Conveyor Throughput Optimization at a Distribution Centre

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ABSTRACT

Conveyor Throughput Optimization at a Distribution Centre

Alexandru Vana

The conveyor system is one of the most popular material handling systems in production and warehouse facilities due to high throughput and safety. The throughput rate of such systems is an essential performance measure. The congestion of the conveyor is a significant problem and as such this issue requires serious attention. FedEx Supply Chain, the 3PL provider for the Canadian Tire distribution centre located at Coteau-du-Lac, Quebec faces productivity issues for their outbound operations during high volume periods. The distribution centre staff at the Company has developed, over the years, their own procedures to prevent bottlenecks at the conveyor. Nevertheless, it remains a challenge to implement different operational scenarios to optimize the throughput. Furthermore, there are a number of operational variabilities along the conveyor, whereas the outbound operations follow a schedule of picking cycles. Hence, a comprehensive simulation model is required to capture various variabilities, identify possible bottlenecks, and predict the effects on throughput of applying different levers. The findings obtained based on the experimentations are analyzed and managerial recommendations are provided. Finally, areas for future research are highlighted.

Keywords: warehouse, distribution centre, material handling, conveyor, clogging, simulation, experimentation

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This thesis is structured into six chapters. But there is one more behind it that relates to life. This chapter is called Epilogue and it concludes my Graduate Education book. As a novice researcher, I overcame many difficulties over the last three years, and this is what makes this achievement so special. The outcome is a consequence of multiple events and of the intervention of so many good people. I will not be able to name each one of you as you are so many but rest assured that you all have your place in my heart.

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This is for my kids: I hope to be able to make up to you for all this time being busy.

Not lastly to my wife, who never ceased to support, encourage, sacrifice, and amaze me.

In the end, it is all about the beginning: thank you mom and dad!

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Glossary

Accumulation time – period during which the wedge does not accept any items; expressed in minutes.

Combined labor utilization (CLU) – derived result based on picker utilization and loader utilization; expressed as a percentage.

Conveyor throughput – derived result based on estimated total time; represents the average number of items circulating in the system per hour.

Cycle – all the items to be picked, sorted and loaded in the trailers for specific stores according to the shipping schedule.

Cycle time – the period during which the items corresponding to one cycle are being processed; it does not include pre-picking time.

Doors clogged – number of shipping doors that get clogged during the simulation.

Estimated total time – time elapsed from the first picked item until the last loaded item; it includes pre-picking time and it is expressed in minutes.

Loader utilization – percentage of time during which the loaders are performing activities during cycle time.

Loaders – employees that load into trailers the items travelling on the conveyor.

Picker utilization – percentage of time during which the pickers are performing activities during cycle time.

Pickers – employees that execute the picking activities at picking modules.

Picking level – any one of the platforms of the picking modules.

Picking levels clogged – number of levels that get clogged during the simulation.

Picking module – racking system with multi-level platforms.

Pre-picking – picking activities related to a cycle that has not been activated yet, usually the consecutive cycle of the cycle currently active; considered to be a method to reduce pickers waiting time.

Sorters clogged – number of sorters that get clogged during the simulation.

Wedge speed – speed of each conveyor segment of the wedge; expressed in feet per minute (FPM).

Chapter 1: Introduction

Managers of warehouses or distribution centres (DCs) are constantly searching for means to streamline their operations. As their business evolves along various trends, flexibility is key, and decisions made in the design phase of a warehouse / DC project may need to be altered. Mathematical and computer models are important in the decision making process, as they support managers to reduce costs, increase space utilization and improve the throughput. When a business displays low variability, deterministic models may produce reliable results. However, highly probabilistic environments require stochastic models (Gong and De Koster, 2011).

Computer simulation serves as a powerful tool in the design phase of a warehouse. Through analysis of different scenarios, decision makers are able to select the one that best serves the company`s interest. For an already running warehouse, simulation allows the analysis of status-quo and to test a number of possible options without interfering in the activities (Sormaz et al., 2017).

This study was carried out at a distribution centre located at Coteau-du-Lac, Quebec. Being one of the three major Canadian Tire distribution centers, this facility was operated by Genco Distribution System since its opening in 2008. Currently it is managed by FedEx Supply Chain (the Company) after they acquired Genco in 2015.

As in any other warehouse management, the goal of FedEx warehouse managers is to continuously improve the responsiveness of their material handling systems in order to provide reliable and shorter delivery lead times. Typically, improved decisions related to order batching policy, picking policy, picking capacity and sorting capacity result in enhancing the customer order throughput times (Van Nieuwenhuyse and de Koster, 2009). However, due to capacitated throughput of the system, it has been observed that variability associated with order size, picking time, sorting time and setup times for picking or sorting a batch also affects the throughput time.

