information	assuming £2 per tonne
Inspection cost per tonne	insufficient information	assuming £2 per tonne
Storing cost per tonne	insufficient information	assuming £2 per tonne
Planning cost per tonne	insufficient information	assuming £2 per tonne
Emission factor	insufficient information	assuming 0.2 emission factor for all material type

Table 6: Limitation and Assumption of the Stocking Parameters.

Second Phase: Delivering (from UCC to construction sites)

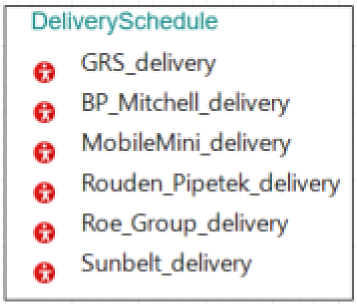


Figure 13: Delivery Schedule from UCC to construction site modelled as multi-agents.

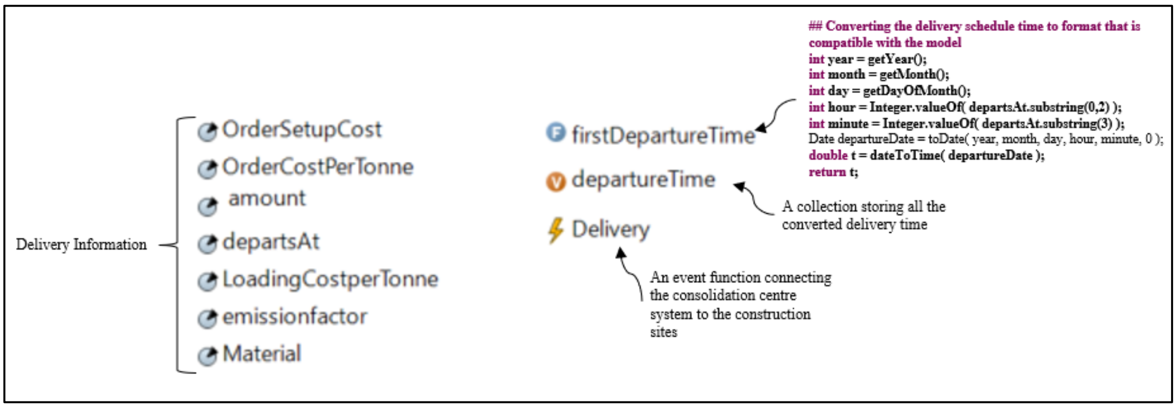


Figure 14: Delivery Parameters in Hybrid Model.

Parameter	Limitation	Assumption
Order setup cost	insufficient information	assuming a £50 initial setup cost for all delivery event
Ordering cost per tonne	insufficient information	assuming a £10 ordering cost per tonne for all supplier
Material amount	insufficient information	material weights are estimated using the delivery vehicle types and its s with a normal distribution of utilisation rate
Departs At	No indication on whether it is the departure time or arrival time	assuming it is the departure time
Loading cost per tonne	insufficient information	assuming £2 per tonne
Emission factor	insufficient information	assuming 0.2 emission factor for all material type

Table 7: Limitations and Assumptions made of the Delivery Parameters.

Direct

In the case of the direct delivery system, the construction materials will be delivered directly from suppliers' sites to the construction sites without going through an intermediate stage like UCC. Therefore, the delivery events might happen during peak hours when traffic levels are overwhelmed and the delivery fleets are not organised.

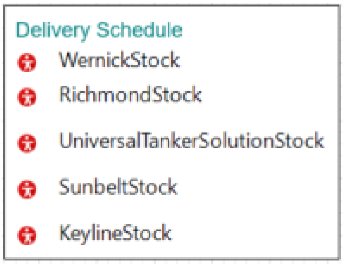


Figure 15: Delivery Schedule from Suppliers to Construction Site modelled as multi-agents.

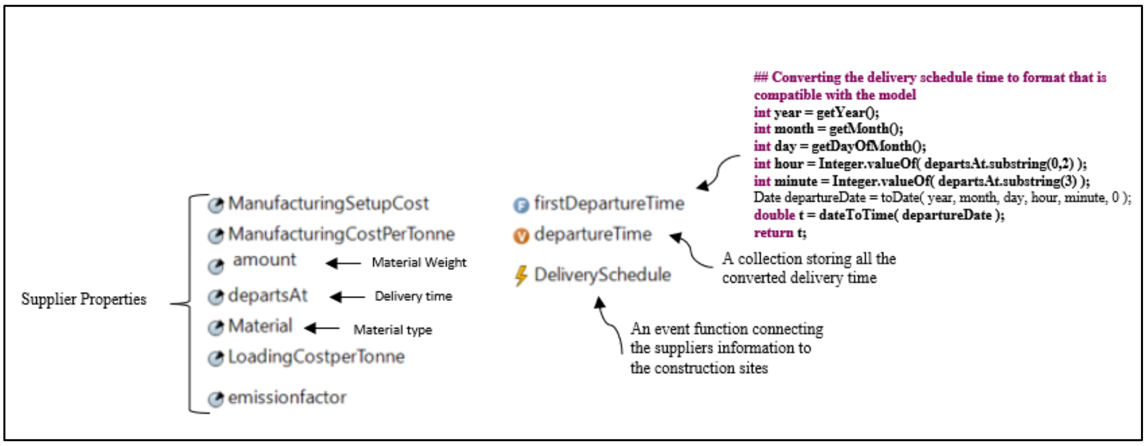


Figure 16: Delivery Parameters in Hybrid Model (Direct).

Parameter	Limitation	Assumption
Manufacturing setup cost	insufficient information	assuming a £50 initial setup cost for all delivery event
Manufacturing cost per tonne	insufficient information	assuming a £10 manufacturing cost per tonne for all supplier
Material amount	insufficient information	material weights are estimated using the delivery vehicle types and its size with a normal distribution of utilisation rate
Departs At	No indication on whether it is the departure time or arrival time	assuming it is the departure time
Loading cost per tonne	insufficient information	assuming £2 per tonne
Emission factor	insufficient information	assuming 0.2 emission factor for all material type

Table 8: Limitation and Assumption made of the Delivery Parameters (Direct).

4.4 Modelling of Measuring Metrics

The three main evaluation metrics in this vehicle routing hybrid model are the delivery wait time, the overall distribution cost and the carbon emission. These parameters are the ultimate objectives the model is trying to optimise. In this section, the modelling methodologies of the evaluation metrics are dissected and explained in detail. When modelling the metrics, some of them could be performed easily owing to the Anylogic built-in function, while some of them would require the explicit definition of event function or other techniques to achieve the goal.

Delivery Wait Time

Delivery wait time minimisation has several fundamental implications for the construction project, as delays in delivery schedules often lead to extra labour costs, and an increase in idle times, resulting in an overall decrease in project efficiency and an increase in project cost. This is achieved through implementing a pair of discrete event operators "Time Measure Start" and "Time Measure End", as they can measure the time the agents or in this case, the events spent between them. The "Time Measure Start" block records the time when an agent goes through, and the time spent between this block and the "Time Measure End" could be computed as displayed in *figures 17 & 18*. Then, the computed measured time will be stored within the block and could be plotted as a distribution in a histogram chart showing the mean value. In addition to that, a time plot of time taken of different delivery processes will be established to understand better the delivery time variations throughout the entire delivery schedule.

UCC

The time measurements that will be taken in this case are the delivery wait time, length of time for the delivery process from suppliers to the UCC, the time length for the material to be transported to the construction site from UCC, and the time taken for the fleets to return to the centre.

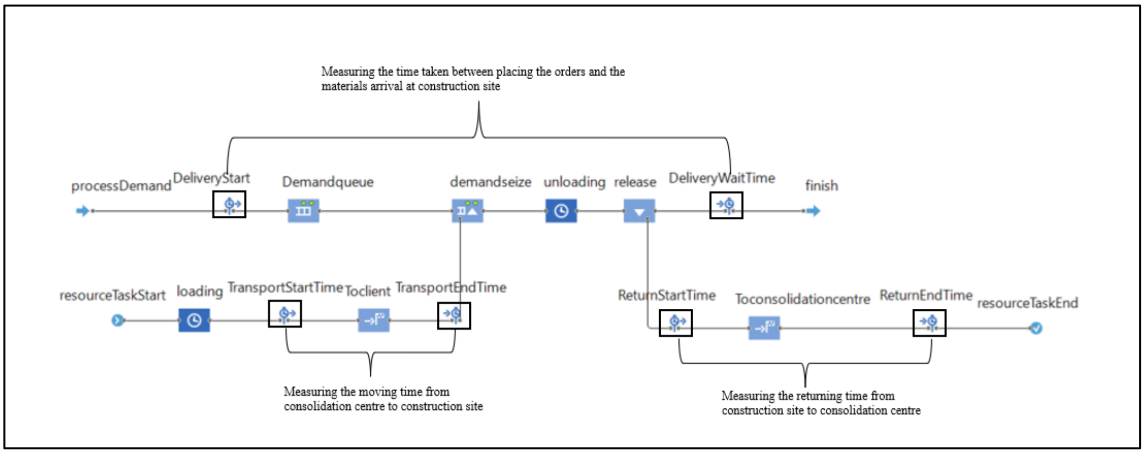


Figure 17: Time measuring function from UCC to the construction site.

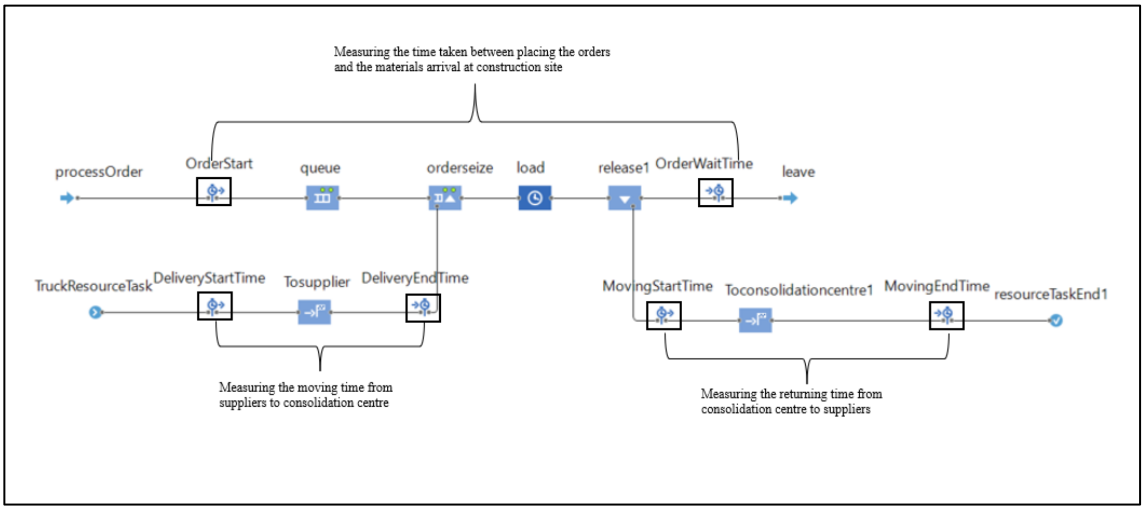
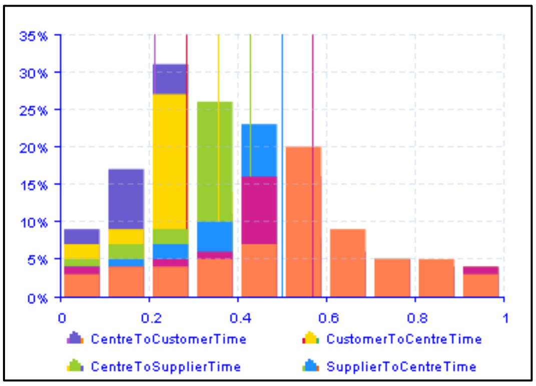


Figure 18: Time measuring function from supplier to UCC.



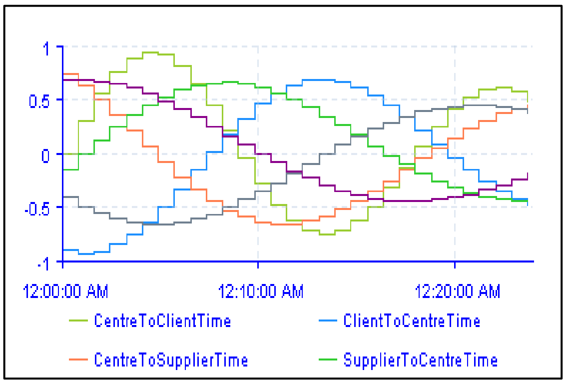


Figure 19: (a) Time Stacked Histogram (b) Time Stacked Graph.

Direct

Similar to the previous case, the delivery wait time will be measured alongside the moving time from suppliers to construction sites and returning to the suppliers' locations.

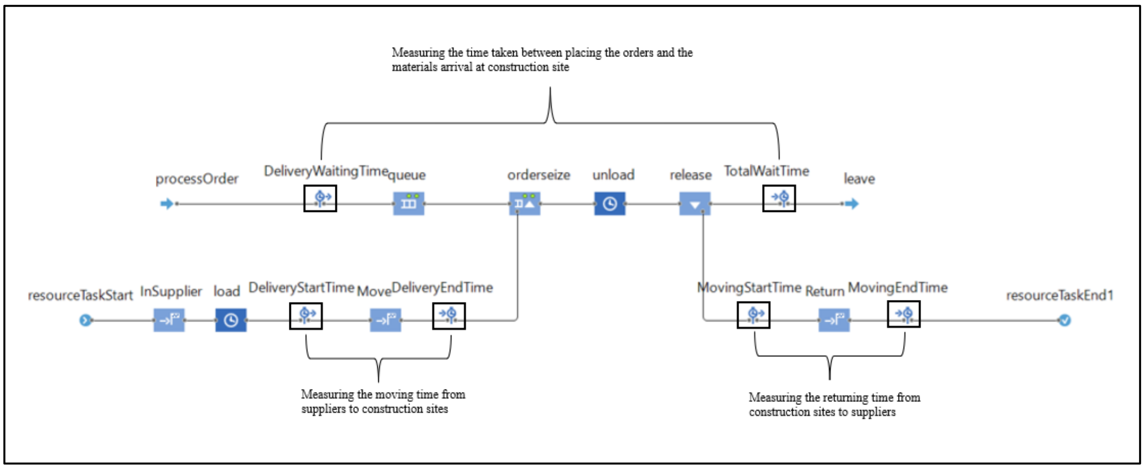
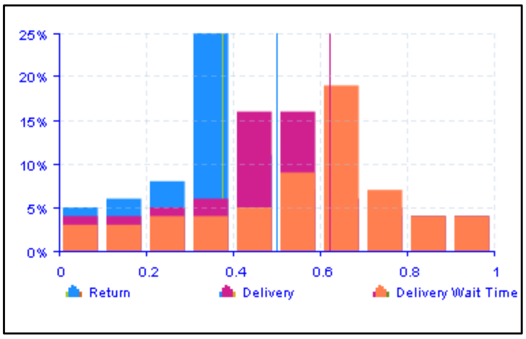


Figure 20: Time measuring function from suppliers to the construction site.



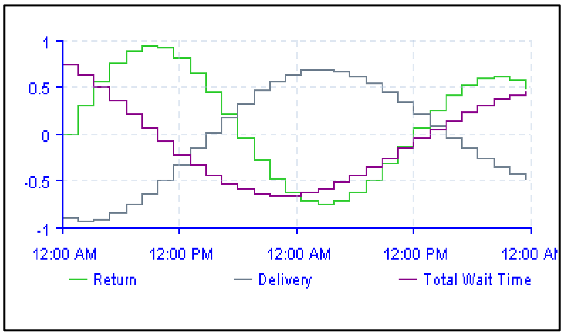


Figure 21: (a) Time Stacked Histogram (b) Time Stacked Graph.

Distribution Cost

The modelling of total delivery cost is inspired by the Activity Based Costing (ABC) approach commonly used in the construction industry. In essence, the ABC concept breaks down the chosen processes of interest into activities with greater granularity and identifies these activities' resources and cost drivers. After that, the relevant cost data could be researched for allocation to each activity, contributing to the total cost perspective. *Figure 22* illustrates the concept of the ABC in detail.

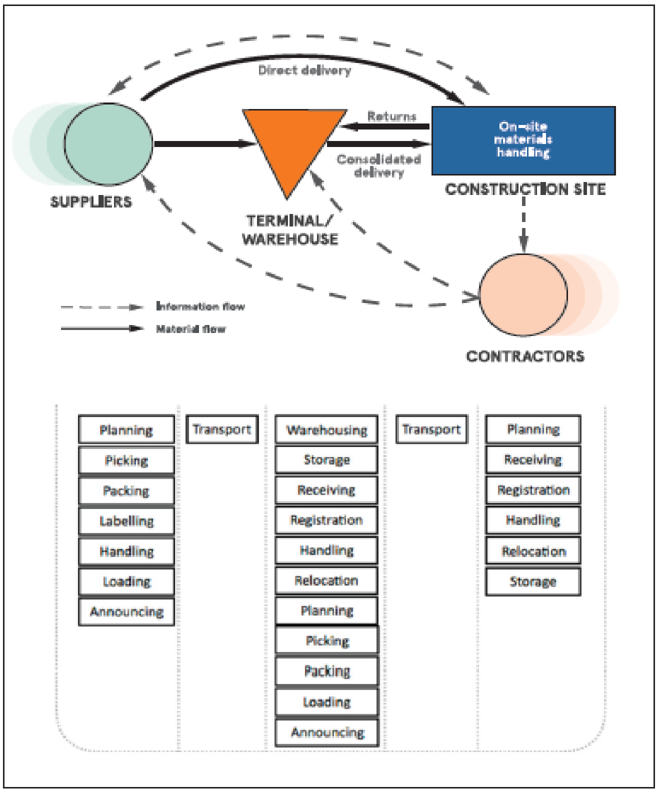


Figure 22:Activity-Based Costing Technique.

Having been motivated by the ABC approach, the entire costing structure has been modelled using the agent-based technique as shown in *Figure 23*. Three main points of interest are determined where some parameters underneath it are being used to represent each sub-activity within each component. For each parameter, an event function will be created to relate itself with its appropriate input to calculate the total logistics system cost.

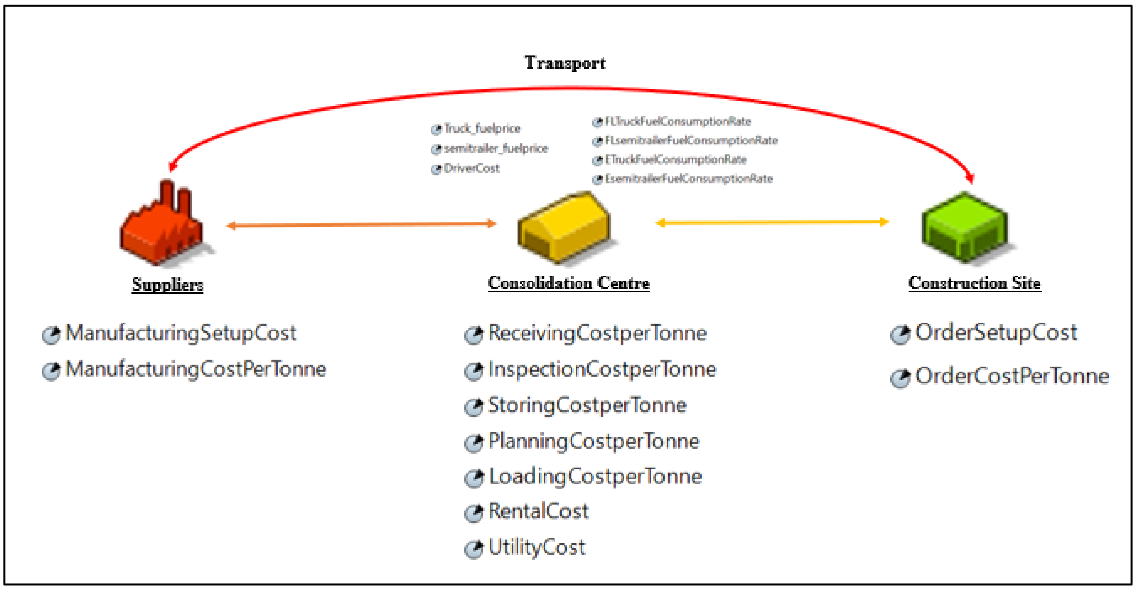


Figure 23:Activity-Based Costing Technique adopted in Model.