Operational variability is common in warehouse operations. In particular, the conveyor system, as a material transportation mechanism, displays variability at order picking, conveyor merging, sorting, packing and unloading. By transporting items between different warehouse areas and by consolidating the transportation lines into a single flow through multiple merges, the conveyor represents a critical part in any warehouse operations. The operational performance is influenced by the congestion at the merges and by the variability related to units that flow through the conveyor system, machine performance and operators (van der Gaast et al., 2018). Moreover, the order pickers may face long waiting times due to congestion at shipping doors.

Warehousing operations may be roughly split into inbound and outbound activities. This study focuses on a part of the outbound activities, more specifically on the conveyor system at FedEx DC at Coteau-du-Lac, Quebec. Fast moving conveyors are common in high throughput warehouses and manufacturing facilities. These are the backbone of internal material handling and movement. Significant improvement in overall efficiency has been observed, attributed to fast moving conveyors, in high volume and large square footage warehouses. However, clogging of any part of these systems may shutdown the overall system partially or completely with detrimental effects in overall efficiency. The Company observed that during peak periods of the year the conveyor operations are affected by clogging. Moreover, pickers and trailer loaders may encounter idle time because of conveyor clogging. Hence, this study focuses on avoiding or reducing the frequency of such disruptions at the Company.

This report is structured as follows. Chapter 2 reviews the existing literature on the analysis methods of conveyor systems. Chapter 3 describes the conveyor operations at the FedEx Supply

Chain facility and how input data was collected. Chapter 4 provides details on the simulation software used and on the simulation model developed. Chapter 5 presents and discusses the outcomes obtained by running 36 simulation experiments using real picking schedule data from FedEx. Statistical analyses were also conducted in Chapter 5. Finally, Chapter 6 summaries the managerial insights and the suggestions for future studies.

Chapter 2: Literature Review

Since the early days of industrialisation, companies benefited from disruptive innovations in their quest for improved productivity, as described by the theory of swift, even flow (Schmenner, 2015). Productivity is a function of technology used, capital equipment, quality of materials, quality of process, product design, efficient allocation/scheduling of resources, workforce education and training, worker effort and management itself. The theory of swift, even flow exposes the two essential factors to achieve gains in productivity: reduction of variation (of quality, quantities and timing) and increase in throughput.

Today's competitive world of business brings challenges for companies' operations as their business models must be able to incorporate multiple sources of uncertainty and variation. At the warehousing level of the operations Gong and de Koster (2011) classified the sources of uncertainty and variation as product arrival, order arrival, putaway, storage, order picking, packaging, accumulation, sortation and shipping.

This large array of uncertainty and variation sources raised the interest of scholars, turning their attention towards analytical stochastic models (Bartholdi et al., 2001; Bozer and White, 1990; Chew and Tang, 1999; de Koster, 1994), as analytical deterministic models were unable to incorporate the variation present in the systems (Karasawa et al., 1980; Ratliff and Rosenthal, 1983; Van den Berg et al., 1998).

Specifically for conveyor systems, deterministic models were used in the design phase (Bastani, 1988; Bastani and Elsayed, 1986; Kwo, 1958; Muth, 1977). As these models could not capture the effects of randomness at different stages of the conveyor operations, stochastic models were developed (Bozer and Hsieh, 2005; Coffman et al., 1988; Disney, 1962; Schmidt and Jackman, 2000; Sonderman, 1982; Zijm et al., 2000).

The study of conveyor congestion and blocking at merges is popular among researchers. In one of the first conveyor studies, Kwo (1958) provides primal knowledge of a basic deterministic closed-loop conveyor system with one input and one output stations. Disney (1962) models the conveyor as a queueing system with order entry. Sonderman (1982) extends Disney`s model to recirculating conveyors with stochastic inputs and outputs. Bastani and Elsayed (1986) measure the impact of different parameters on system performance in the design phase of closed-loop conveyors. Xue and Proth (1987) identify the non-blocking conditions of a steady closed-loop conveyor with recirculation and with one input and one output stations. Similarly, Bastani (1988) studies a closed-loop conveyor with one input and multiple output stations with deterministic parameters. The conveyor issues are analyzed by Bastani (1990), who provides a matrix-geometric analysis of a closed-loop conveyor using an M/M/S queueing system with one loading station and multiple unloading stations. The author also introduces variability in the model by assuming that the unloading stations were exposed to breakdowns and their respective repairs. Atmaca (1994) approaches a circular conveyor with limited capacity and introduced machine failure in the analysis. Coffman et al. (1988) study input and output dependencies for one processing station along a conveyor that serves multiple stations. The paper also discusses whether the loading and unloading of the conveyor should be performed either by one or two robots.

Schmidt and Jackman (2000) extended the research on closed-loop conveyor by modeling it as a network of queues. Their model allows the units to return on the conveyor after receiving service in order to transport these units to the unloading station. Bozer and Hsieh (2004) estimate the waiting times of the items reaching loading stations for discrete-space fixed-window close-loop conveyors. Later, Bozer and Hsieh (2005) analyze the conveyor performance in a similar setup. Hur and Nam (2006) analyse the performance of an Automatic Storage and Retrieval System (AS/RS) with single and dual command operation modes and stochastic arrival rates.

The impact of conveyor merges was studied by van der Gaast et al. (2018), who obtained an approximate throughput of a closed-loop sequential zone picking system by implementing an aggregation technique and matrix-geometric methods.

Our problem in context is very similar to the study by de Koster (1994), who used an approximation method to provide insight in the design phase of a pick-to-belt order picking in a parallel zone picking system. This method is based on Jackson network modeling and analysis. The conveyor system considered in de Koster's article consists of a central conveyor collecting from 13 picking stations and transporting the products to three packing stations. Our study builds on de Koster (1994) and introduces a higher level of complexity by considering variability in case size (some of them being even grouped in totes), different cycle volumes, inconsistencies in automated sorting, and variability in item picking and trailer loading duration. Our goal is to study and improve the complex outbound process at the FedEx facility at Coteau du Lac.

Analytical queueing models are seldom used because of the laborious modeling of the congestion propagation over the conveyor system. Therefore, most of these models assume infinite capacity queues (Osorio and Bierlaire, 2009) and are based on the Jackson network model (Jackson, 1957). Overall, simulation-based models represent the most popular approach among researchers to analyse finite capacity queueing networks (Osorio and Bierlaire, 2009).

Simulation is a powerful technique for the analysis of a system involving multiple sources of variability. The technique attracted the interest of numerous researchers due to its capacity to incorporate variability. As examples of simulation modelling in production and warehousing, simulation was used by Huang et al. (2003) to improve the factory level of productivity through the analysis of metrics like overall equipment effectiveness and overall throughput effectiveness. Babiceanu and Chen (2009) used simulation to study a holonic-based material handling system in manufacturing. Yan and Lee (2009) predicted through simulation the cost and the efficiency of AS/RS. Drießel and Monch (2012) studied through simulation the performance of a shifting bottleneck heuristic in a dynamic job shop environment that benefits from an automated material handling system. Kou et al. (2018) used simulation to compare parallel storage system to AS/RS.

Simulation modeling is fundamental for our research, as the problem on hand is more complex than most of similar problems reported in the literature. This is due to the combination of different sources of variability, a complex conveying system and a shipping schedule organized in cycles. Simulation would be able to handle multiple statistical distributions associated with these sources of variability. Although time consuming, the simulation approach has the potential of achieving a high level of output accuracy which in turn is dependent on the accuracy of the input data (Korporaal et al., 2000). Parameters, as the pick rate, may be better estimated through historical data analysis (Gong and de Koster, 2011). It should be noted that our findings in this study are driven by actual data collected in the Company during one of the peak periods of the year.

Chapter 3: Analysis of Current Warehouse Operations

Strategically positioned at Coteau-du-Lac, the FedEx DC serves 360 Canadian Tire stores located in Eastern Canada. Acknowledged as the largest distribution centre in Canada at its opening in 2008, the structure extends over a 1.5 million square feet and benefits of a conveyor system of 25 km in total length. Managing around 8,300 SKUs of general merchandise and tires and 64,000 SKUs of automotive hard parts, the overall throughput of the DC operations exceeds 50 million cubic feet per annum. During the peak period, the DC output volume exceeds 1.3 million cubic feet over a 6-day business week, specifically more than 0.5 million cubic feet through the conveying system over the same period. The remaining volume is being handled by other means due to the bulk nature of these SKUs.

Currently, the DC faces efficiency issues during the peak period due to flow interruptions over the conveying system. The Company identified bottlenecks at pick modules, merges, wedge and shipping lanes. In this study, simulation modeling is adopted to identify the blockings on the overall conveyor system and test different options that would ameliorate the throughput without interfering with the actual operations. The model simulates one picking cycle and uses real input data provided by the Company.

The order picking process in the Canadian Tire DC is a low-level picker-to-parts operation (Gong and de Koster, 2011), portrayed by the pickers that walk along the aisles to pick items. Picking time, likewise the trailer loading time, is not constant but is a function of picker's (or loader's) movements and fatigue and may be represented by exponential distribution as argued in de Koster (1994). Item characteristics do not influence these parameters, according to Company's previous studies.