Figure 24 illustrates graphically an example of an event function created and codes written to calculate the cost of one component within the delivery supply system whereas *table 9* describes the parameters and values used for the cost calculation. The same methodologies replicate the similar cost calculation function for ordering cost and UCC operating cost.

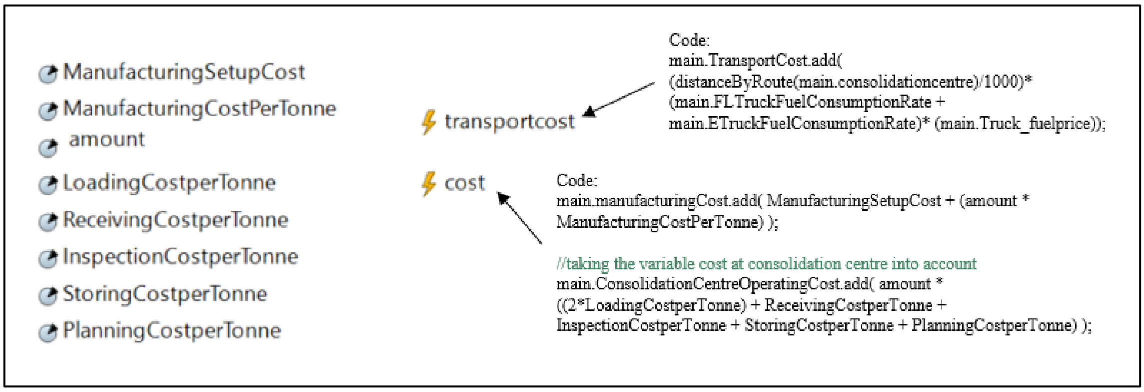


Figure 24: Event Function and Cost Computed to calculate the associated Cost of Delivery Event.

uniform distribution: uniform (min, max)

Parameter	Values
Rental Cost	£100
Utility Cost	£100
Truck Fuel Price	£1.45
Semi Trailer Price	£1.45
Driver Cost	£100 * (number of truck + number of semi trailer)
Fully loaded truck fuel consumption rate	uniform (0.3, 0.4)
Empty loaded truck fuel consumption rate	uniform (0.2, 0.3)
Fully loaded semitrailer fuel consumption rate	uniform (0.2, 0.3)
Empty loaded semitrailer fuel consumption rate	uniform (0.1, 0.2)
Order setup cost	£50
Order cost per tonne	£10
Loading cost per tonne	£2
Manufacturing setup cost	£50
Manufacturing cost per tonne	£10
Loading cost per tonne	£2
Receiving cost per tonne	£2
Inspection cost per tonne	£2
Storing cost per tonne	£2
Planning cost per tonne	£2

Table 9: Parameter and Values adopted for Cost Calculation Function.

In addition to that, the total delivery cost will be evaluated in real-time and plotted in a time chart as shown below.

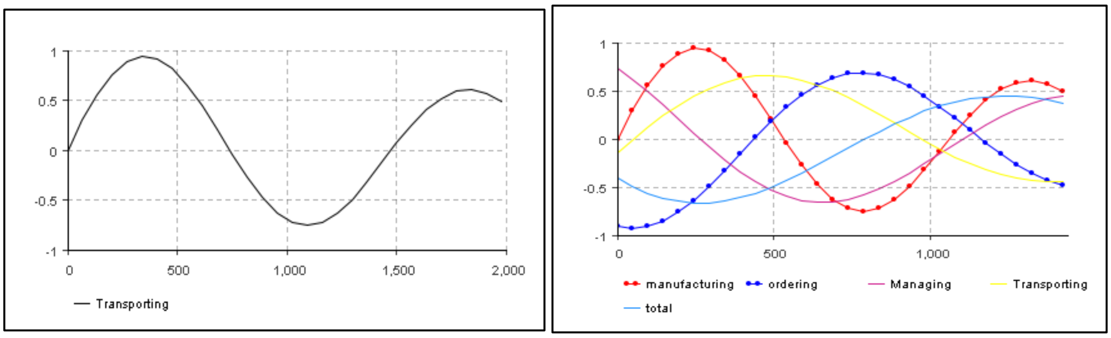


Figure 25: a) Transport Delivery Cost Evaluated in Time Chart (minutes) (b) Multi-activity and Total Delivery Cost Evaluated in Time Chart (minutes).

Carbon Emission

The modelling of carbon emission consists of two main components: carbon emission incurred by the burning of diesel fuel in moving from one place to another and carbon emission produced by the material manufacturing process itself. The first component is calculated by using the travel distance of the vehicle multiplied by the vehicle fuel consumption rate to work out the total amount of fuel being used in each delivery event. Then, the number will be multiplied by an emission factor to figure out the carbon emission. The calculation of carbon emission incurred by fuel consumption can be described by the equation below:

$$Carbon\ Emission_{fuel}\ (KgCO2e) = Travel\ distance \times\ fuel\ consumption\ rate\ \times fuel\ emission\ factor$$

Similarly, the second component is computed by using the total weight of the material and multiplying it by its respective carbon emission to calculate the carbon emission generated by its life-cycle process. The algorithm can be described by the equation below:

$$Carbon\ Emission_{material}\ (KgCO2e) = Material\ Weights \times emission\ factor$$

Within the model environment, the calculation has been achieved automatically by defining an event function that will be triggered every delivery event. *Figure 26* below shows the event function and codes used to automatically compute the carbon emission produced by each delivery event, followed by *Table 10* which displays key parameter values in the algorithm. Finally, the result will be plotted in a time chart as shown in *Figure 27*.

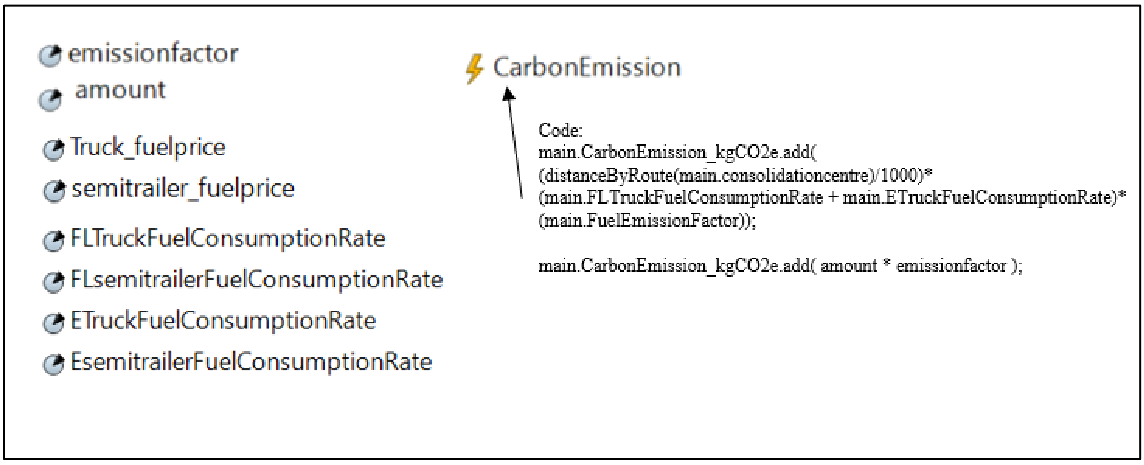


Figure 26: Event Function and Codes Computed Carbon Emission produced on Delivery Event.

uniform distribution: uniform (min, max)

Parameter	Values
Material emission factor	0.2
Fuel emission factor	2.62
Fully loaded truck fuel consumption rate	uniform (0.3, 0.4)
Empty loaded truck fuel consumption rate	uniform (0.2, 0.3)
Fully loaded semitrailer fuel consumption rate	uniform (0.2, 0.3)
Empty loaded semitrailer fuel consumption rate	uniform (0.1, 0.2)

Table 10: Parameter and Values adopted for Carbon Emission Function.

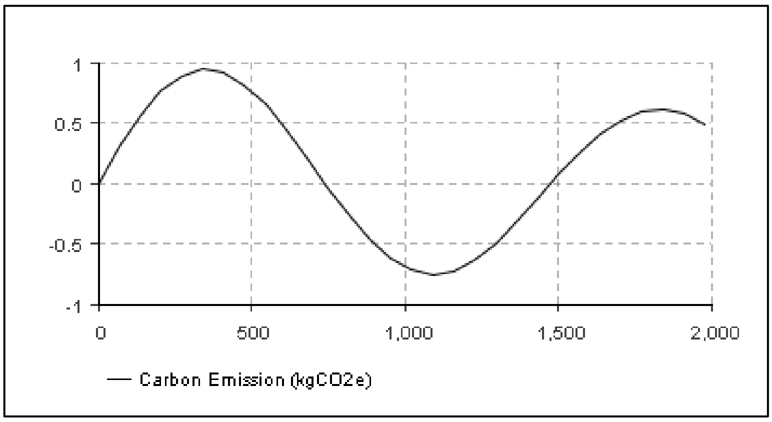


Figure 27: Total Carbon Emission Evaluated in Time Chart (minutes).

Chapter 5: Result, Discussion & Validation

In this section, brief descriptions of the selected construction projects that have been used to experiment with the model will be given. Relevant model outputs will be displayed, followed by quantitative and qualitative analysis. After that, the validation of the model will be performed through sensitivity analysis to establish its credibility to the model. In this study, two projects have been selected to test with the model and both projects will be modelled in two different scenarios, the UCC implementation and direct schemes.

5.1 Prologis Park Hemel Hempstead

Prologis Park Hemel Hempstead is a 234,971 square feet large industrial logistic park located at Buncefield Lane, off Breakspear Way, Hemel Hempstead HP2 7HY. It is less than a mile from J8 of the M1 motorway and fronts Breakspear Way (A414) dual carriageway, providing the highest-profile position for business in Hemel Hempstead. From the given spreadsheet, 251 delivery events are recorded with 68 different suppliers. In this case, 29 suppliers are selected after cleaning and processing the data to remove those with incomplete information. Since suppliers' information is anonymous with uncertain exact locations, assumptions have been made to replace the exact location with the approximate location estimated by the search engine. In addition, a normal distribution of the delivery distances between all suppliers and construction sites is computed and provided in the appendix to compensate for the errors and generate more samples in future works.

5.1.1 With UCC

Metrics	Result
<u>Delivery Wait Time</u>	
First phase delivery time	229.9 mins
Second phase delivery time	105.14 mins
Consolidation centre to supplier	41.8 mins
Supplier to consolidation centre	41.98 mins
Consolidation centre to construction site	15.29 mins
construction site to consolidation centre	15.87 mins
<u>Cost</u>	
Manufacturing	£2,962.11
Ordering	£2,962.11
Managing	£2,619.38
Transporting	£3,515.58
Carbon Emissions	2798.98 kgCO2e
Truck utilisation rate	53.00%
Semitrailer utilisation rate	16.00%

Table 11: Summary of model outputs (UCC).

Table 11 summarises the key metrics results measured by the model throughout the entire delivery sequence. According to the first section of the table, the times taken to complete different processes for one full cycle of delivery events are shown, with the second phase delivery time being concerned the most in this study as it informs the total wait time for the client. The process taking the most time is the first phase as expected where the materials will be delivered to UCC first over long distances and reduced number of available transporting fleets before the scheduled delivery time. The shortening of the travel distance through the addition of UCC can decrease significantly the time needed for the material to be delivered on-site. Moreover, *table 13* shows the total costs under different categories over the entire delivery sequence. It can be seen that transporting imposed the highest cost, £3,515.58, whereas managing costs the least, £2,619.38 with manufacturing and ordering cost the same which is £2962.11. The similarity in costs for both manufacturing and ordering are expected as identical parameter settings are defined for both categories with the purpose of comprehensiveness for this study. A total of 2798.98 kgCO2e carbon emissions are generated with 53% and 16% utilisation rates respectively on trucks and semitrailers. The detailed time distributions, time plots, the variation of different cost categories over time, carbon emissions plot and vehicle utilisation chart are provided in the appendix.

Parameter Variation and Optimisation

When test-running the model, it is found that different combinations of parameter values will yield different performance metrics results. In this case, the number of trucks and semitrailers is varied over a range of randomised values for optimization purposes on the performance metrics:

average delivery wait time, total distribution cost, and carbon emission. This is achieved through the 'CompareRun' experiment built-in function within the Anylogic, and the results of the experiments are displayed in *Table 12*.

Parameter combination		Performance metrics		
Number of trucks	Number of semitrailers	Average delivery time(mins)	Transport cost(£)	Carbon emission(kgCO2e)
5	15	103.2	3515.58	2798.98
10	10	121.33	3515.58	2798.98
8	12	114.3	3515.58	2798.98
7	13	108.13	3515.58	2798.98
14	15	105.47	4415.58	2798.98
12	15	107.06	4215.58	2798.98
14	11	115.44	4015.58	2798.98
9	20	107.78	4415.58	2798.98
5	5	144.91	2515.58	2798.98
5	10	123.29	3015.58	2798.98

Table 12: Parameters adopted and outputs obtained for optimisation of Prologis Hemel Hempstead.

According to the analysis, the parameters combination of 5 trucks and 15 semitrailers seems to generate the shortest average delivery time, 103.2 mins out of all different combinations, £3515 distribution cost, and 2798.98 kgCO2e. The parameters combination of 5 trucks and 5 semitrailers gives the greatest delivery time, 144.91 mins, albeit having the lowest cost, £2515.57. Increasing the number of trucks and semitrailers doesn't reduce the average delivery time as what is assumed intuitively and vice-versa with reducing the total number of fleets. In terms of transport cost, it varies proportionally to the total number of vehicles involved when distributing the materials. In addition, carbon emissions remain constant in all different runs as expected because the independent variable for that function is the total delivery distance, which remains constant in all scenarios.

5.1.2 Direct

The parameter optimisation experiment is not being conducted in this scenario as it is assumed that all suppliers will have their vehicle fleet to transport the materials to the destination.

Metrics	Result
Delivery Wait Time	
Total order process time	130.19 mins
Supplier to construction site	42.65 mins
Construction site to supplier	42.06 mins
Cost	
Manufacturing	£3,761.16
Ordering	£3,761.16
Transporting	£4,133.24
Carbon Emissions	2258.063 kgCO2e
Truck utilisation rate	8.00%

Table 13: Summary of model outputs (without UCC).

According to *Table 13*, the total delivery wait time for the client is computed to be 130.19 mins with 42.65 mins for the materials to be delivered to the destination and 42.06 mins for the logistic fleets to return. The costs for both manufacturing and order are the same which are £3,761.16 respectively, whereas the transporting cost is slightly higher than the former case, £4,133.24. Nonetheless, the recorded carbon emissions are found to be 2257.063 kgCO2e with an 8% truck utilisation rate.

5.1.3 Comparative Analysis

Delivery Wait Time

Process	Output
Total delivery waits time (without UCC)	130.19 mins
Second Phase delivery time (with UCC)	105.4 mins
Percentage difference	19 %

Table 14: Comparison of delivery wait time between UCC and without UCC.

According to the analysis results, it can be observed that the average delivery wait time with UCC has a significant improvement compared to the one without UCC, with approximately a 19% increase in delivery efficiency. This increase in efficiency can be explained because of the addition of temporary material storing sites resulting in a shortening of the final travel distance upon the arrival of the actual delivery schedule while the majority of travelling tasks are completed in advance.

Delivery Cost

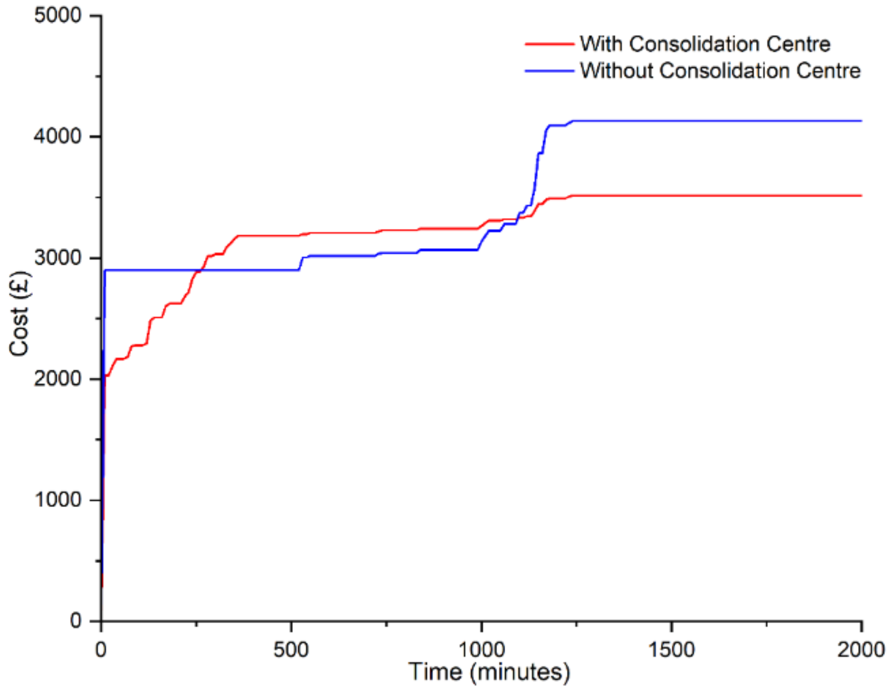


Figure 28: Delivery Cost (£) between the implementation of with and without UCC.

Our analysis of the numerical results indicates that the project delivery cost is decisive for the eventual profitability of the UCC scheme. *Figure 28* presents the project delivery cost with the implementation of UCC and without UCC. The scheme with the implementation of UCC performs notably better with around an 18% reduction of the total cost. The majority of the cost-saving could be accounted to the decrease in the total number of vehicle fleets, thus lowering the fixed cost such as driver costs despite having more costs coming from the operation and material management of UCC.

Delivery Carbon Emission

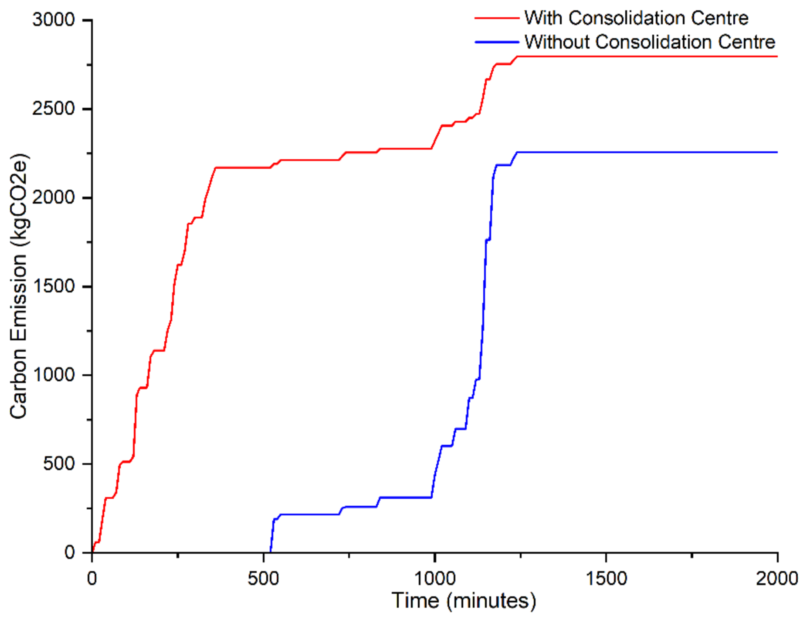


Figure 29: Carbon Emission (kgCO2e) between the implementation of with and without UCC.

The scheme without UCC performs better than in the scenario with UCC in terms of carbon emission. The implementation of UCC increases carbon emission by around 18%, contributed mainly by the functioning of UCC and the total distance travelled. Although the implementation of UCC reduced the total number of vehicles in the city by up to 30% but increased the total travel distance by up to 5%.