The daily picking activities are organized in picking cycles, which consist of one picking wave for most of the items but can include up to 5 waves in certain cases. Wave picking has been described by Petersen (2000) as a picking policy that primarily satisfies the shipping schedule. Picking in multiple zones of the warehouse is executed continuously over waves that extent anywhere between 30 to 120 minutes. Picked items receive a barcode for sorting purposes and are transported on the conveyor to the sorter. A consequent wave picking can begin only when the pickers completed the current wave. However, as picking and sorting do not start and do not finish concomitantly, two consecutive cycles are expected to partially overlap. The workforce should be balanced in such a way to minimise the waiting time at picking and at trailer loading.

The three shifts operating the conveyor have developed their own individual preventive measures over the years for the situations considered as potential bottlenecks. Therefore, it is necessary to develop a tool to formally reveal and tackle the bottlenecks that may materialize, thus allowing the management to take formal, standardized appropriate corrective actions.

3.1 Description of Facility Layout

In general, the purpose of simulation modeling is twofold. First, it can be used in the design phase to predict the performance of a future setup under different scenarios. It may also serve as an analysis tool for improving an existing setup.

The purpose of our model is to identify conveyor bottlenecks for an existing system through approximation of the aggregate impact of the following variabilities: picking, items characteristics, conveyor merging, items routing, items diverting and trailer loading. The conveyor failure data are not formally recorded by the company as breakdowns rarely occur and they are promptly dealt with. Moreover, manual manipulation of the merges and transportation lanes by the conveyor system operator is not formally recorded by the Company and, hence, is not captured in our model.

The storage areas of this facility are organized in multiple level parallel pick modules and they can store bulk items or conveyable items. Therefore, the transportation of these items to the shipping docks is done either by the conveyor or by other specialized vehicles. Distinct sections of the DC are used for shipping and receiving operations.

The pick modules at FedEx DC are multi-level structures that incorporate carton and/or pallet storage systems. These modules are similar to the pick module in Figure 1 (*Pick Module Racking*, 2019).

Figure 1

Pick module example

The conveyor system collects cases and totes from 10 pick modules composed of a total of 34 levels. The conveyor operates inside each level and the cases are stored on both sides of the conveyor. These items are further consolidated on a single line through multiple merges and channelled to their sorters according to their designated store. Example of a merge is provided in Figure 2 (*Lineshaft Roller Conveyor Merges*, n.d.).

Figure 2

Conveyor merge example

There are four conveyor sorters that serve a total of 57 shipping docks. Multiple transportation lanes connect the storage areas to these shipping docks.

3.2 Description of Conveyor Activities

The overall picking operation in a day is executed in cycles. For the totes, each cycle may be further divided into 3 to 5 picking waves according to the number of stores allocated in that cycle, as picking is executed for 3 Canadian Tire stores at a time. For the cases, usually one wave per cycle is adequate. It is rare that, due to high volume, a case requires a second picking wave. This is generally solved through the allocation of a second picking location.

The feeder lanes, a part of the conveyor system, are used to transfer the cases and the totes picked from the pick modules. Through multiple merges, the collection lanes lead these items to a wedge, which consolidates them onto a single lane. After passing the cases and the totes through a very fast scan process, these items are diverted onto various transportation lanes leading to the four sorters. From the sorters, the cases and the totes are diverted onto the dock lanes according to their destination store. Items enter the recirculation lane at their sorter and can be diverted on the shipping lane corresponding to their allocated store if lane capacity is available. Otherwise, the item continues to recirculate. The process flow diagram for the conveyor operations is provided in Appendix A.

3.3 Data Collection and System Parameter Setting

According to the conveyor operations, we used the following input data for our simulation model: picking time, loading time and percentage of items recirculating at wedge. Historical data was made available by the Company related to picking and trailer loading during one of their peak periods of the year. The structure of the data did not allow it to be used as is. Therefore, the manipulation of data was necessary. Specifically, the picks or the loadings did not have an individual timestamp, but they were grouped in any number of activities between 1 and 300 for any one timestamp. Hence, we assumed an equal period of time for each one of the activities that have the same timestamp and we divided the time period between their timestamp and the precedent timestamp to the number of activities registered on their timestamp. The time parameters for picking and loading activities are provided in Table 1.

Table 1

Time parameters for picking and loading activities (in seconds)

Activity	Area	Min	Max	Mean	Standard deviation
Totes picking	151	6	525	153	132
	161	4	310	83	71
	211, 212, 213, 214, 251, 252	4	314	96	75
Items picking	131, 141	1	12	3	3
	151, 161	1	72	21	20
	211, 212, 213, 214, 251, 252	1	253	72	63
	153, 154, 253, 254	0	0	0	0
	the other 20 levels	1	70	19	17
Trailer loading	all doors	3	1680	14	40

The company also provided data related to the number of items recirculating at the wedge due to label read errors at the scanner and to the number of items that need verification by the operators due to their size. These data were used to obtain the percentages of such events and apply them accordingly in the model.

Real picking data were used for the experiments. Furthermore, real operations events and duration of real-life cycles were used to validate the behavior and outcome of the simulation model.

Chapter 4: Simulation Model

4.1 Simulation Software Used

Thanks to the advancements of information technology, on the market there are several simulation software packages with different features, capabilities and fees. Despite the fact that knowledge was readily available on the Arena software and that the FlexSim software was initially proposed by FedEx, the final choice was the Simcad Pro software, backed by a long-time license availability to FedEx and the support offered by the software developers CreateASoft. Although this software allows 3D development, due to the limitations of the computer used for this research, our simulation model was developed in 2D, nevertheless respecting the dimensions of real-life conveyor sections at the FedEx distribution centre. Simcad Pro uses a discrete event simulation engine and allows model interaction during execution of simulation. Around two months of self study and multiple meetings with CreateASoft representatives were necessary to learn the basic functionalities of the software and test the behavior of smaller sections of the conveyor system.

4.2 Simulation Model Development

Developing a realistic simulation model requires a thorough study of the system in question. In order to understand the problem and the technicalities of the conveyor operations, observations took place on numerous occasions and on multiple sections of the conveyor, such as the pick modules, the merges, the wedge, the sorters and the shipping doors. Due to the large size of the warehouse that covers 1.5 million square feet, we first analyzed the drawing of the integrated layout of the facility to better understand the overall operations. A couple of weeks were necessary to acquire a minimal understanding of the conveyor operations, with a total length of 25 km of conveyor system at the FedEx facility studied. Initially, smaller sections of the conveyor system were developed separately to observe whether these partial models were able to capture the real life behavior and carry out necessary adjustments. These smaller sections were later integrated in a single complete model. Aiming to achieve a high level of detail in our simulation model, we allocated close to six months for the full model development. The wedge section itself required about three months to model, as we could not access to any logic of the behavior of that section and we had to model based on our observations, which were then validated by the Company's management. As the simulation model developed over time, more observations took place at the conveyor sections that required implementation of specific logic in the model, such as the merges and the wedge. The existing logic at the merges, at the wedge and at the sorters were replicated in our simulation model as close as possible to the reality. All the conveyor segments in the simulation model developed use the lengths and the speeds of the actual conveyor system. After all the data and information required in the simulation model were collected, we adopted the following assumptions:

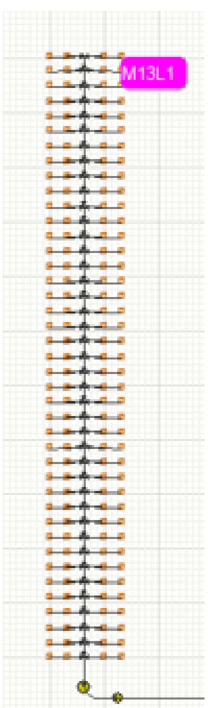
1. The path assignment probability at decision points throughout the conveyor is independent of the item characteristics.
2. The service time at the picking modules for cases is independent of the item characteristics and of the picker fatigue.
3. The service time at the picking modules for totes is independent of the totes content and of the picker fatigue.
4. The service time at the loading stations is independent of the item characteristics and of the loader fatigue.
5. Conveyor breakdowns occur rarely and have minimal impact on results.
6. There are no stock-outs in the picking area.

7. Walking time is captured in the picking/loading time.
8. There is only one picking wave per cycle.

In the simulation model, the items are created at the picking locations based on the cycle data provided by the Company. The data file that is used to create the items includes item size, picking location and shipping door. Each pick duration follows the distribution obtained through statistical data analysis presented in Table 1. In Figure 3, we present an example of such picking level that was introduced in our simulation model.