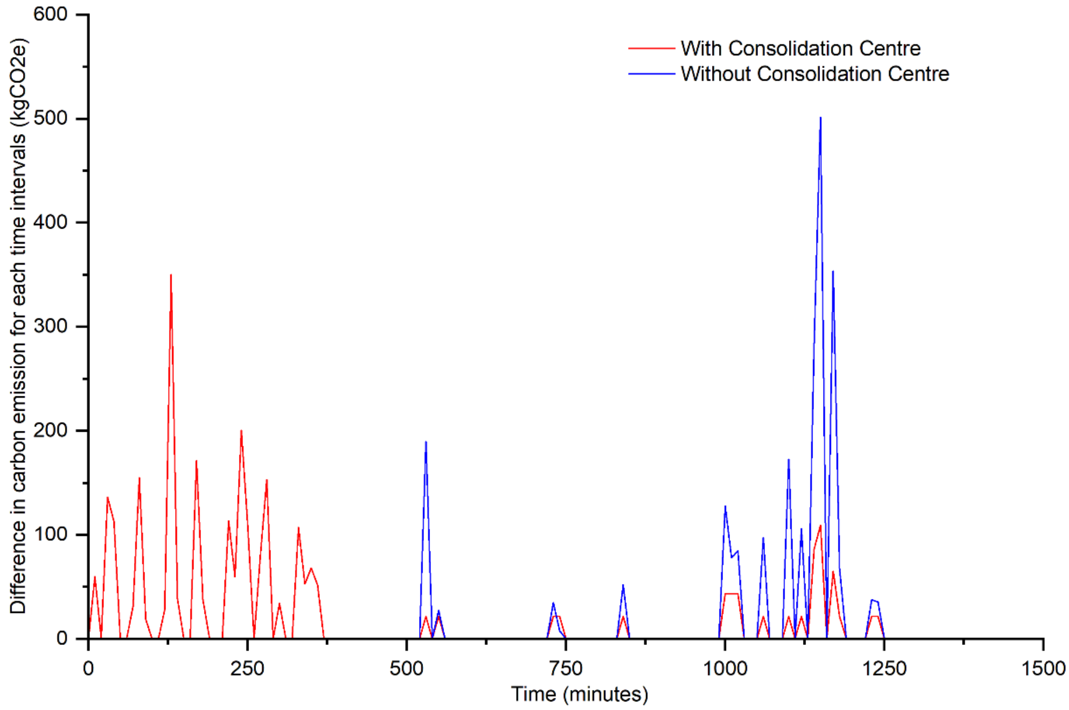


Figure 30: Carbon Emission for each time interval (kgCO2e) between the implementation of with and without UCC.

Although an overall increase in the total carbon emission, the deployment of UCC can spread out the carbon emissions across the whole delivery period, intentionally allocating the footprints at off-peak hours, reducing the absolute carbon emission during peak hours.

5.2 Bishop Square

Bishop Square is a commercial property development in the Spitalfields area of London located exactly at London E1 6AD, UK. It comprises 3700 square metres of retail space, 72000 square metres of offices, and apartments, community facilities, cafes, and restaurants. According to the given dataset, 23 delivery events are found with 15 different suppliers, and all of the suppliers are inputted into the model in this case.

5.2.1 With UCC

Metrics	Result
Delivery Wait Time	
First phase delivery time	243.54 mins
Second phase delivery time	113.58 mins
Consolidation centre to supplier	61.25 mins
Supplier to consolidation centre	61.37 mins
Consolidation centre to construction site	27.52 mins
construction site to consolidation centre	27.72 mins
Cost	
Manufacturing	£1,156.34
Ordering	£1,156.34
Managing	£850.14
Transporting	£1,768.91
Carbon Emissions	863.519 kgCO2e
Truck utilisation rate	44.00%
Semitrailer utilisation rate	16.00%

Table 15: Summary of model outputs (UCC).

Table 15 summarises the results obtained from the model. The second phase delivery time has recorded a 113.58 mins total wait time for the client, while the first phase delivery time has recorded a 243.54 mins total wait time for the material to be sent to the UCC. In addition, a total of £1,768.91 has been computed, which is the highest among other cost categories, with managing being the lowest, £850.14. The model also measures 863.519 kgCO2e carbon emissions with 44% and 16% truck and semitrailer utilisation rates respectively.

Parameter Variation and Optimisation

Similarly, the number of trucks and semitrailers is varied over different values to optimise the average delivery wait time and distribution cost needed to finish all the scheduled delivery events.

Parameter combination		Performance metrics		
Number of trucks	Number of semitrailers	Average delivery time(mins)	Transport cost(£)	Carbon emission(kgCO2e)
5	5	133.65	1468.91	863.52
3	8	114.31	1568.91	863.52
4	7	118.88	1568.91	863.52
5	7	116.1	1668.91	863.52
4	8	117.54	1668.91	863.52
4	9	113.58	1768.91	863.52
5	8	118.42	1768.91	863.52
7	8	118.67	1968.91	863.52
5	10	119.29	1968.91	863.52
3	11	115.88	1868.91	863.52

Table 16: Parameters adopted and outputs obtained for optimisation of Bishop Square.

According to the results, as shown in *Table 16*, the parameters combination of 4 trucks and 9 semitrailers generates the lowest average delivery time, 113.58 minutes out of all different combinations, £1768.91 and 863.52 kgCO2e. Resonated greatly with the Hemel Hempstead project, increasing or decreasing the number of trucks and semitrailers does not affect the average delivery time as observed in the previous project. In terms of transport cost, it still varies proportionally to the total number of vehicles involved when distributing the materials with constant carbon emissions in all runs.

5.2.2 Direct

Metrics	Result
Delivery Wait Time	
Total order process time	144.03 mins
Supplier to construction site	53.12 mins
Construction site to supplier	57.40 mins
Cost	
Manufacturing	£1,289.43
Ordering	£1,289.43
Transporting	£1,821.67
Carbon Emissions	588.928 kgCO2e
Truck utilisation rate	11.00%

Table 17: Summary of model outputs (without UCC).

The total delivery wait time for the client is computed to be 144.03 mins with 53.12 mins for the materials to be delivered to the destination and 47.40 mins for the logistics fleets to return. The costs for both manufacturing and order are the same, which are £1289.43 respectively. On the other hand, the transporting cost is measured to be slightly higher, £1821.67. Moreover, the recorded carbon emissions are 588.928 kgCO2e, with an 11% truck utilisation rate.

5.2.3 Comparative Analysis

Delivery Wait Time

Process	Output
Total delivery waits time (without UCC)	144.03 mins
Second Phase delivery time (with UCC)	113.58 mins
Percentage difference	21.14 %

Table 18: Summary of Optimisation Output without Consolidation Centre.

According to the results, the deployment of UCC leads to an increase of around 21.14% in delivery wait time predominantly due to the shortening of final travel distance upon the actual delivery scheduled time.

Delivery Cost

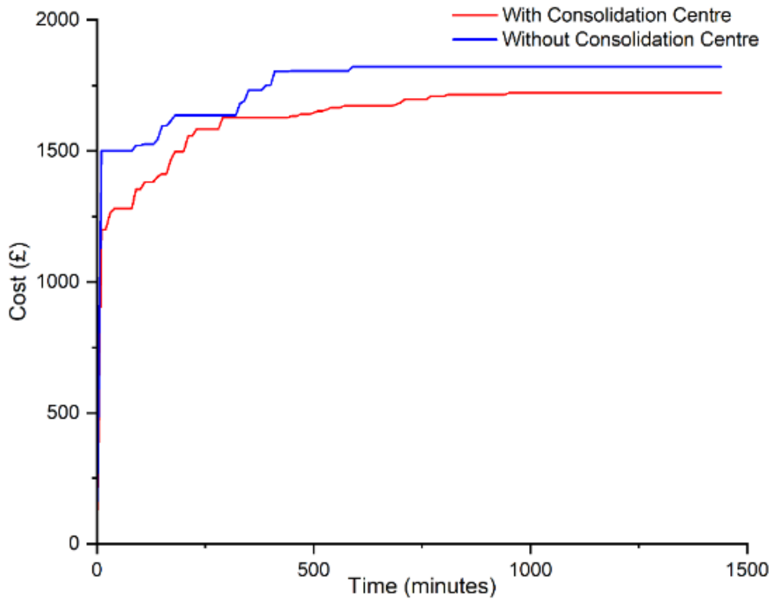


Figure 31: Delivery Cost (£) between the implementation of with and without UCC.

Based on the graph, the UCC can reduce the delivery cost by approximately 14% due to fewer vehicles being mobilised, leading to a decrease in total driver cost.

Delivery Carbon Emission

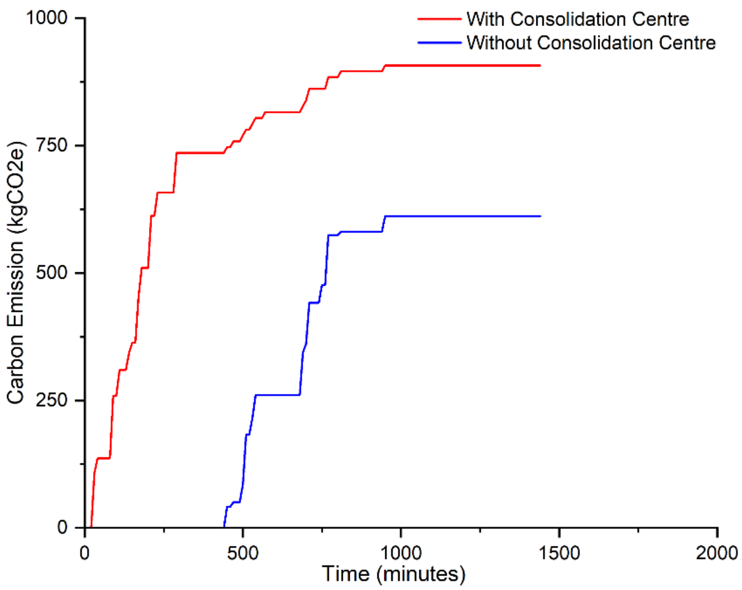


Figure 32: Carbon Emission (kgCO2e) between the implementation of with and without UCC.

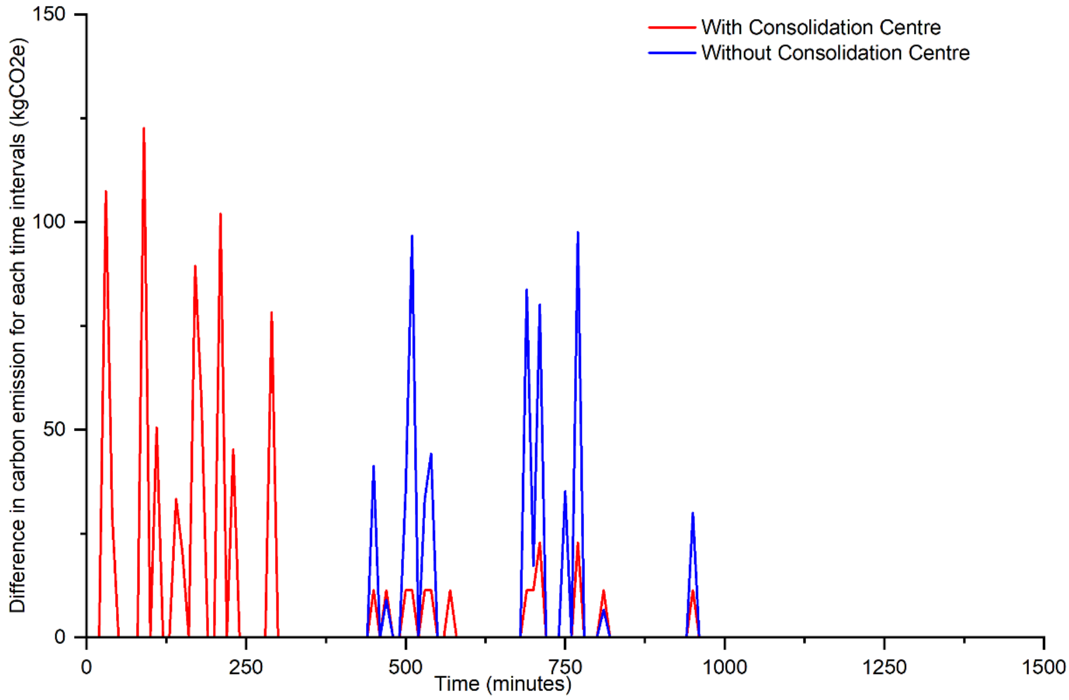


Figure 33: Carbon Emission for each time interval (kgCO2e) between the implementation of with and without UCC.

Referring to *Figure 33*, The carbon emission has increased by 28.6% in the scenario with UCC in comparison to the one without UCC. Similar to the Hemel Hempstead project, the benefit of spreading out the carbon emission at any time throughout the delivery cycle as portrayed in *Figure 34* should be emphasized.

5.3 Similarities and differences between projects

To summarise, both case studies have demonstrated a similar change with and without the implementation of UCC. In the Hemel Hempstead project, the decrease in delivery wait time and delivery costs are 19% and 18% respectively. In the case of the Bishop Square project, the reduction in delivery wait time and delivery costs are 21.14% and 14%. However, the carbon emission outputs in both projects recorded a significant increase, 18% in the former and 28.6% in the latter. Nevertheless, the carbon emissions can be flatted out throughout the whole delivery period instead of concentrating at one certain peak hour. The UCC implementation increases the vehicle utilisation rate by approximately 70% on average considering both performed case studies.

On the contrary, the observable differences between these two projects are the number of delivery events, different vehicle types distribution, different timings and geographical locations of suppliers, construction site, and UCC. From the analysed findings, it is sufficient to say the improvements in delivery wait time tend to be less apparent with increasing delivery events. However, the reduction in delivery cost varies proportionally with the number of delivery events or project size, because more flexibility could be mobilised in terms of resource optimisation. Last but not least, the increase in carbon emissions could be minimised with the increase in delivery events, indicating a potential horizontal asymptote as the project size scale up infinitely.

5.4 Discussions

As per section 5.2.4, the introduction of UCC has some promising positive impacts on the logistics processes in both case studies. However, the effects are very dependent on several factors like existing logistics processes and geographical locations among the actors in the system which in this study have been assumed to be favourable to the analysis. In practice, different suppliers will receive different degrees and polarity of impacts according to their previous operating mechanism with UCC might add a step to some of them or a reduction of the process to others. J.Dreischerf and Buijs (2022) have supported the following statement, through contrasting opinions on reflecting the potential effects of a UCC from interviewing suppliers. Cost-wise, the reduction in total transport cost resonates greatly with the impact analysis on UCC performed by Isa et al. (2021), concluding that UCC reduces the last miles deliveries distances, the number of vehicles circulating in the city, the severity of traffic congestion and traffic accidents likelihood. According to the research concerning the financial viability of UCC schemes, its implementation is indeed profitable provided optimal resources utilisation particularly the human resources which account for the biggest category of costs, showing great consistency with our findings identifying the biggest cost-saving coming from the reduction of the driver (Janjevic and Ndiaye, 2017). In terms of carbon emission from the considered supply chain, there is an observable increase with the UCC implementation predominantly due to the total travel distance has increased which has been considered the worst-case scenario for this study owing to the addition of the UCC as the vehicles are not travelling directly to the construction sites but to UCC first then arriving at the final destination. This has shown similar findings to a study conducted by Veličković et al. (2018) where the study explored different consolidation schemes and showed that all proposed consolidation options increase the total driving distance in the urban area but reduce significantly the driving distance of less manageable vehicles in last-miles deliveries. From the greater environmental scheme perspective, the UCC implementation can reduce the carbon emission contributed by the CLO at any given time by spreading out flexibly the emissions. The benefits of UCC to the delivery time, cost, and sustainable components of the supply chain could be further enhanced with a higher level of material organisation to enable pool delivery, which is not being modelled in this study. Not only that, the human perspective of the UCC implementation should not be ignored. For instance, it will create environmental awareness for the shippers, commonly recognised as industrial polluters to implement more environmentally friendly processes (Vieira, Mendes and Suyama, 2016).

The deployment of more electric vehicles (EV) in the logistics industry with increased EV technology maturity is likely to reduce significantly the carbon emission generated by the transport sector (Ofgem, 2018). Browne, Allen and Leonardi (2011b) conducted a study on UCC with EVs and the result of the study showed that the total distance travelled and CO2e emission dropped by 20% and 54% respectively. On top of that, adopting a highly-integrated and flexible EV charging scheduling system is likely to optimise the distribution cost even further. Deng et al. (2022) proposed coordinated operational planning methods for EVs that have been analysed to assess the charge-discharge operation of the EVs in the depot to minimise the total distribution cost and energy cost. This idea could be applied to the UCC by installing a charging system inside the facilities and enabling the energy to be transmitted back to the UCC or the grid network when it is not in service for a financial incentive return.

The introduction of UCC for the construction logistics scheme seems environmentally and economically friendly without accounting for its energy consumption. The implementation of the UCC would raise an immediate concern about the UCC's energy consumption and carbon footprint generated, which vary based on the technology adopted in the UCC. Energy consumption and carbon footprint have become the crucial design and operational considerations for most industrial warehouses. Rai et al. (2011) studied industrial warehouses' operational and carbon footprint and proposed that material substitution for construction materials accounted for a significant carbon impact. Electric energy drives most UCC, and the majority of the consumption is related to the operation of handling equipment. Carli et al. (2020) proposed a system focusing on the details of material handling equipment and layouts to identify the main carbon driver. The research conducted by Carli et al. (2020) reverses the current trend where the research focuses on transport activities as the main source of air pollution. Therefore, an in-depth analysis of the operational energy of UCC should be conducted alongside the efficiency, cost, and carbon footprint for future model development. Energy usage in UCC affects the overall implementation cost of the supply chain and is also a marketing factor in conveying the environmentally friendly properties of UCC.

5.5 Sensitivity Analysis

A sensitivity analysis on parameters that are both subject to considerable variability and are expected based on comparative analysis to have a significant impact on the results is conducted, namely (a) Number of trucks; (b) Number of semi-trailers; (c) Fuel price; (d) Fuel emission factor; and (e) Fuel Consumption rate. The simulation with multiple numerical values for each parameter of interest, while keeping all other parameters at default levels. The table below summarises the results obtained from the sensitivity analysis. Details about the sensitivity analysis are provided in the appendix.

Parameter	Range			Sensitivity (%)		
	min	max	step	Delivery wait time	Delivery cost	Carbon emission
Number of trucks	1	20	1	2.00	4.00	-
Number of semitrailers	5	20	1	3.00	10.00	-
Fuel price	1.35	1.55	0.02	-	0.60	-
Fuel emission factor	2.52	2.72	0.02	-	-	0.36
Fully loaded truck fuel consumption rate	0.3	0.4	0.01	-	1.50	1.20
Fully loaded semitrailer fuel consumption rate	0.2	0.3	0.01	-	0.43	0.47
Empty truck fuel consumption rate	0.2	0.3	0.01	-	1.60	1.48
Empty semitrailer fuel consumption rate	0.1	0.2	0.01	-	0.42	0.46

Table 19: Results of sensitivity analysis on model parameters.

Table 19 displays the range of values for each parameter of interest being iterated over, the respective increment used and the sensitivity results obtained. According to the analysis, the highest sensitivity obtained is 10%, contributed by the number of semitrailers parameter on the delivery cost output. This particular result is expected as it resonates greatly with the activity-based analysis conducted by Janjevic and Ndiaye (2017) on UCC has revealed that the majority of the distribution cost is coming from the driver cost and the number of vehicles influenced significantly the number of drivers which governs the driver cost. On the contrary, the fuel emission factor gives the lowest sensitivity value, 0.36% on the carbon emission model output. Overall, it can be concluded that the model output is not overly dependent or sensitive on one particular parameter, indicating a lower chance of over idealising certain parameter assumptions.

Chapter 6: Conclusion, Limitations and Future Work

Conclusion

UCC opened up new possibilities to reduce the externalities associated with transportation activities by reducing total travelled distance, the number of freights circulating in the city and associated carbon (Isa et al., 2021). To examine the pros of adopting construction consolidation centres in the supply chain, this paper studied the adoption of UCC and provided quantitative research using a hybrid model. A three-echelon model is constructed to simulate a real-world construction supply chain incorporating the DEM, SDM and ABM approach. Our research introduced multi-metric performance metrics to conduct analytics in scenarios with and without UCC.

Our research paper makes several contributions to the field of CSCs. The proposal of three echelons hybrid simulation approaches can quantitatively analyse the impact of integrating UCC in construction. Integrating DEM, SDM and ABM methods into a hybrid system in simulating as close as possible the real-world problem enabled researchers to gain insights into the potential of hybrid modelling. Secondly, this study also conceptualised the automation of communication between fleets and UCC in serving construction sites, which results in safety, efficiency, congestion, and emission-level improvements, with high-level coordinated control. Thirdly, the simulation of dynamic behaviour in the delivery fleet in response to unexpected events like traffic jams and critical weather undeniably provides an added value to practitioners to understand better the vehicle routing under the UCC context in an urban environment.

This study has demonstrated the impacts of UCC through a direct comparison between idealised highly integrated logistics systems and existing disconnected logistic systems. Despite all the bespoke advantages brought by UCC implementation, the degree of impact to different stakeholders varied depending on external and internal factors like geographical location, transport accessibility, population density, and stakeholders' existing logistic network. More research and in-depth analysis should be conducted to assess the feasibility of the proposed VRP solution, preferably in the region outside of London with different transport networks and properties.

Nevertheless, through the findings and insights obtained from the hybrid modelling, this research improves the understanding of the roles of UCC and its prospects in the logistics processes, enlightening the importance of DAS to scholars, catalysing the development of the automation technology field.

Limitations

- **Insufficient data information**
  The real-life data collected is incomplete information leading to some essential explicit conversions or assumptions based on engineering rules of thumb. For example, the suppliers' locations and material weights are anonymous for privacy, leading to suppliers' precise locations on the map and material capacity flow being impossible to track down. As a feasible solution, the study assumes the materials will be supplied by the most well-searched company on google, complemented by a travel distance distribution. The results will be used as the approximate locations. Similarly, the material capacities are estimated with a normal distributed utilization rate applied to the given vehicle type information described in a histogram provided in the appendix.
- **The logic of the model might be oversimplified and unrealistic**
  There is a lack of human behaviour consideration in the model, assuming the resources like fleets are performing at constant productivity and efficiency throughout the entire

delivery cycle. In reality, a drop in delivery efficiency is inevitable due to various unpredictable factors like decreased attention level and various driving experience

- **Suitability of materials to be stored at the consolidation centre for common delivery**
  In this study, the materials considered are all storable within the UCC. In practice, certain material properties might affect its storability in UCC like wet concrete due to its time-sensitive factor requiring specialised handling or tailored logistics service.
- **Model evaluation metrics accuracy**
  The carbon emission calculation in this model is entirely based on the distance travelled by the vehicles and material weights coupled with the emission factors, which indicate some possible underlying errors. For instance, vehicles travelling at certain speeds might generate fewer carbon emissions which are outside the scope of this study

Future Works

As this proposed research idea is still at the very early stage with a high level of novelty, further development is open to scholars for future research. Some potential research directions on this model and its hypothesis on the implementation of UCC include more than one UCC to form a more complex distribution network, more construction sites to be served, more vehicle fleets characteristics like refuelling time and maintenance time, and independent decision-making ability of suppliers for stochastic demand generation. In addition, the impacts of UCC implementation could be expanded to other geographical locations with different road infrastructure development and characteristics to investigate the key drivers of its feasibility. Concerning the system behaviour, rearrangement or reorganisation of the materials from different suppliers could be performed for continuous delivery to multiple sites for higher fleet utilisation and reduced delivery trips. The modelling of performance metrics on delivery time, cost and carbon emission could be enhanced further or evaluated with a different approach to achieve higher accuracy or explore the more underlying potential of UCC implementation. In addition to that, more dynamic systemic disruptive events like road accident occurrence, road closures, and road restrictions that might cause re-routing of the vehicle could be introduced to simulate even closer to reality the impacts of UCC implementation.

Model Development Reflection

In retrospect, the authors were able to gain a comprehensive understanding of the system implications of DAS across different industries and identified one of the research gaps in construction logistics. The literature review was conducted solely with the software Publish or Perish, making the filtering of relevant papers extremely convenient, resulting in a significant increase in the productivity and reliability of the study. The development of the hybrid model using multiple modelling techniques has been successful, particularly in the modelling of fluctuating vehicle speed and able to achieve the purpose of this study in conceptualising the impacts of UCC. The authors were able to gain practical experiences in ABM, DEM and SDM and learnt their potential in solving other engineering problems. On the contrary, the authors found that the drawing of clear modelling framework and system boundaries at the initial stage is particularly important to the entire model development process as it will avoid the need for extensive or repetitious modification at a later stage. In hindsight, a trial study on modelling software other than Anylogic will create more possibilities for the modelling results. Furthermore, different approaches to simulating certain components of the model could have been carried out given more time to determine the best approach for that particular case. More research could have been done on assuming parameter values to increase the model simulation accuracy. Lastly, cooperation and distribution of modelling tasks could have been done better as Anylogic does not support the editing of multiple users in one model at the same time which decreases the overall productivity.

Chapter 7: References/ Bibliography

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Chapter 8: Appendices

Model Links

Prologis Hempstead

UCC Scheme

https://cloud.anylogic.com/model/baaae1de-51c6-4f19-808e-54d67c92605d?mode=SETTINGS&tab=GENERAL

Direct Scheme

https://cloud.anylogic.com/model/60ae024c-773b-4962-8c33-64de8687daab?mode=SETTINGS&tab=GENERAL

Bishop Square

UCC Scheme

https://cloud.anylogic.com/model/4076992e-a6f9-4171-90dd-888ff068a16d?mode=SETTINGS&tab=GENERAL

Direct Scheme

https://cloud.anylogic.com/model/3d4a4558-68f3-484c-8d05-7f8cacb69e07?mode=SETTINGS&tab=GENERAL

Appendix A: Modelling input data and components

Delivery Distance Distribution

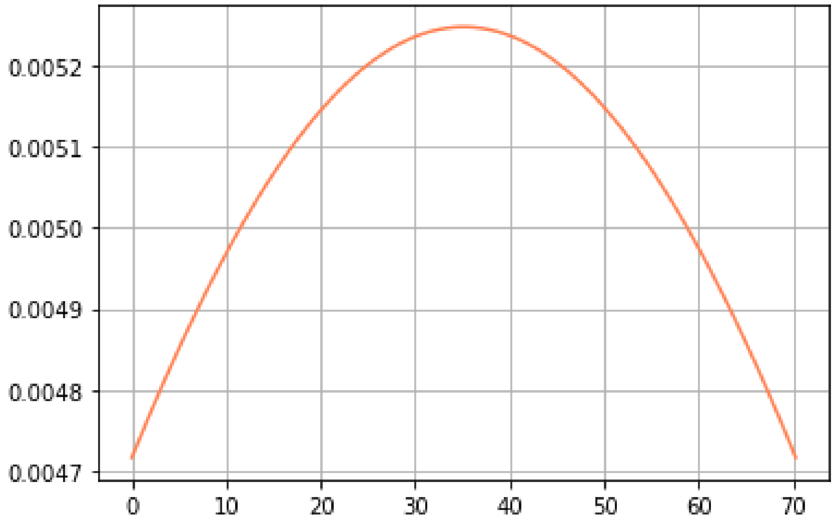

Figure A1: Probability density function (PDF) of delivery distance.

Vehicle Type Distribution

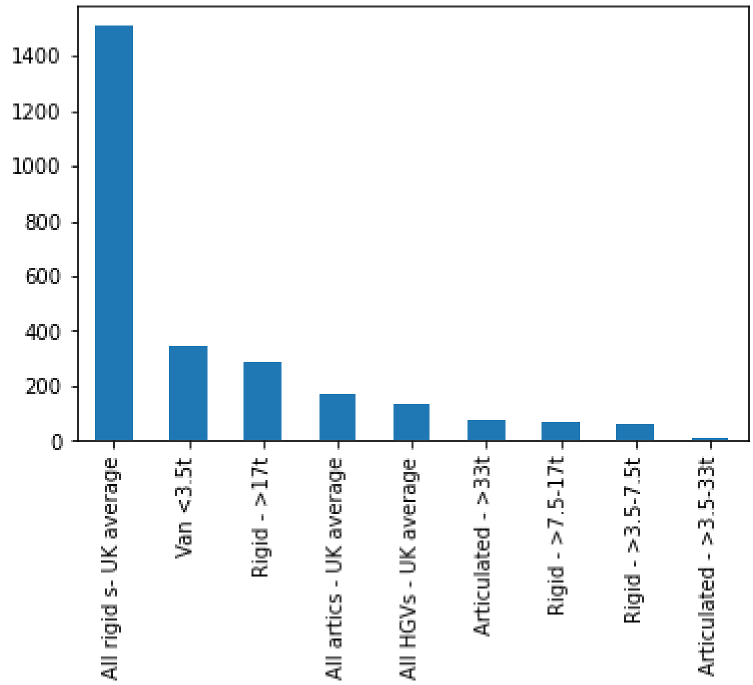

Figure A2: Histogram of vehicle type.

CCC	Address	CCC	Address
	Hallett Sibermann Ltd Travellers Lane Welham Green Hatfield Herts AL9 7HF		Muztrans Unit 1 River Wharf Mulberry Way Belvedere DA17 6AR
	The London Construction Link Leslie Ford House Port of Tilbury Tilbury Essex RM18 7EH		Rendrive Haulage Ltd Pioneer Works Crabtree Manorway South Belvedere Kent DA17 6AH
	Premier Carriers (Barking) Choats Road Barking RM9 6RJ		Wincaton Greenford Consolidation Centre Rockware Avenue Greenford Middlesex UB6 0AA
	Premier Carriers (Bow) 120 Bow Common Lane Bow London E3 4BH		Avondale: The Assertive Centre, 8 Stucley Place, London, NW1 8NS
	Wilson James: London Construction Consolidation Centre Silvertown London E16 2EZ		CSB Logistics (Charlton) Stone Foundries Estate 669 Woolwich Road Charlton London SE7 8LH
	Lightwood Logistics Hanger 2 North Weald Airfield Epping Essex CM16 6HR		DHL Barking Logistics Centre Box Lane Renwick Road Barking Essex IG11 0SQ

Table A3: UCC address across London.

A Avondale: The Assertive Centre
B The London Construction Link
C Premier Carriers (Bow)
D Premier Carriers (Barking)
E DHL Barking Logistics Centre
F Lightwood PLC
G Wilson James: London Construction Consolidation Centre
H Wincanton Greenford Consolidation Centre
I CSB Logistics (Charlton)
J Muztrans
K Rendrive Haulage Ltd
L Hallett Silberman Ltd

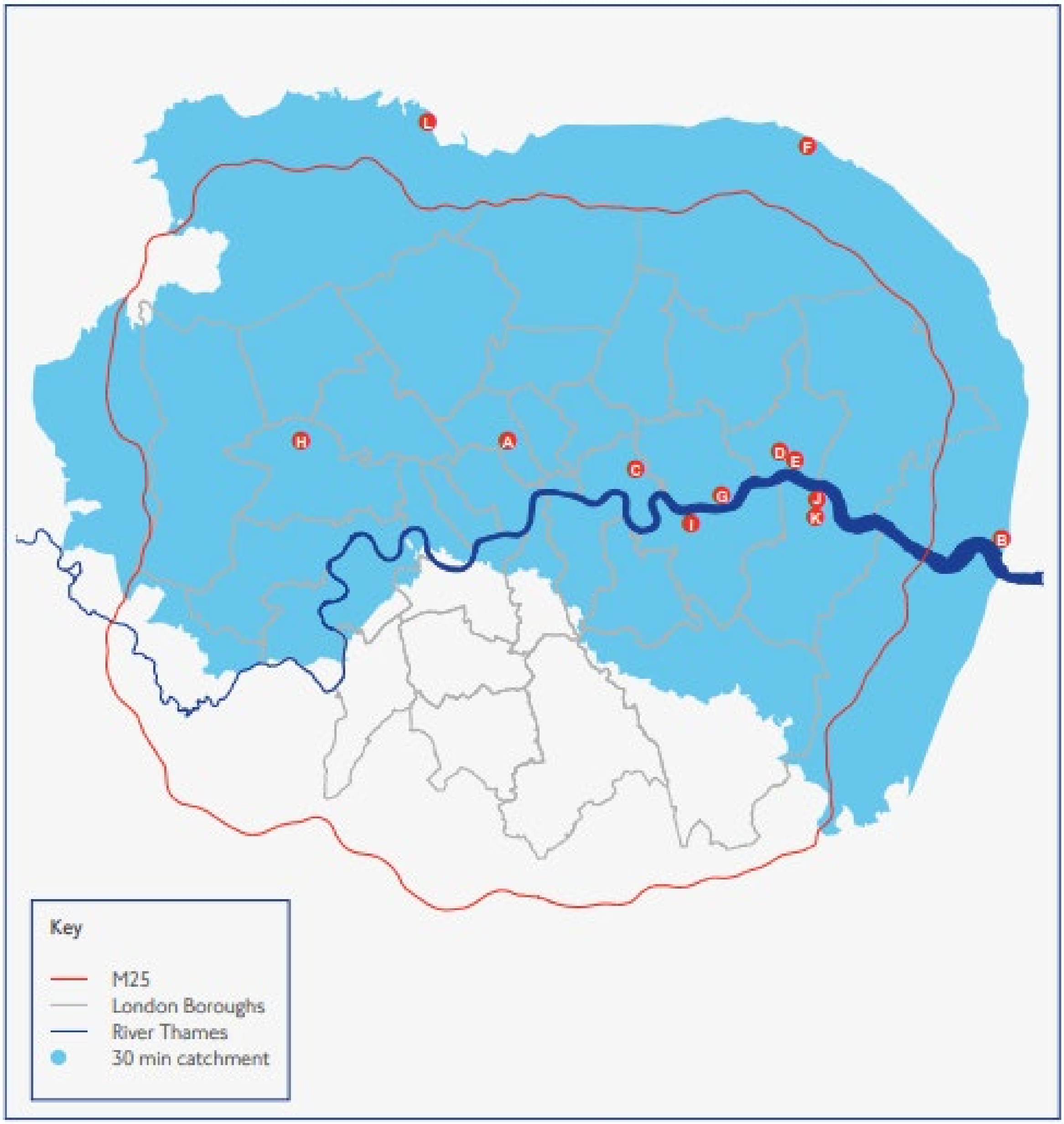

Figure A4: UCC locations across London.

Appendix B: Mathematical formulation of the vehicle routing problem under UCC implementation

Table of parameters and notations

Parameters	Description	Unit
x_{idj}	indicator function for delivery event, outcome:{1, successful delivery event; 0, unsuccessful delivery event}	-
$t_{id,\ dj}$	travel time between distribution center and suppliers/ distribuition center and customers	minutes
$d_{id,\ dj}$	travel distance between distribution center and suppliers/distribution center and customers	miles
n	number of delivery events	-
l_{ij}	loading wait time	minutes
v(x)	vehicle speed	miles/hour
$T_{id,\ dj}$	delivery wait time	minutes
w	average delivery wait time	minutes
c_m	manufacturing cost per unit material	£/tonne
c_{ms}	manufacturing fixed cost	£
c_0	ordering cost per unit material	£/tonne
c_{os}	ordering fixed cost	£
q_i	demand at customer i	tonne
Fs	semitrailers driver cost	£
Ft	trucks driver cost	£
c_s	storing cost per unit material	£/tonne
c_r	receiving cost per unit material	£/tonne
c_I	inspection cost per unit material	£/tonne
c_p	planning cost per unit material	£/tonne
c_f	fuel cost	£/litre
T_{sE}	fuel consumption rate by an empty semitrailer	litre/miles
T_{sL}	fuel consumption rate by a fully-loaded semitrailer	litre/miles
T_{vE}	fuel consumption rate by an empty truck	litre/miles
T_{sL}	fuel consumption rate by a fully-loaded truck	litre/miles
e_f	fuel emission factor	kgCO2e/litre
e_m	material emission factor	kgCO2e/tonne

Table B1: Tabulation of model parameters and their descriptions.

Notation	Description
I	set of suppliers
J	set of customers
D	set of consolidation centre
$A_{id,dj}$	set of the paths between distribution center and suppliers / distribution center and customer)
N	set of delivery events
K	set of vehicles

Table B2: Tabulation of model notations and their descriptions.

<table>
<tr><th></th><th>Algorithm: Vehicle Speed</th></tr>
<tr><td>1</td><td>setSpeed(normal(5, 50), MPH); ## setting a normal distribution of speed to the vehicle
dest.setText(getSpeed(MPH)); ## creating a label on top of the fleet icon with the assigned speed</td></tr>
<tr><td>2</td><td>main.OuterTrafficZone && main.OuterTrafficArea.contains(getX(), getY()) ## Checking the location of the vehicle to check whether its within the speed limit zones</td></tr>
<tr><td>3</td><td>## checking the traffic zone and assigning speed to the vehicle from appropriate speed distribution
if(main.CentralTrafficZone && main.CentralTrafficArea.contains(getX(), getY())) {
setSpeed(normal(1,8), MPH);
dest.setText(getSpeed(MPH));
} else if(main.InnerTrafficZone && main.InnerTrafficArea.contains(getX(), getY())) {
setSpeed(normal(2,12), MPH);
dest.setText(getSpeed(MPH));
} else {
setSpeed(normal(4,20), MPH);
dest.setText(getSpeed(MPH));
}</td></tr>
<tr><td>4</td><td>! main.OuterTrafficArea.contains(getX(), getY()) || ! main.OuterTrafficZone</td></tr>
<tr><td>5</td><td>## enforcing the reassignment of speed from appriopriate speed distribution according to traffic level when disruptive events have been triggered
if (main.CentralTrafficZone && main.CentralTrafficArea.contains(getX(), getY())){
setSpeed(normal(0.5,5), MPH);
dest.setText(getSpeed(MPH));
}
else if (main.InnerTrafficZone && main.InnerTrafficArea.contains(getX(), getY())){
setSpeed(normal(1,8), MPH);
dest.setText(getSpeed(MPH));
}
else if (main.OuterTrafficZone && main.OuterTrafficArea.contains(getX(), getY())){
setSpeed(normal(2,15), MPH);
dest.setText(getSpeed(MPH));
}
else {
setSpeed(normal(4, 45), MPH);
dest.setText(getSpeed(MPH));
}</td></tr>
</table>

Pseudocode B1: Tabulation of model notations and their descriptions.

<u>Delivery Wait time</u>

The path network of the distribution centre and consumers can be illustrated by a directed graph $G = (\mathrm{I}, J, \mathrm{D}, \mathrm{A})$, where $I = \{1,2, \dots, m\}$ is the set of suppliers, $D = \{1,2, \dots, m\}$ is the set of distribution centres, $J = \{1,2, \dots, m\}$ is the set of customers, and $A = \{(i,d),(d,j) \mid i \neq \mathrm{d} \neq j\ \Lambda i, \mathrm{d}, j \in L\}$ is the set of paths between suppliers and distribution centres or distribution centres and customers. The distance and travel time between consumers i and j are denoted as $d_{id,dj}$ and $t_{id,dj}$, respectively. For consumer I, the demand is denoted as q_i; the number of scheduled delivery events is denoted as $N = \{1,2, \dots, n\}$.