Figure 3

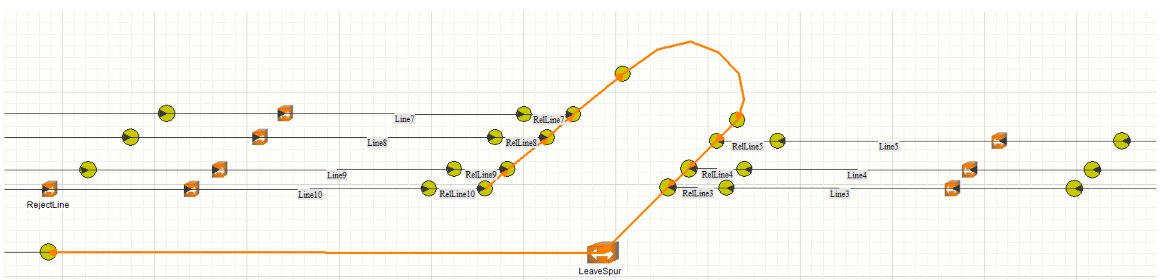
Simulation model – picking level sample (view from the top)



These items are conveyed on the transportation lanes and may pass through several merges before reaching the wedge, where they all consolidate on a single transportation line. The development of the wedge in our model was particularly challenging because of the complex logic present in that conveyor section. In Figure 4 we present the wedge section of our simulation model.

Figure 4

Simulation model – wedge section



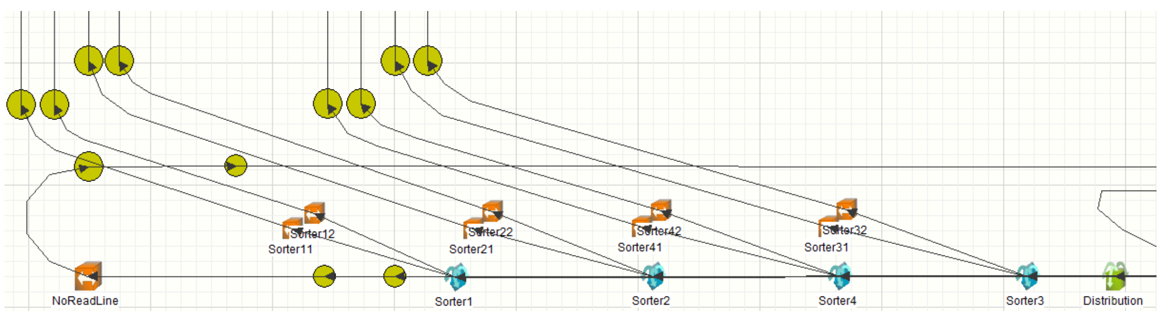
At the scanner node all the items are routed to the next destination according to the percentages calculated for labels read error and item size issues. Further, the items are routed towards the sorter that serves the shipping door that they are assigned to. The routing area is similar to Figure 5 (*What Is a Conveyor Belt?*, 2020). The routing area of our simulation model is represented in Figure 6. If any of the transportation lanes reach a full status in the routing area, no more items are allowed to enter the wedge. This behavior was implemented to simulate a manual wedge stop performed by the conveyor operator.

Figure 5

Routing area example

Figure 6

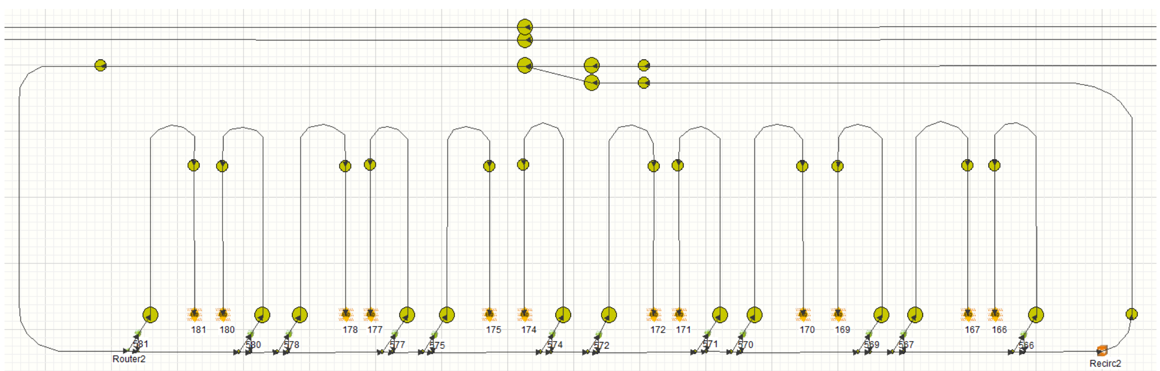
Simulation model - routing area



Reaching their sorter, the items join the recirculating line through a merge. From the recirculating line, the items may be diverted on their shipping line if line capacity is available, otherwise they will continue travelling on the recirculation line. One of the sorters with the respective shipping doors, as developed in our simulation model, is presented in Figure 7. If a recirculation line reached a full status, no more items are allowed to join the recirculation line. This behavior was implemented to simulate a manual stop of the induction section of the merge to the recirculation line.

Figure 7

Simulation model – sorter 2 with the respective shipping doors



At the end of the shipping line, the items exit the simulation. The duration of loading of the items into the trailers follows the distribution obtained through statistical data analysis presented in Table 1.