Let $K = \{1,2, \dots, m\}$ be the set of vehicles. For vehicle k, the load capacity is denoted as Q_k; the service time at consumer i is denoted as t_i; the delivery start time at consumer i is denoted as S_i.

$$Average\ delivery\ wait\ time, w = \frac{1}{N} \sum_{i,j=1}^{m} {T_{id,dj}}^{n}$$

$$Delivery\ wait\ time, {T_{id,dj}}^{n} = {t_{id,dj}}^{n} + {l_{ij}}^{n}$$

$${t_{id,dj}}^{n} = \frac{{d_{id,dj}}^{n}}{v(x)_k}$$

The loading wait time at suppliers i and consumers j are denoted as l_{ij} and is assumed to follow the triangular distribution as described below:

$$l_{ij} \sim triangular(a, \mathrm{b}, \mathrm{c})$$

where, a = lower limit, b = upper limit and c = mode

$$l_{ij} = \begin{cases} \dfrac{2(x-a)}{(b-a)(c-a)} & for\ a \leq x < c, \\ \dfrac{2}{b-a} & for\ x = c, \\ \dfrac{2(b-x)}{(b-a)(b-c)} & for\ c < x \leq b \end{cases}$$

The travel speed is a traffic flow feature. The speed constraints are categorised into three zones are central London zone, inner London zone and outer London where vehicle speeds are allocated according to the location of the vehicle. The travel speed distribution follows a normal distribution and can be summarised as follows:

$$v(x) \sim Normal(\mu, \sigma^2)$$

$$f(v(x)) = \begin{cases} \dfrac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(v(x)-\mu)^2}{2\sigma^2}} & x \in x_1, x_2, x_3 \end{cases}$$

$$E(v(x)) = \mu \text{ and, var } (v(x)) = \sigma$$

where, $\mu = \begin{cases} \lambda_1, x \in x_1 \\ \lambda_2, x \in x_2 \\ \lambda_3, x \in x_3 \end{cases}; \sigma v = \begin{cases} \sigma v_1, x \in x_1 \\ \sigma v_2, x \in x_2 \\ \sigma v_3, x \in x_3 \end{cases}; \lambda_1, \lambda_2$ and λ_3 are the expected travel speeds in central London zone x_1, inner London zone x_2, and outer London zone x_3 respectively; σ_{v1}, σ_{v2} and σ_{v3} are the standard deviations of travel speed in the central London zone, inner London zone and outer London zone, respectively. In addition to that, the general vehicle speed during a smooth free traffic zone is also assumed to follow above normal distribution with expected travel speeds, λ_s and standard deviation, σ_{vs}

The VRP model with UCC implementation can be created using the time-varying traffic flow.

f(x):

$$w = \frac{1}{N} \sum_{i,j=1}^{m} {T_{id,dj}}^{n}$$

$${T_{id,dj}}^{n} = {t_{id,dj}}^{n} + {l_{ij}}^{n}$$

$${t_{id,dj}}^{n} = \frac{{d_{id,dj}}^{n}}{v(t)_k}$$

$$\forall i, j \in I, J\ ; \forall k \in K; \forall n \in N$$

$$l_{ij} \sim triangular(a, \mathrm{b}, \mathrm{c})$$

$$l_{ij} = \begin{cases} \dfrac{2(x-a)}{(b-a)(c-a)} & for\ a \leq x < c, \\ \dfrac{2}{b-a} & for\ x = c, \\ \dfrac{2(b-x)}{(b-a)(b-c)} & for\ c < x \leq b \end{cases}$$

$$v(t) \sim Normal(\mu, \sigma^2)$$

$$f(v(x)) = \begin{cases} \dfrac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(v(x)-\mu)^2}{2\sigma^2}} & x \in x_1, x_2, x_3 \end{cases}$$

$$\mu = \begin{cases} \lambda_1, x \in x_1 \\ \lambda_2, x \in x_2 \\ \lambda_3, x \in x_3 \end{cases}; \sigma v = \begin{cases} \sigma v_1, t \in x_1 \\ \sigma v_2, t \in x_2 \\ \sigma v_3, t \in x_3 \end{cases}; \lambda_1, \lambda_2, \lambda_3$$

Distribution Cost

An activity-based costing (ABC) technique might be utilised to make the supply chain management costs more apparent. It is an effective cost accounting technique that highlighted the relationship between overheads and activities by treating the cost's drive-by activities. ABC involved a technique whereby assigning different activities to respective cost pools and analysing the profitability to the targeted client.

$$C = c_{TC} + C_{CLC} + C_{FC} + C_{manufacturing} + C_{ordering}$$

Where,

$C_{manufacturing}$= cost of manufacturing the product

$C_{ordering}$= cost of ordering the product

C_{TC} = cost of transport from suppliers to consolidation centers (CLC) = $C_{loading} + C_{transport}$

C_{CLC} = cost of CLC operations = $C_{storing} + C_{receiving} + C_{inspection} + C_{planning} + C_{vehicles}$

C_{FC} = cost of transport from CLC to customers = $C_{loading} + C_{transport}$

$$C_{manufacturing} = \sum_{n \in N} \sum_{i \in I} c_m q_i^n + c_{ms}{}^n$$

$$C_{ordering} = \sum_{n \in N} \sum_{j \in J} c_o q_i^n + c_{os}{}^n$$

$$C_{vehicles} = \sum_{n \in N} \sum_{d \in D} \sum_{j \in J} x_{d,j}^n Fs + \sum_{n \in N} \sum_{d \in D} \sum_{i \in I} x_{d,i}^n Ft$$

$$C_{storing} = \sum_{n \in N} \sum_{i \in I} c_s q_i^n$$

$$C_{receiving} = \sum_{n \in N} \sum_{i \in I} c_r q_i^n$$

$$C_{inspection} = \sum_{n \in N} \sum_{i \in I} c_I q_i^n$$

$$C_{planning} = \sum_{n \in N} \sum_{i \in I} c_p q_i^n$$

$$\begin{aligned} C_{TC} &= \sum_{n \in N} \sum_{(d,j) \in A1} d_{dj}{}^n c_f x_{dj}^n [Ts_E + Ts_L] \\ &+ \sum_{n \in N} \sum_{(i,d) \in A2} d_{id}{}^n c_f x_{id}^n [Tv_E + Tv_L] \end{aligned}$$

Carbon Emission

CO_2 emissions result from the respective mean of transport is defined as (E_t) whereas the material is defined as a function (E_m). Hence, the total carbon emission measured can be quantified by summing E_t and E_m together as described below:

$E = E_t + E_m$

$$
\begin{aligned}
E_t \quad &= \sum_{n \in N} \sum_{(d,j) \in A1} d_{dj}{}^{n} e_F x_{dj}^{n} [Ts_E + Ts_L] \\
&+ \sum_{n \in N} \sum_{(i,d) \in A2} d_{id}{}^{n} e_F x_{dj}^{n} [Tv_E + Tv_L]
\end{aligned}
$$

$$E_m = \sum_{n \in N} \sum_{i \in \mathrm{I}} e_m q_i^n$$

Appendix C: Results

Hemel Hempstead (With Urban Consolidation Centre)

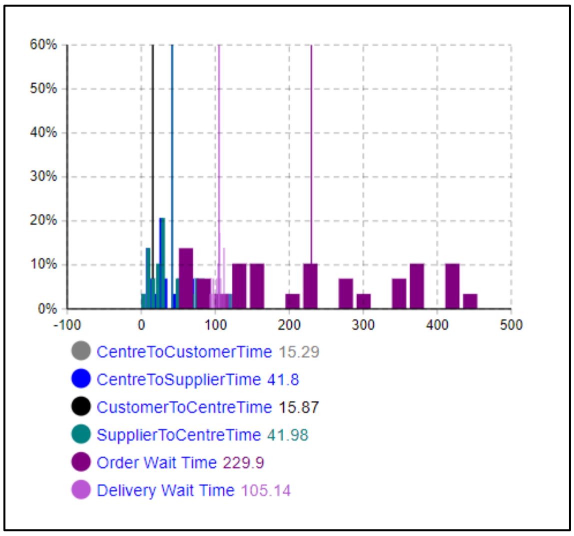

Figure C1: Delivery waits time distributions of each process (UCC).

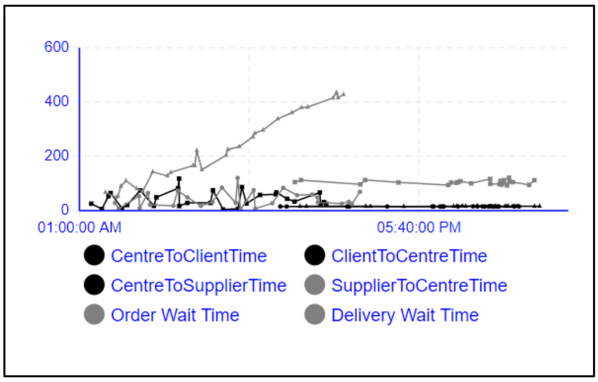

Figure C2: Time plots of each process (UCC).

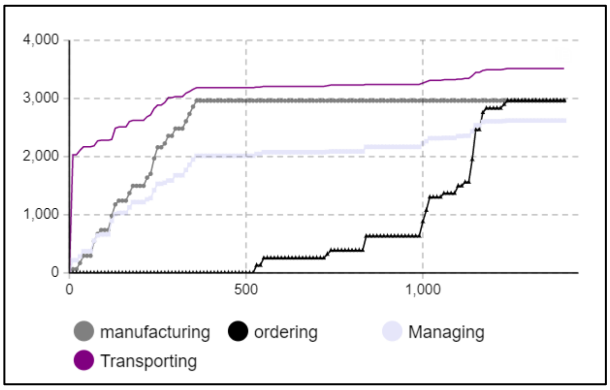

Figure C3: Time plots of each cost category (UCC).

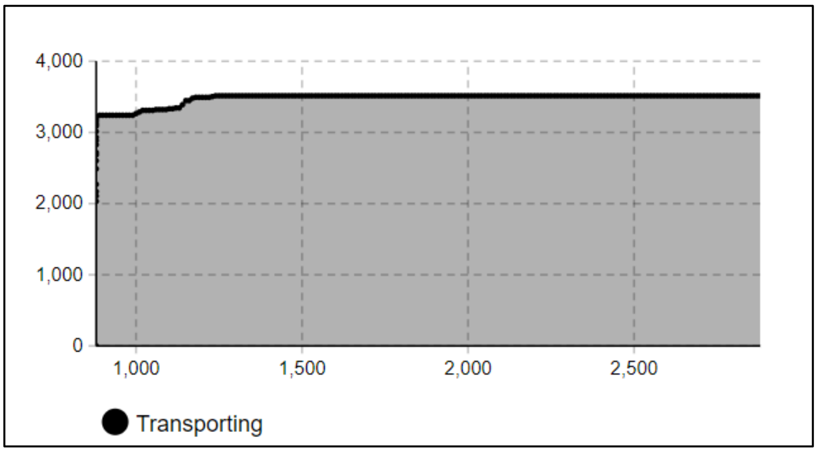

Figure C4: Time plots of transport cost (UCC).

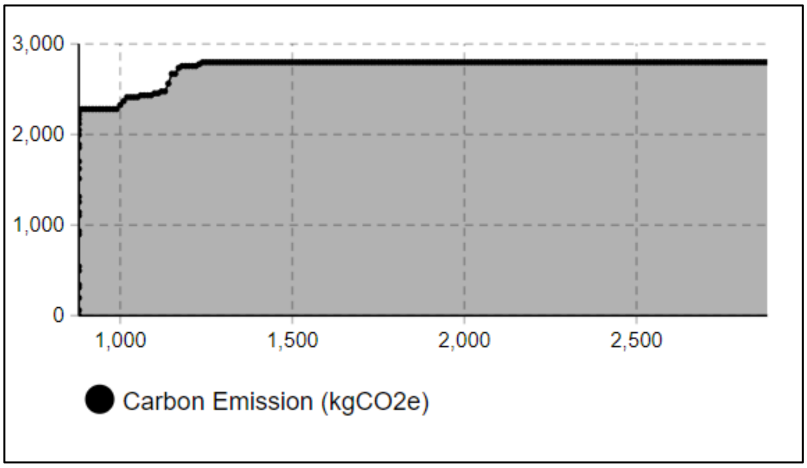

Figure C5: Time plots of carbon emissions (UCC).

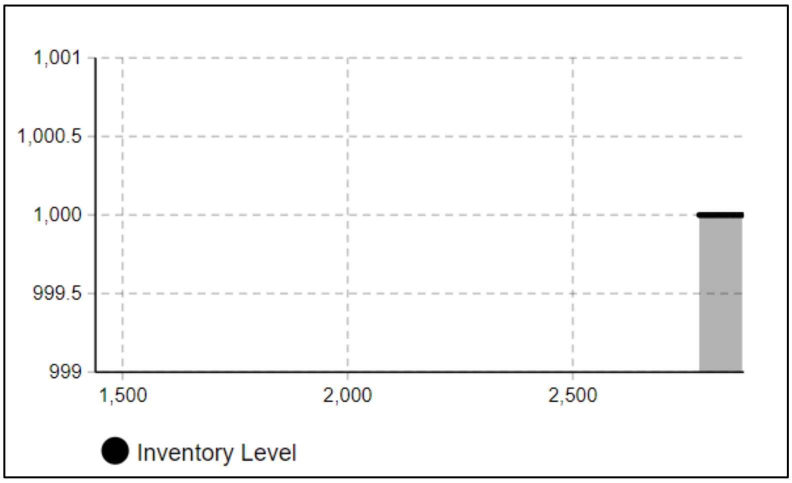

Figure C6: Time plots of inventory levels (UCC).

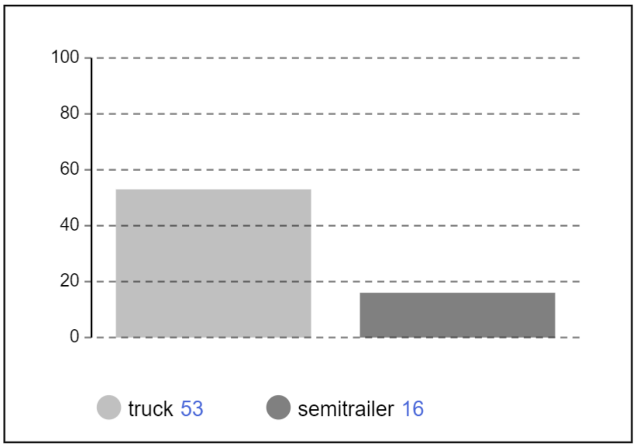

Figure C7: Utilisation rate of trucks and semitrailers (UCC).

Hemel Hempstead (Without Consolidation Centre)

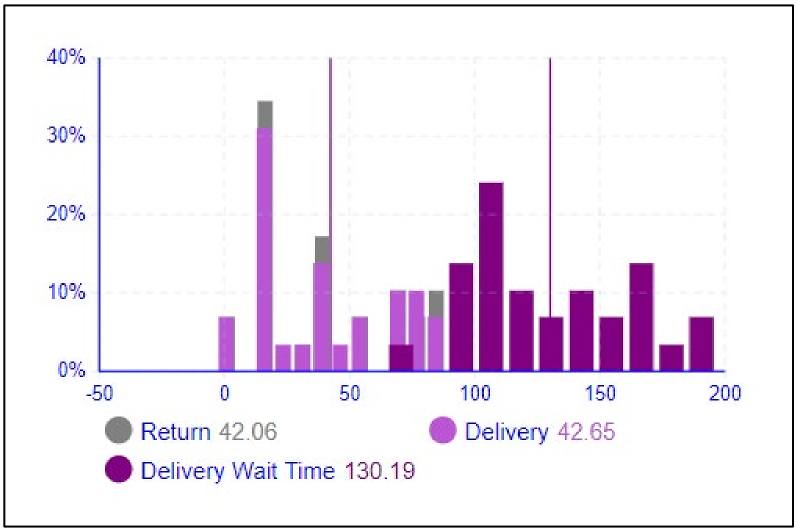

Figure C8: Delivery waits time distributions of each process (without UCC).

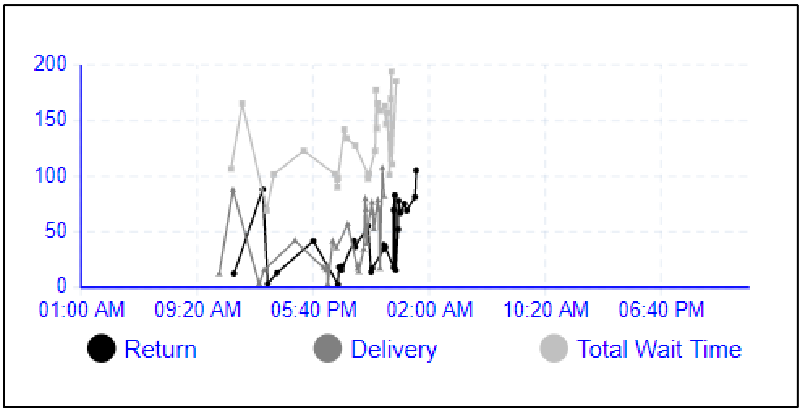

Figure C9: Time plots of each process (without UCC).

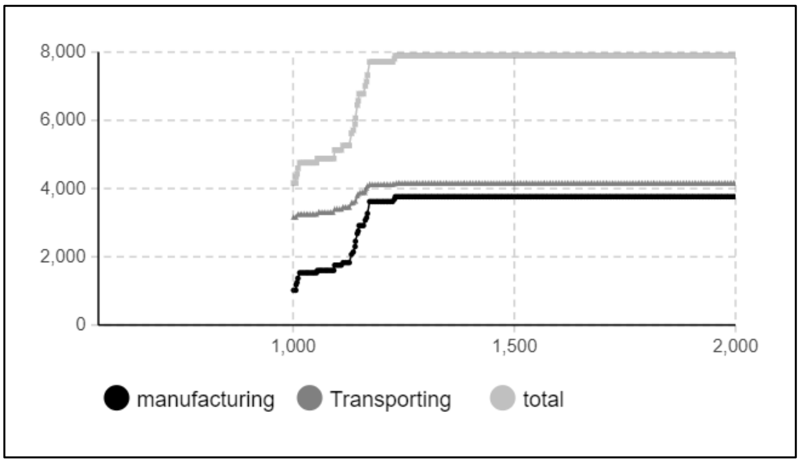

Figure C10: Time plots of each cost category (without UCC).

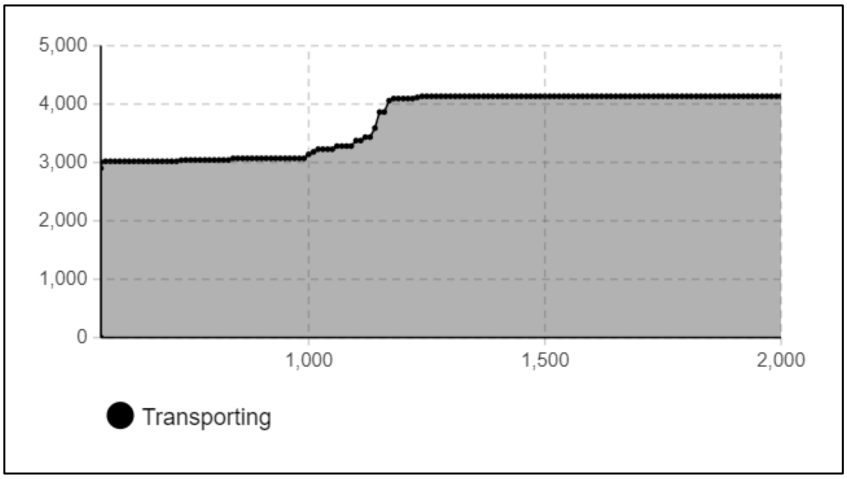

Figure C11: Time plots of transport cost (without UCC).

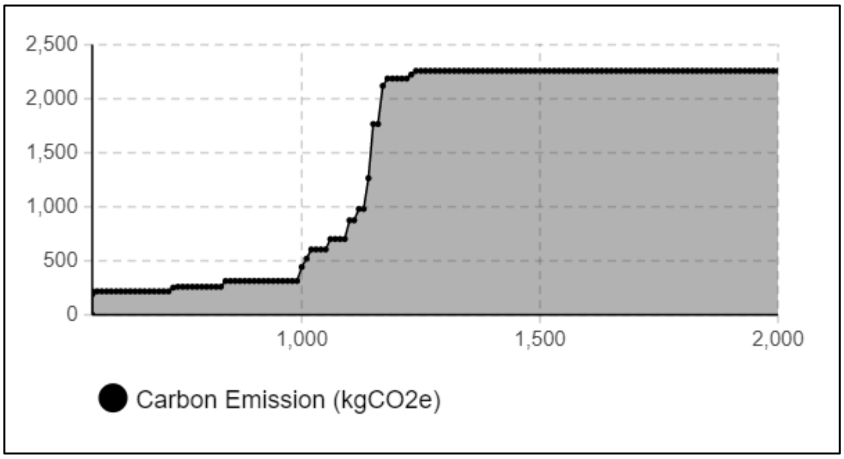

Figure C12: Time plots of carbon emissions (without UCC).

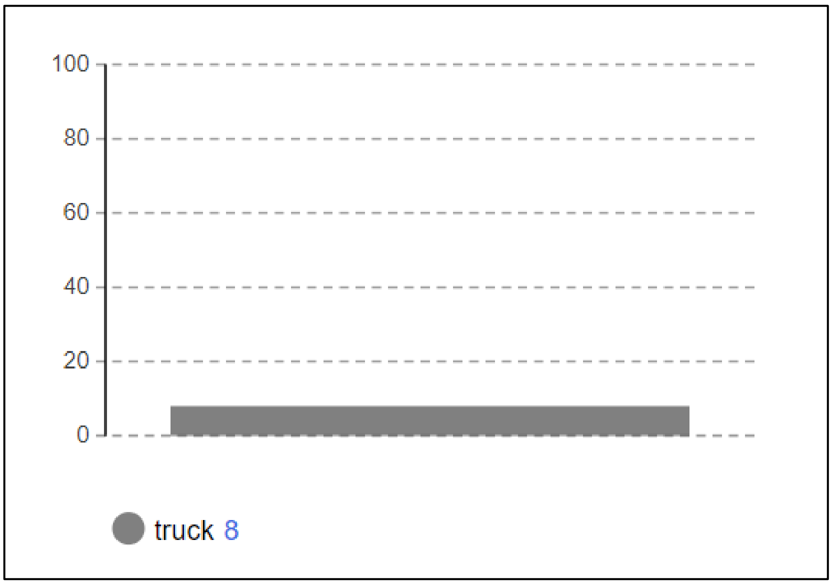

Figure C13: Utilisation rate of trucks (without UCC).