Our simulation does not require an initialization run as the picking is not continuous but is organized in waves, therefore there is no steady-state to be reached before simulating a cycle.

A sample of simulation software Simcad Pro coding is presented in Figure 8. A sample output is exhibited in Figure 9.

Figure 8

Sample of coding

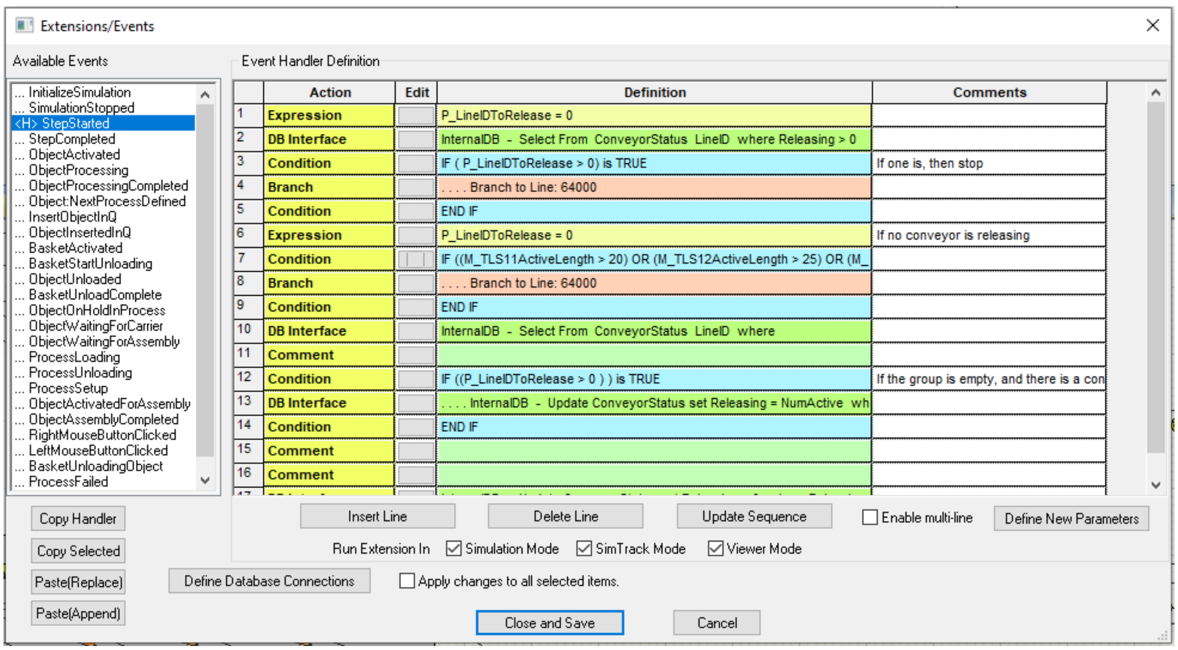
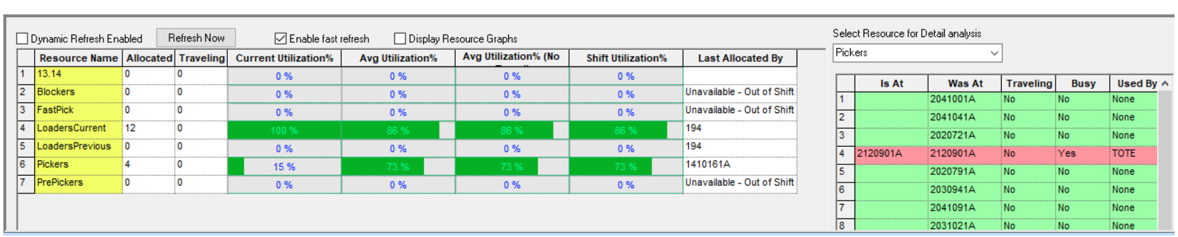


Figure 9

Sample of output



Chapter 5: Experimentation and Analysis of Findings

5.1 Features of Experimentation

The simulation model will replicate the picking of 248 totes and 5269 cases corresponding to the real picking schedule of November 10, 2020, a day in a pick period for the Company, processing orders for the Christmas season. As every two consecutive cycles overlap partially, the simulation extends from the moment the pickers start pre-picking of cycle 7 until the last object is loaded in its trailer and it includes the items of cycle 6 that were left to be picked when the pre-picking of cycle 7 started. For each experiment, we use the same picking schedule; specifically, for each item there is an assigned picking location and an assigned shipping door that do not change from one experiment to the other.