Bishop Square (With Consolidation Centre)

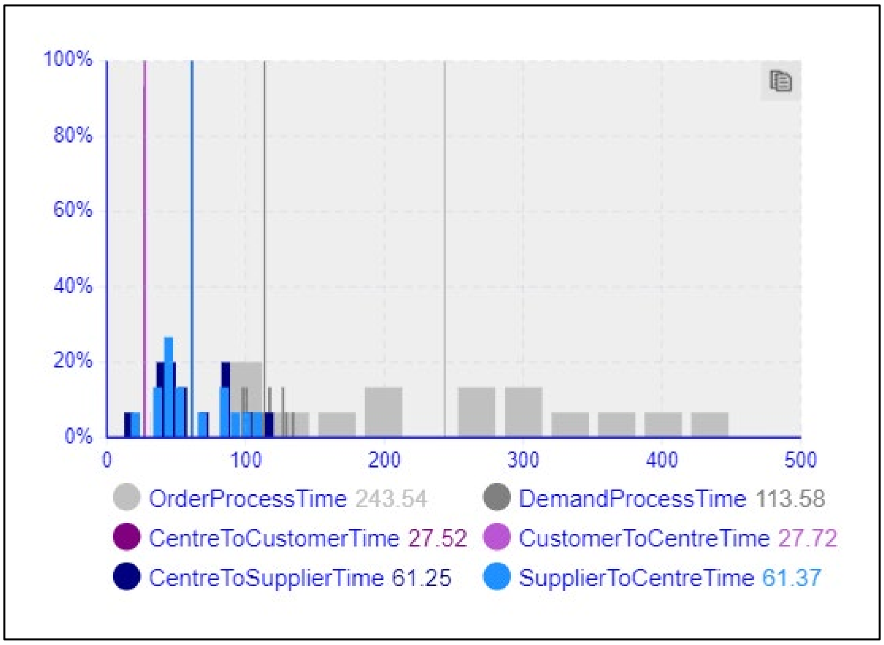

Figure C14: Delivery waits time distributions of each process (UCC).

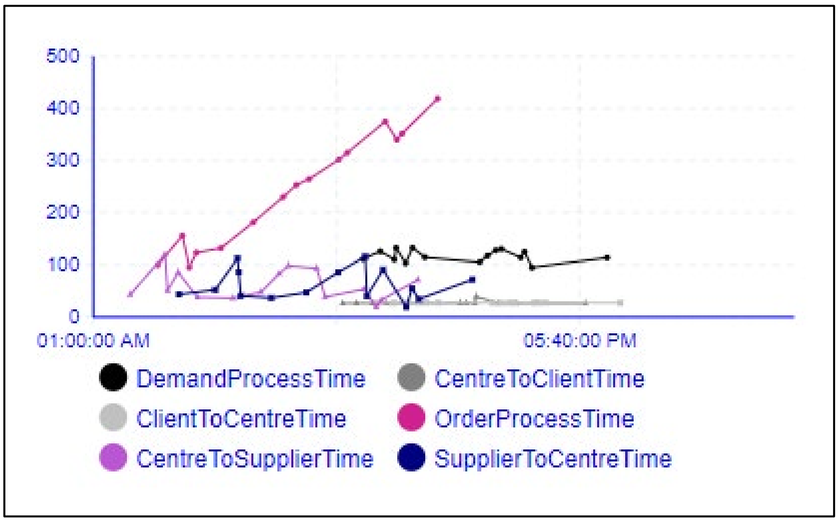

Figure C15: Time plots of each process (UCC).

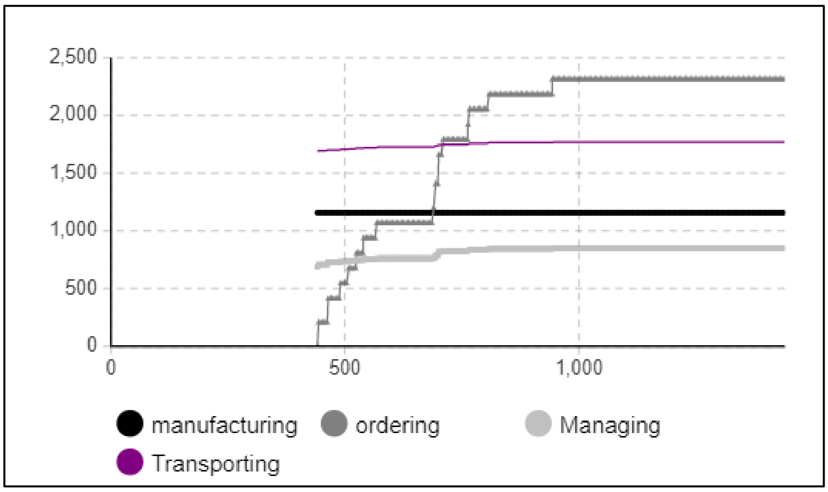

Figure C16: Time plots of each cost category (UCC).

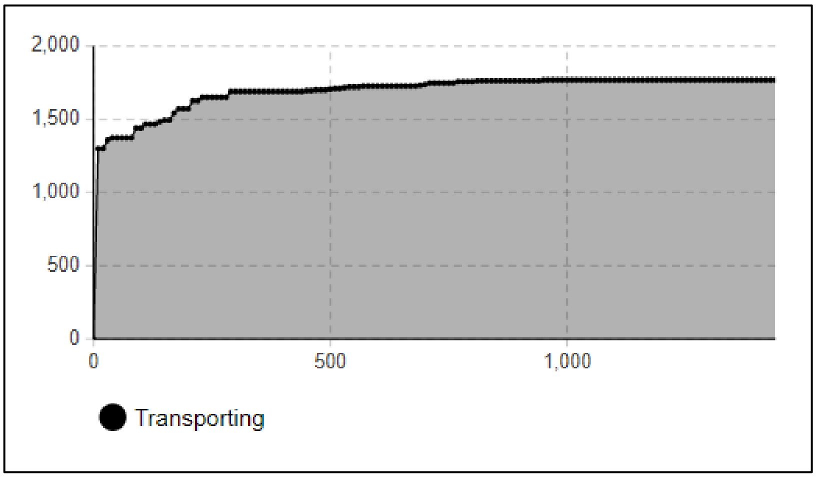

Figure C17: Time plots of transport cost (without UCC).

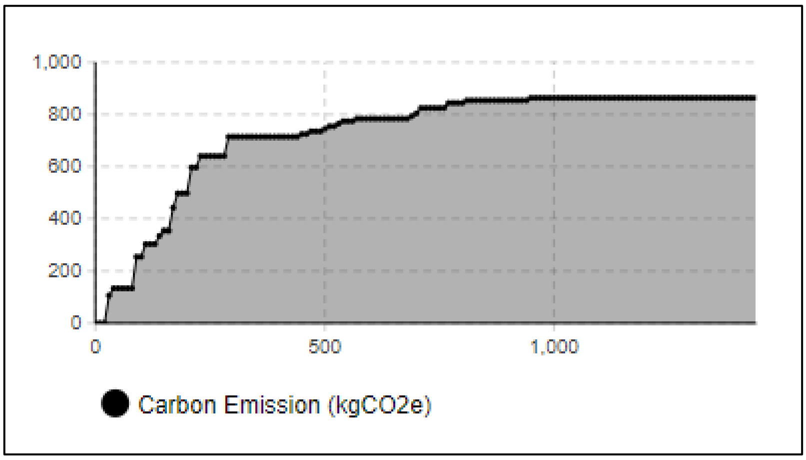

Figure C18: Time plots of carbon emissions (UCC).

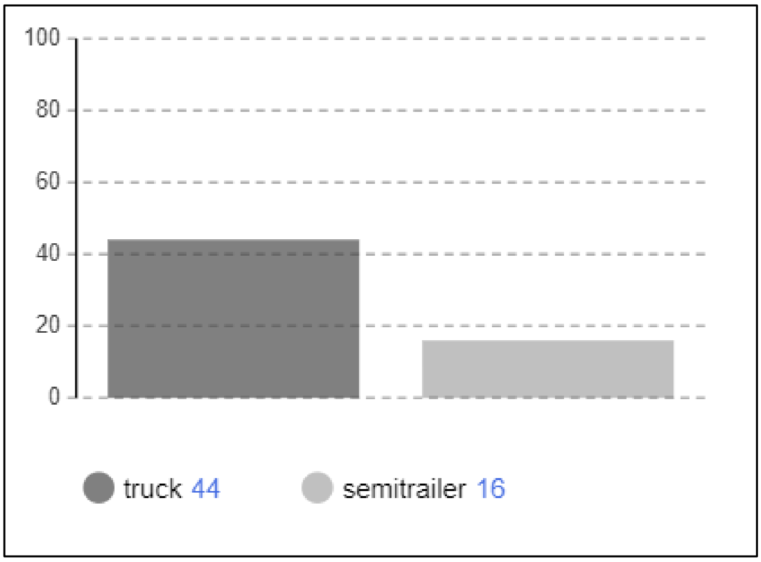

Figure C19: Utilisation rate of trucks and semitrailers (UCC).

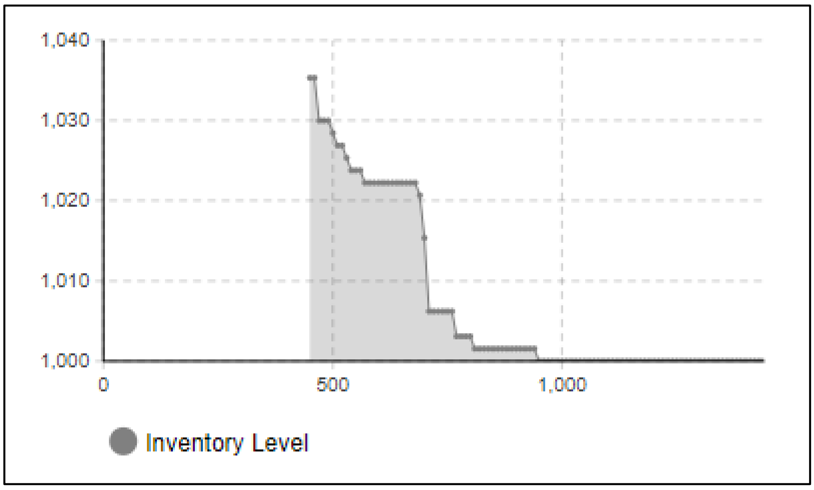

Figure C20: Time plots of inventory levels (UCC).

Bishop Square (Without Consolidation Centre)

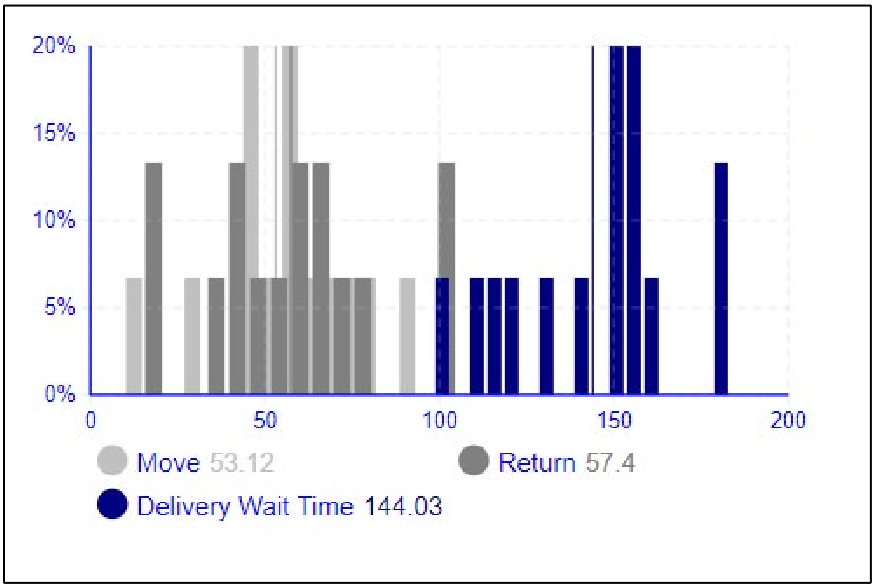

Figure C21: Delivery waits time distributions of each process (without UCC).

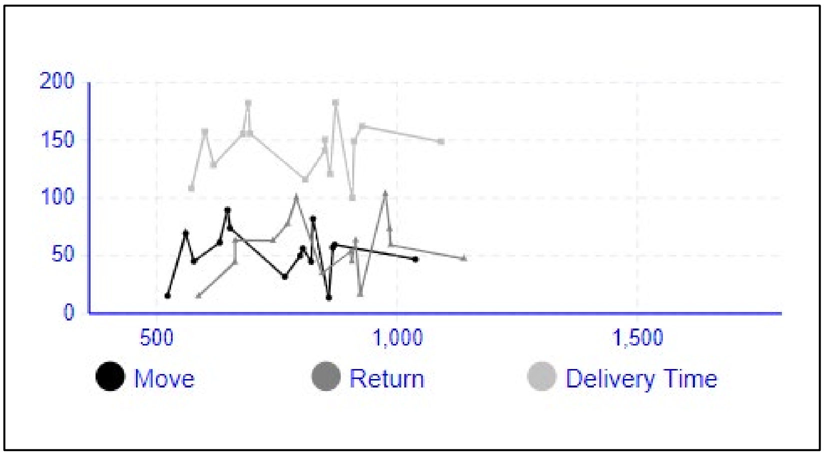

Figure C22: Time plots of each process (without UCC).

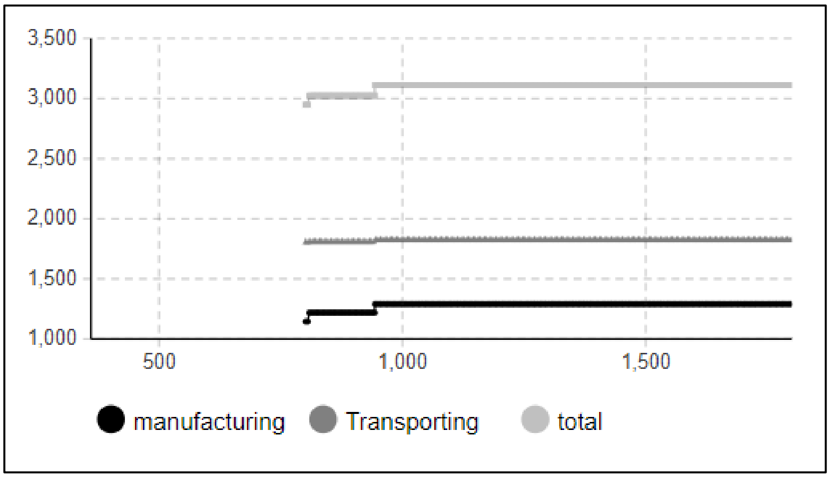

Figure C23: Time plots of each cost category (without UCC).

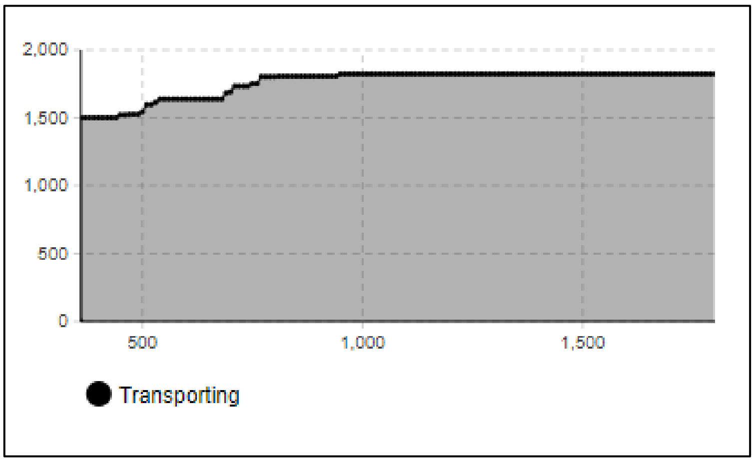

Figure C24: Time plots of transport cost (without UCC).

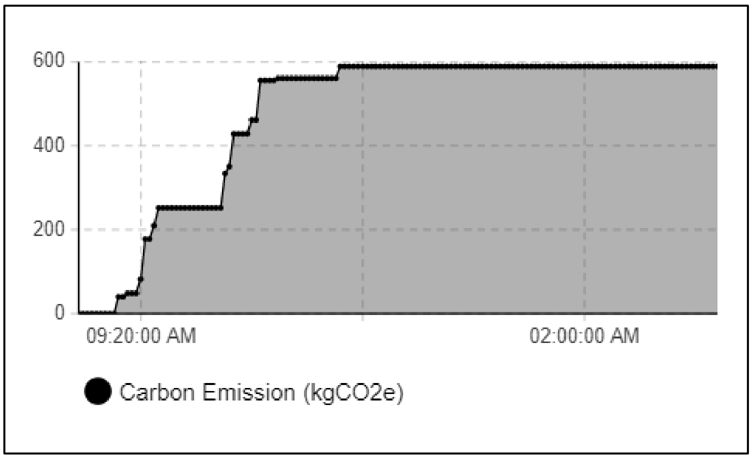

Figure C25: Time plots of carbon emissions (without UCC).

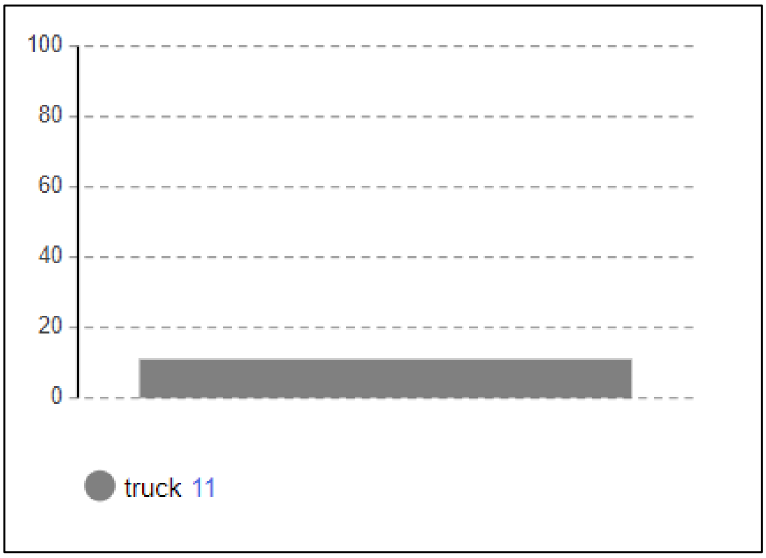

Figure C26: Utilisation rate of trucks (without UCC).

Appendix D: Parameter's optimisation results

Prologis Hemel Hempstead

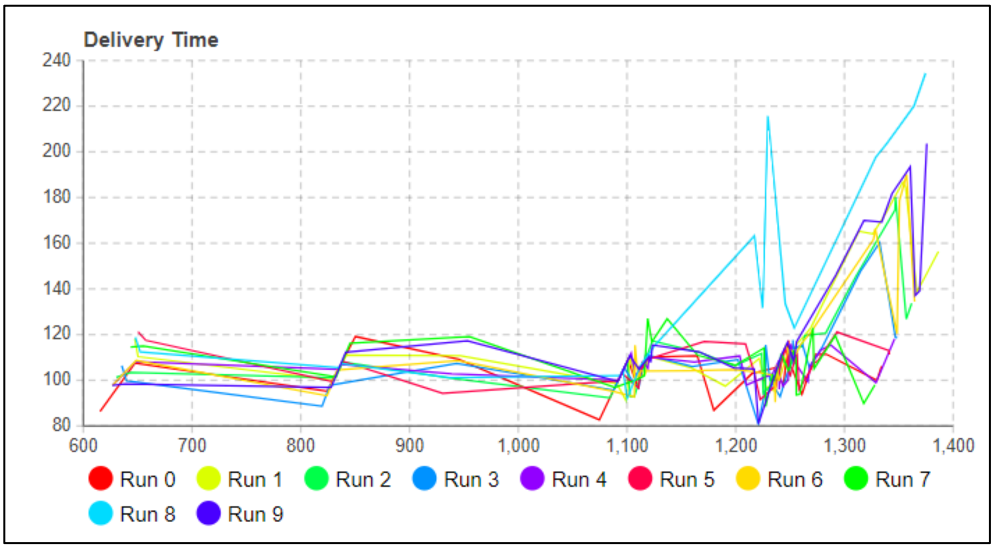

Figure D1: Optimisation Output for Prologis Hemel Hempstead (Time Plots of Delivery Time for different input values).

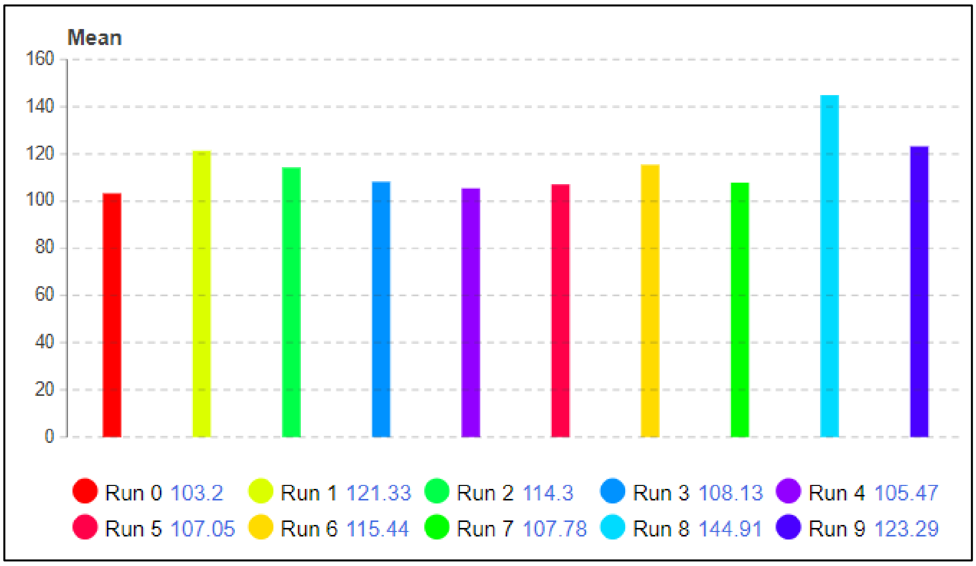

Figure D2: Optimisation Output for Prologis Hemel Hempstead (Average Delivery Times formulated for different input values).

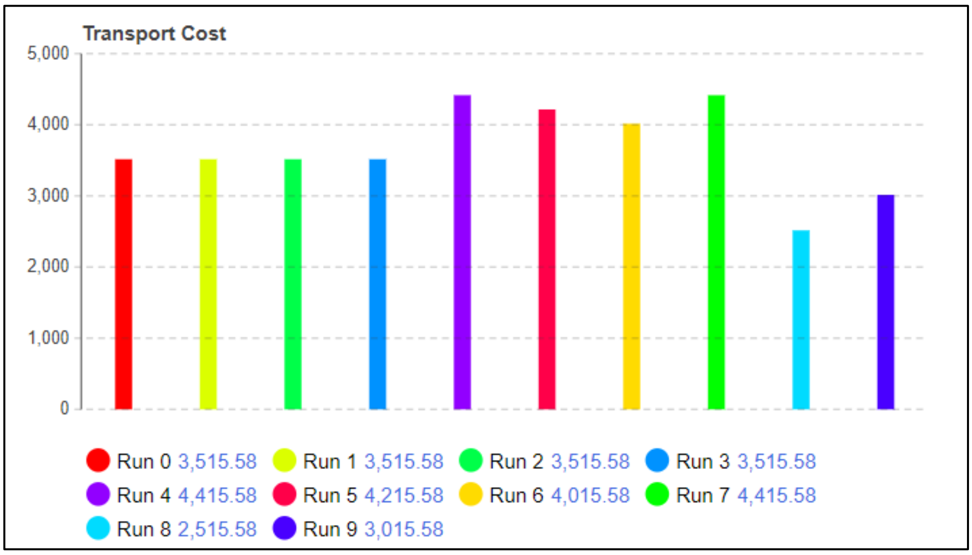

Figure D3: Optimisation Output for Prologis Hemel Hempstead (Transportation Costs formulated for different input values).

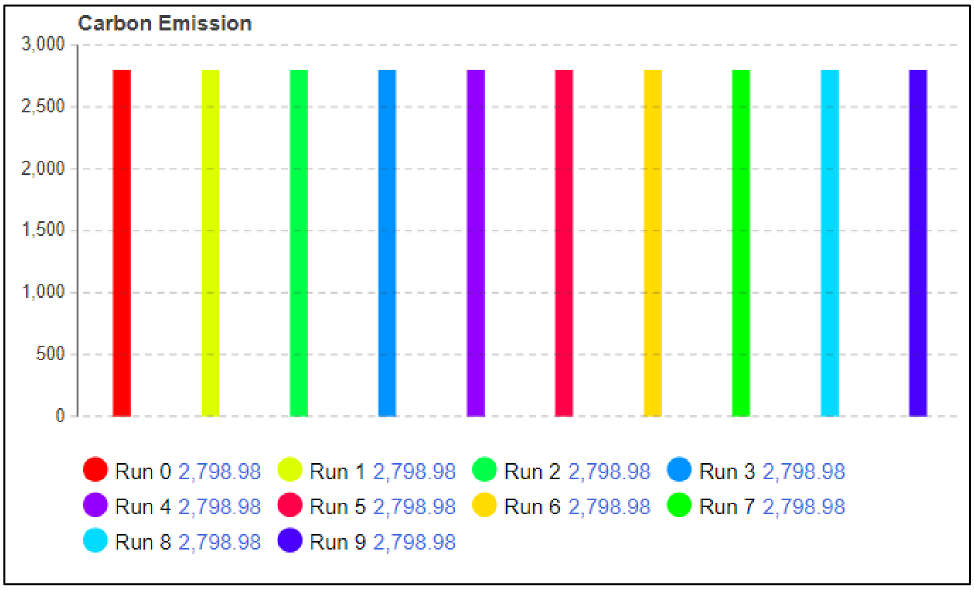

Figure D4: Optimisation Output for Prologis Hemel Hempstead (Carbon Emissions formulated for different input values).

<u>Bishop Square</u>

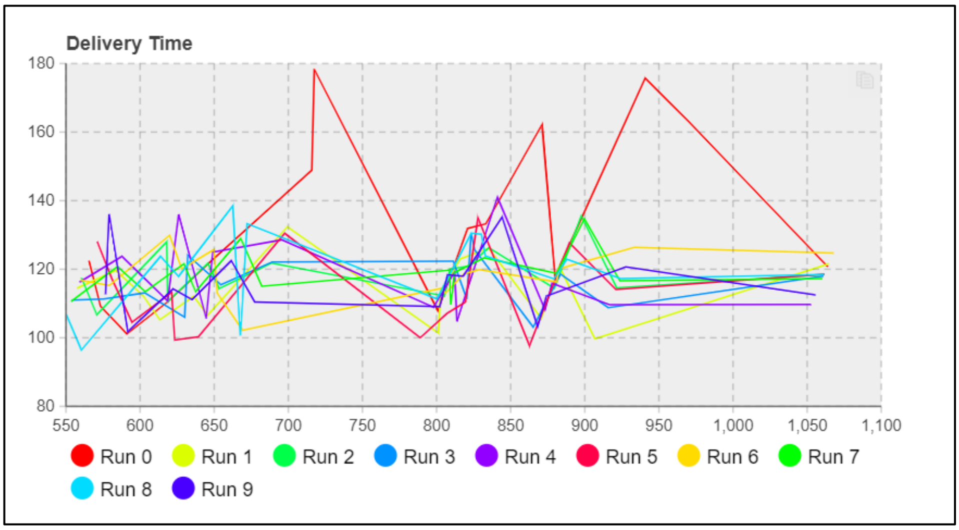

Figure D5: Optimisation Output for Bishop Square (Time Plots of Delivery Time for different input values).

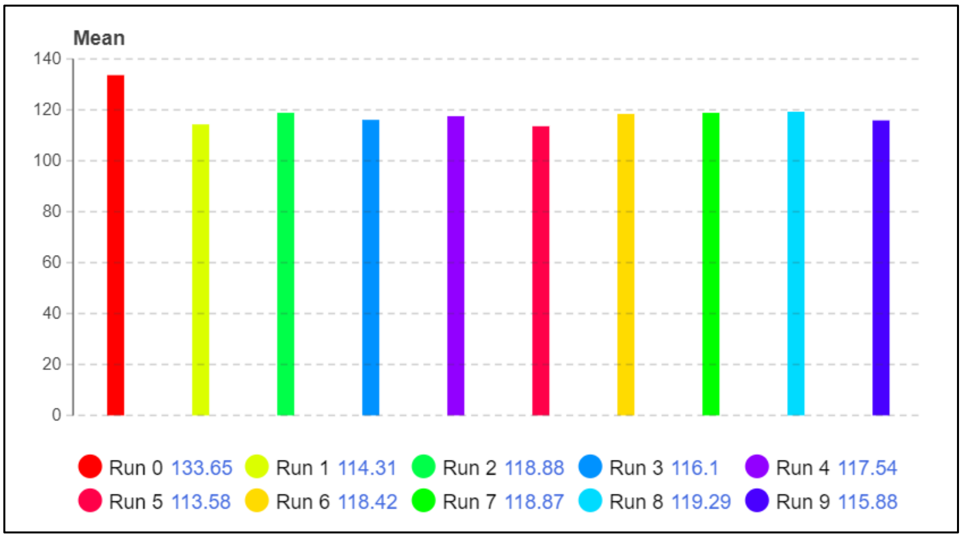

Figure D6: Optimisation Output for Bishop Square (Average Delivery Times formulated for different input values).

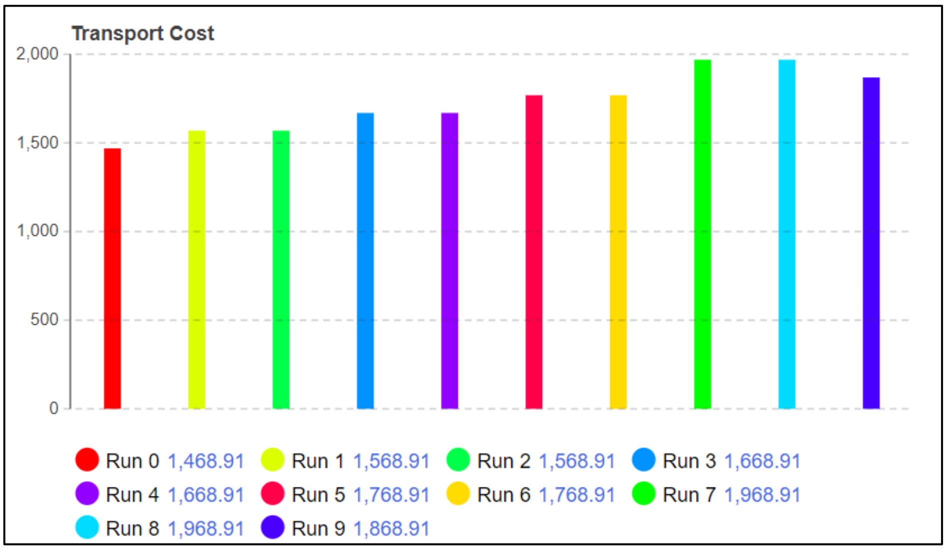

Figure D7: Optimisation Output for Bishop Square (Transportation Costs formulated for different input values).

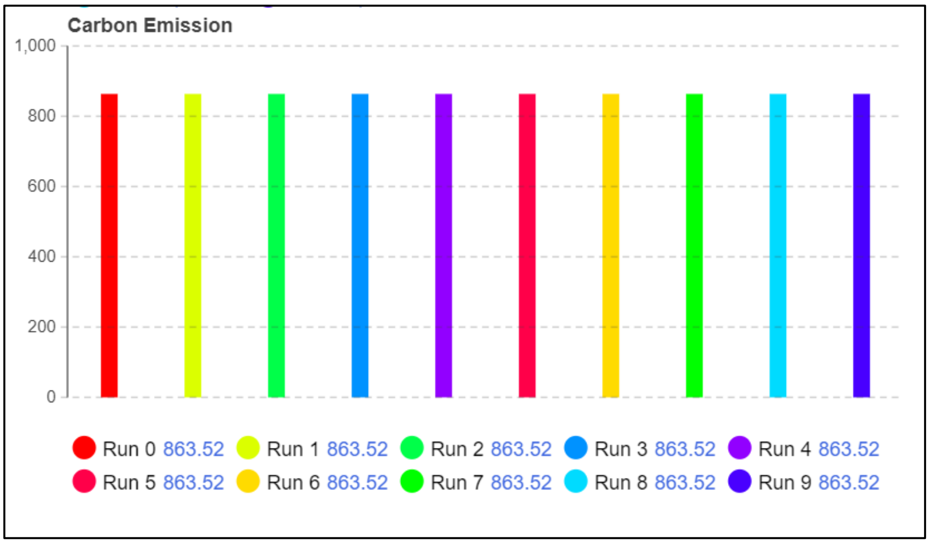

Figure D8: Optimisation Output for Bishop Square (Carbon Emissions formulated for different input values).

Appendix E: Sensitivity Analysis

Number of trucks

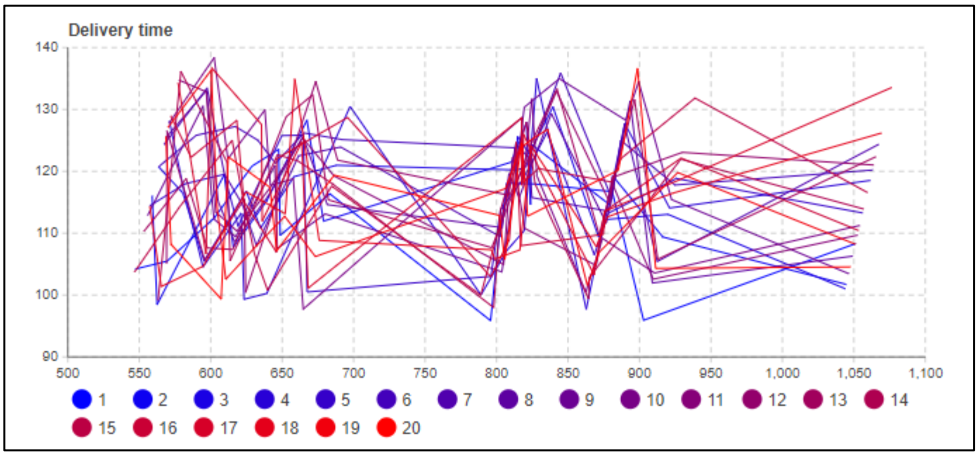

Figure E1: Time plot of sensitivity analysis results of number of trucks on delivery time.

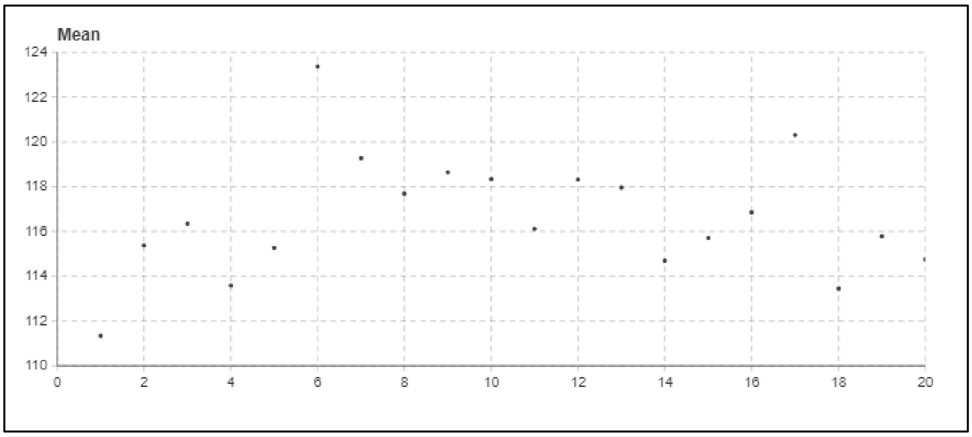

Figure E2: Sensitivity analysis results of number of trucks on average delivery wait time.

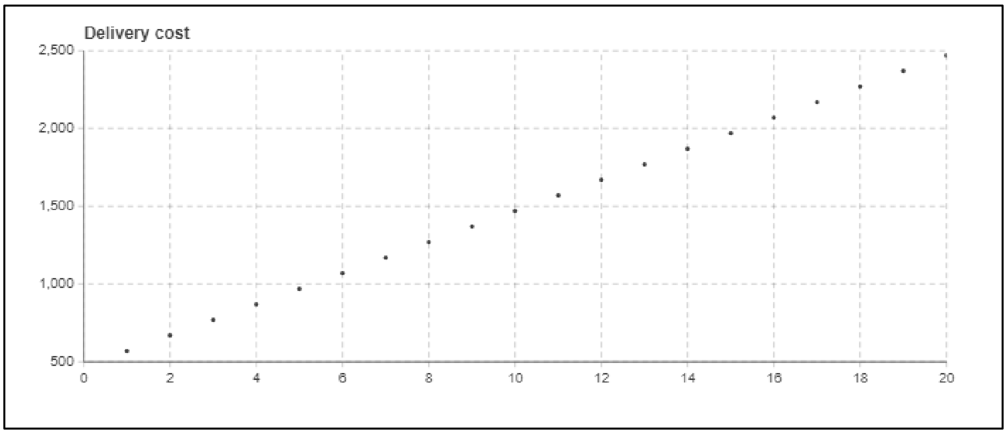

Figure E3: Sensitivity analysis results of number of trucks on delivery cost.

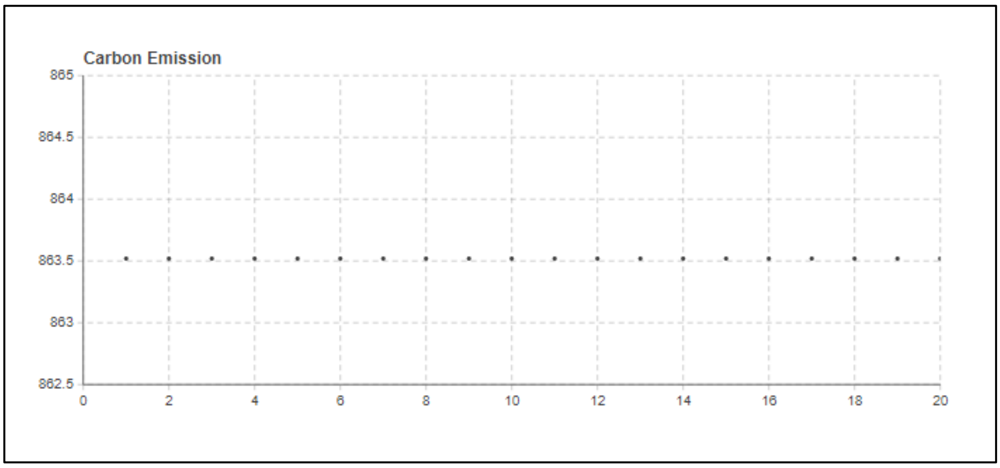

Figure E4: Sensitivity analysis results of number of trucks on carbon emission.

<u>Number of semi-trailers</u>

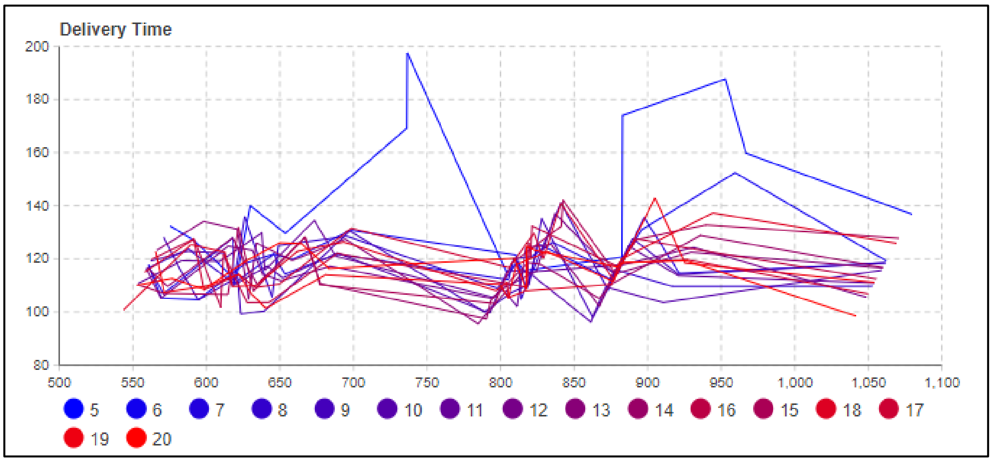

Figure E5: Time plot of sensitivity analysis results of number of semitrailers on delivery wait time.

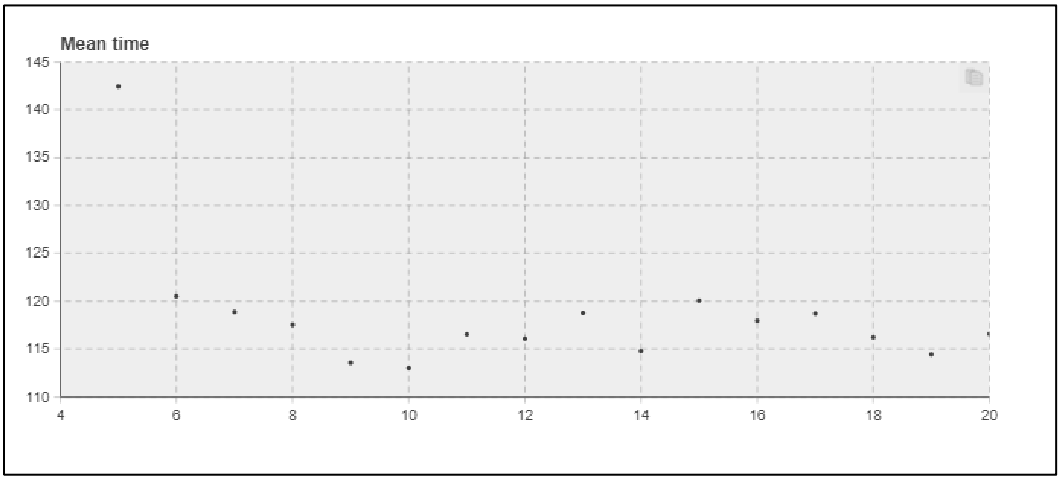

Figure E6: Sensitivity analysis results of number of semitrailers on average delivery wait time.

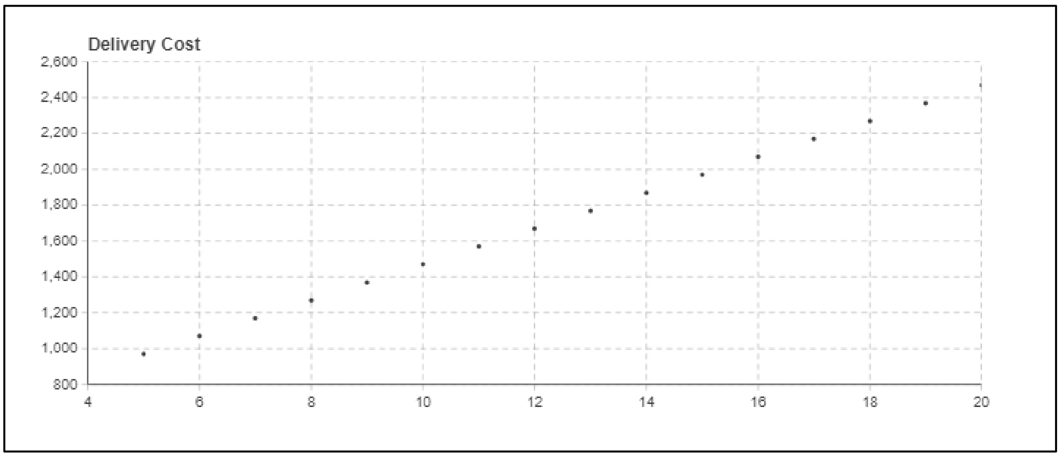

Figure E7: Sensitivity analysis results of number of semitrailers on delivery cost.

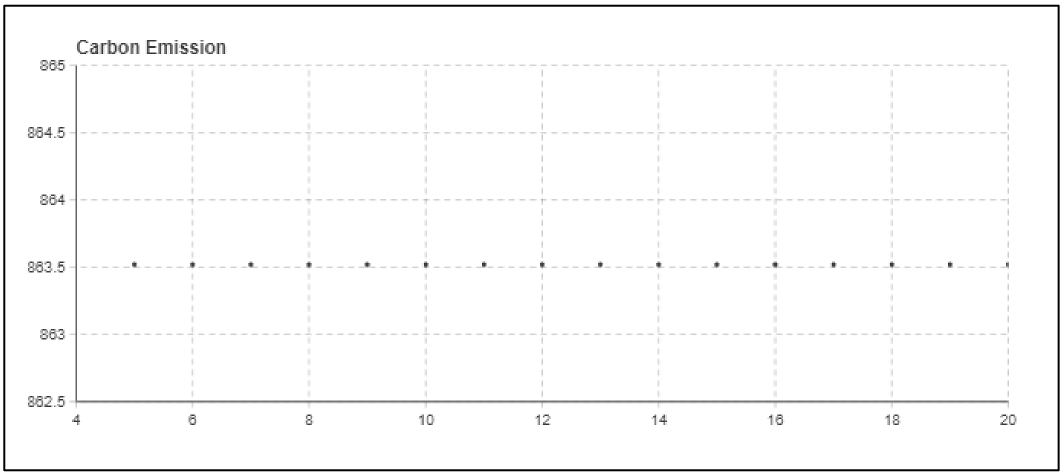

Figure E8: Sensitivity analysis results of number of semitrailers on carbon emission.

Fuel Price

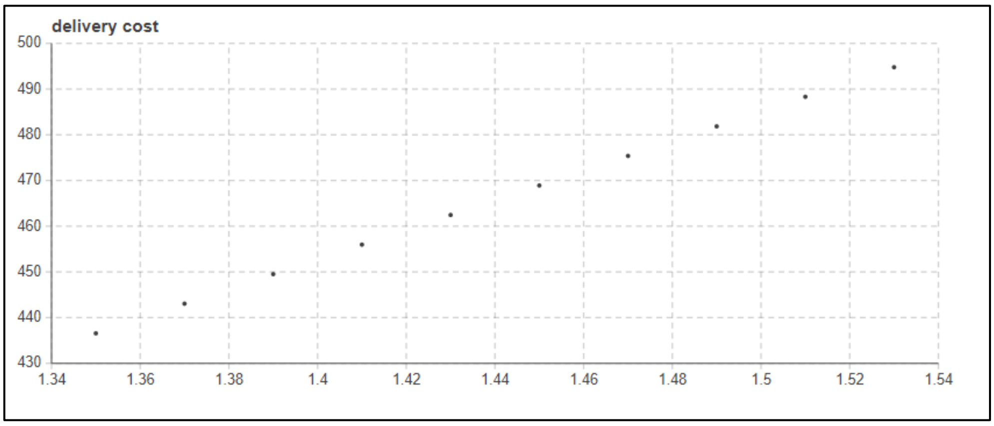

Figure E9: Sensitivity analysis results of fuel price on delivery cost.

Fuel Emission Factor

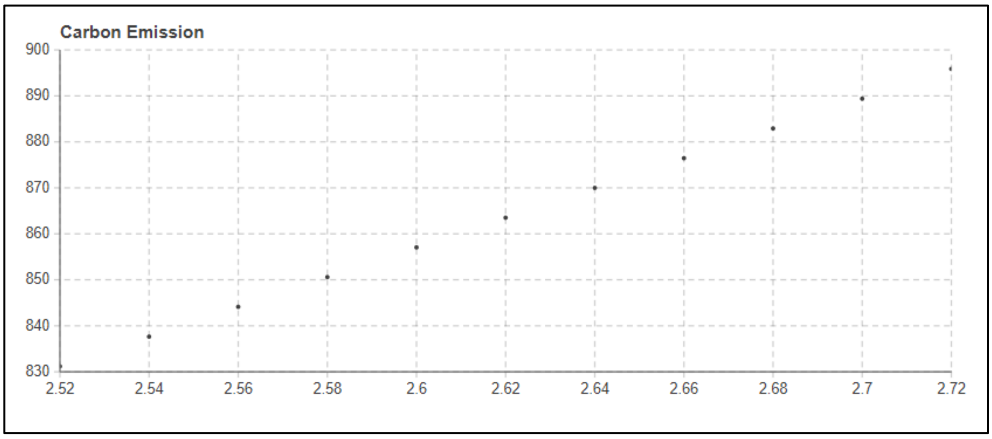

Figure E10: Sensitivity analysis results of fuel emission factor on carbon emission.

Fully Loaded Truck Fuel Consumption Rate

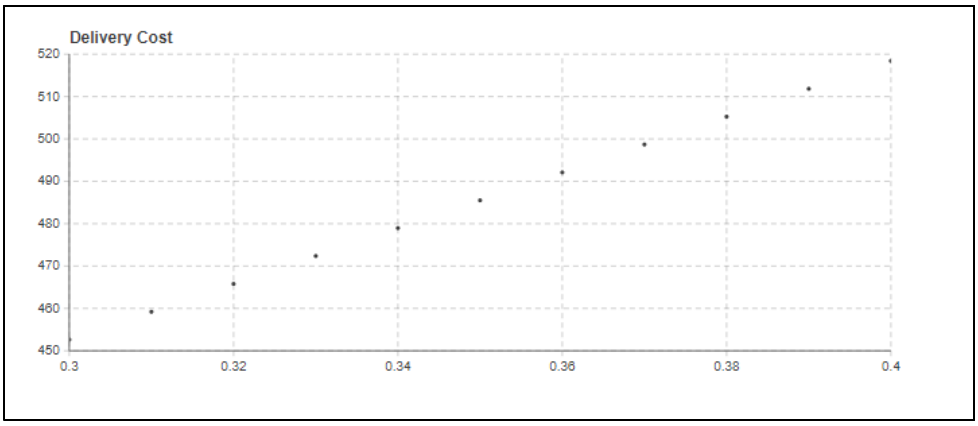

Figure E11: Sensitivity analysis results of fully loaded truck fuel consumption rate on delivery cost.

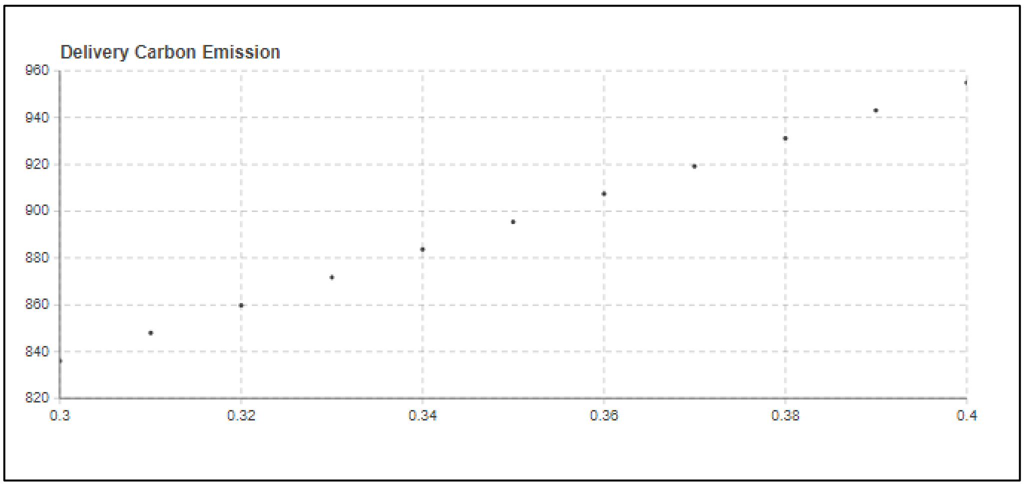

Figure E12: Sensitivity analysis results of fully loaded truck fuel consumption rate on carbon emission.

Fully Loaded Semitrailer Fuel Consumption Rate

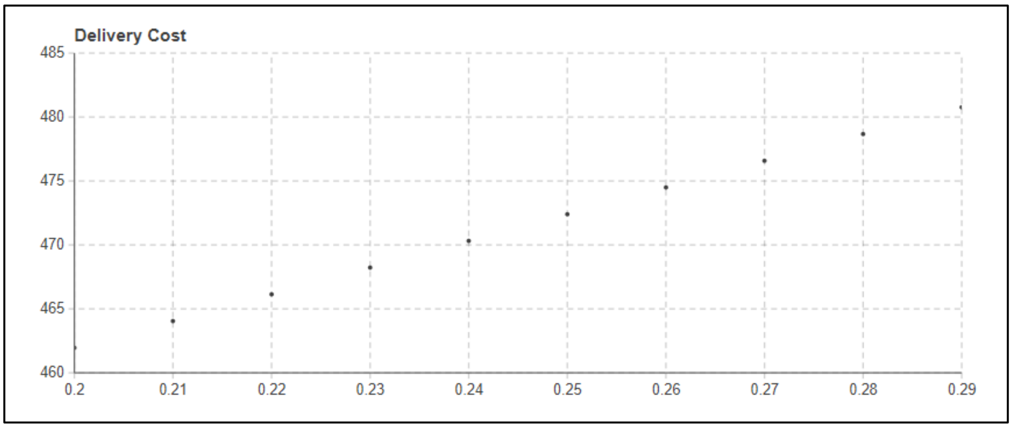

Figure E13: Sensitivity analysis results of fully loaded semitrailer fuel consumption rate on delivery cost.

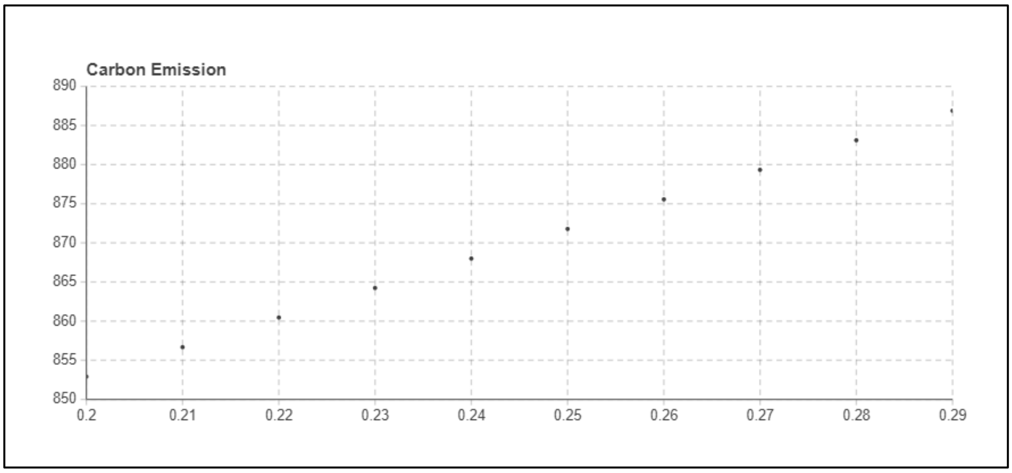

Figure E14: Sensitivity analysis results of fully loaded semitrailer fuel consumption rate on carbon emission.

Empty Truck Fuel Consumption Rate

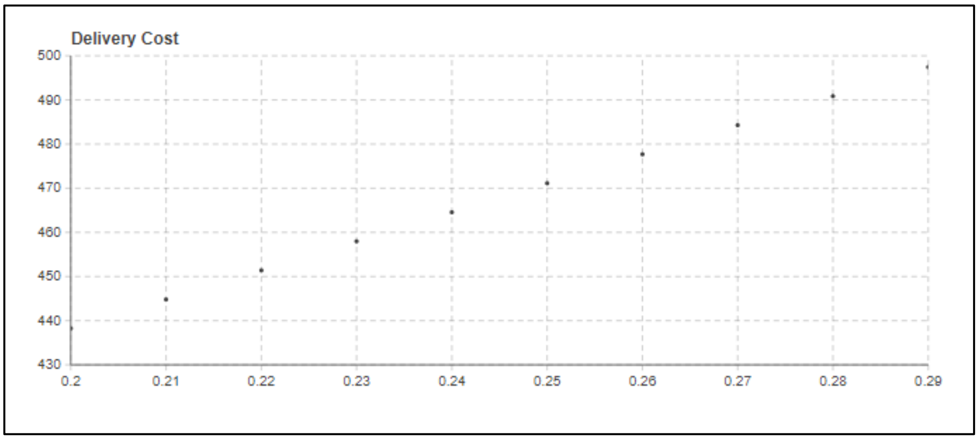

Figure E15: Sensitivity analysis results of empty truck fuel consumption rate on delivery cost.

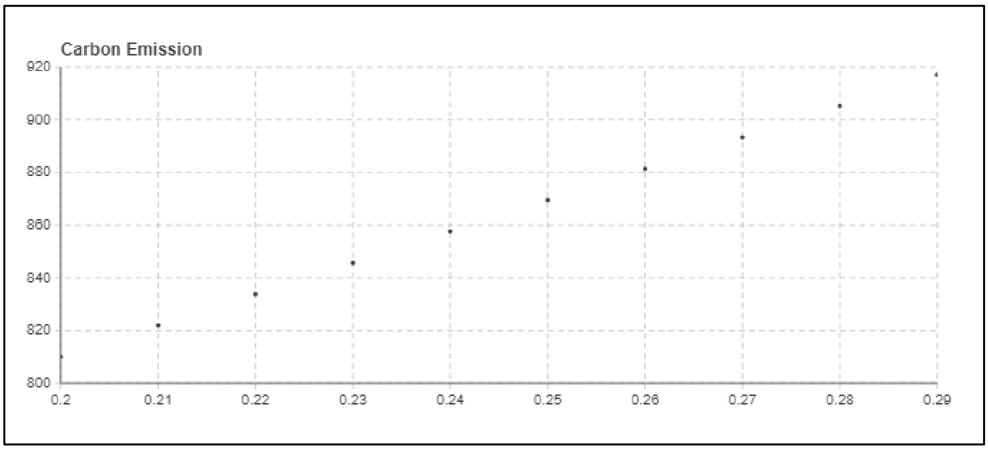

Figure E16: Sensitivity analysis results of empty truck fuel consumption rate on carbon emission.

Empty Semitrailer Fuel Consumption Rate

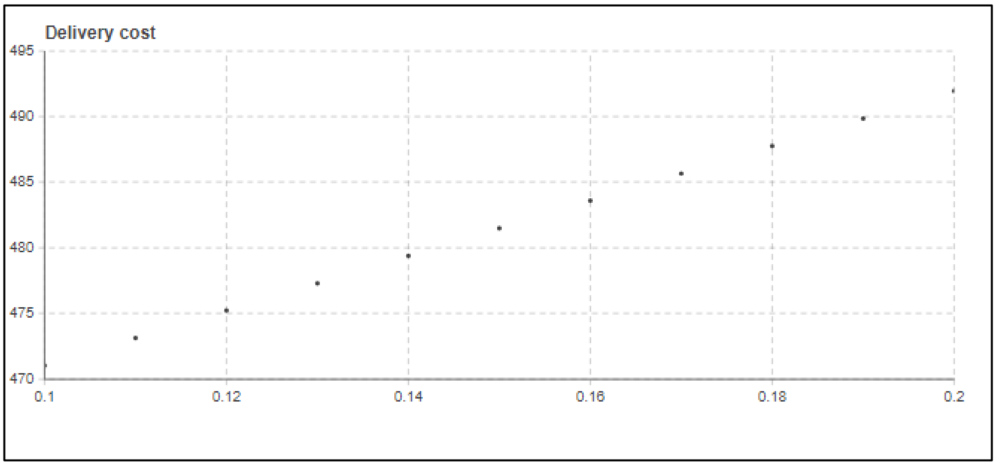

Figure E17: Sensitivity analysis results of empty semitrailer fuel consumption rate on delivery cost.

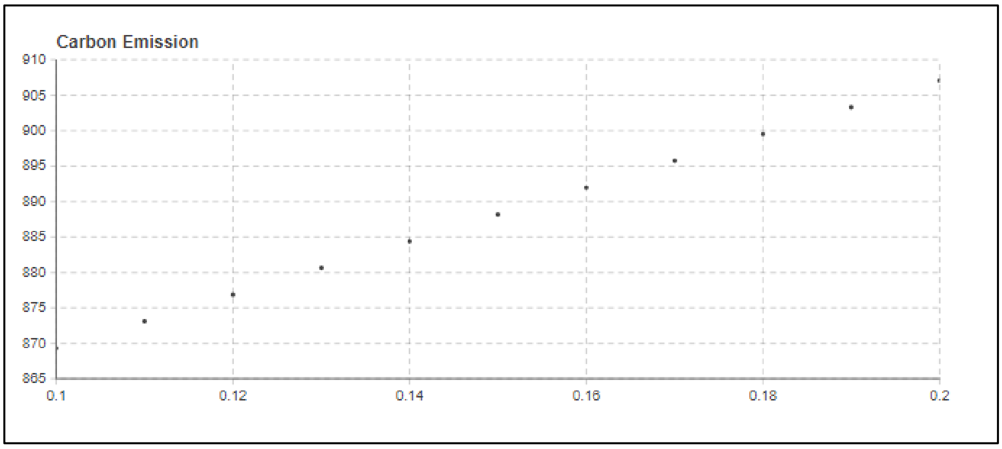

Figure E18: Sensitivity analysis results of empty semitrailer fuel consumption rate on carbon emission.