As the conveyor system is never empty when a cycle starts (except for the first cycle of the week), we adopted in the model the accumulation of items at the wedge in order to be able to replicate the pre-picking behaviour and to capture the effect of the items of cycle 6 already travelling to their shipping doors when the pre-picking starts. The accumulation period extends until cycle 7 is activated.

As described in Table 2, the experiments are based on four factors: i) number of pickers, ii) number of loaders, iii) wedge accumulation and iv) speed of wedge. The levels selected for these factors are considered to be the most representative. As the real life cycle that we adopted for our simulation used 26 pickers and 16 loaders, we wanted to observe also the impact of a lower or a higher amount of pickers and / or loaders. Therefore, the levels of these factors consider an approximate 25% decreased and an approximate 25% increased number of employees. Because the pre-picking period for this specific cycle extended over 60 minutes, we included a wedge accumulation period of 60 minutes. As we wanted to observe the impact of a shorter pre-picking period, we included another level of 30 minutes of wedge accumulation. The speed of the wedge can be set by the conveyor operator and has three levels: 400, 475 and 550 feet per minute. The highest speed is in general avoided because it generates jams, therefore we limited the experimentation to two levels: 400 and 475 feet per minute. The setting of each of the 36 experiments conducted is a unique combination of the levels of the four factors, as presented in Table 3.

Table 2

Experimentation factors and their levels

Factors	Levels
Number of pickers	20
	26
	32
Number of loaders	12
	16
	20
Wedge accumulation minutes	30
	60
Speed of wedge (FPM)	400
	475

Table 3

Experimentation setting

Parameters	Experiments																																			
	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	E16	E17	E18	E19	E20	E21	E22	E23	E24	E25	E26	E27	E28	E29	E30	E31	E32	E33	E34	E35	E36
20 pickers	x	x	x	x	x	x	x	x	x	x	x	x																								
26 pickers													x	x	x	x	x	x	x	x	x	x	x	x												
32 pickers																									x	x	x	x	x	x	x	x	x	x	x	x
12 loaders	x	x	x	x									x	x	x	x									x	x	x	x								
16 loaders					x	x	x	x									x	x	x	x									x	x	x	x				
20 loaders									x	x	x	x									x	x	x	x									x	x	x	x
30 minutes accumulation	x	x			x	x			x	x			x	x			x	x			x	x			x	x			x	x			x	x		
60 minutes accumulation			x	x			x	x			x	x			x	x			x	x			x	x			x	x			x	x			x	x
400 FPM wedge speed	x		x		x		x		x		x		x		x		x		x		x		x		x		x		x		x		x		x	
475 FPM wedge speed		x		x		x		x		x		x		x		x		x		x		x		x		x		x		x		x		x		x

While the number of pickers and loaders can be adjusted by the management as needed, the pre-picking depends on timeliness of bulk loading. In other words, if the loading of bulk items in their respective trailers has not finished, then pre-picking for the next cycle occurs, aiming to reduce the pickers waiting time. The speed of the wedge section of the conveyor can be adjusted by the conveyor operators and is measured in feet per minute (FPM). Experiment E20 is the replication of the actual conditions of cycle 7 of November 10, 2020 and it will be used as a baseline in our analysis.

As described in Table 4, the primary measures used in the simulation model are: i) picker utilization, ii) loader utilization, iii) estimated total time, iv) picking levels clogged, v) doors clogged and vi) sorters clogged. The picker utilization is measured from the start of simulation until last item picked, while the loader utilization is measured from the end of accumulation period until the end of simulation. The estimated total time represents the time elapsed from the first picked item until the last loaded item. Picking levels clogged is the number of picking levels where pickers cannot insert more items on the transportation lines due to the total number of items already circulating on these lines. Doors clogged is the number of shipping doors that cannot accept more items on their transportation lines due to the items already filling these lines. Sorters clogged represents the number of sorters that cannot accept more items due to the items already filling their respective recirculating lines and are a consequence of doors getting clogged. Some observations related to points of clogging for the 36 experiments conducted are presented in Appendix B.

Considering the targets set by the Company, we developed two secondary measurements: combined labor utilization (CLU) and conveyor throughput. Equations (1) and (2) provide the formulas for these measurements.

$$CLU = \frac{(number\ of\ pickers * picker\ utilization) + (number\ of\ loaders * loader\ utilization)}{number\ of\ pickers + number\ of\ loaders} \quad (1)$$

$$Conveyor\ Throughput = \frac{number\ of\ items\ picked}{estimated\ total\ time} \quad (2)$$

Table 4

Findings of the 36 experiments

Experiments	Parameters				Primary Measures						Derived Secondary Measures	
	pickers	loaders	acc_time	wedge_speed	picker_utilization	loader_utilization	estimated_total_time	picking_levels_clogged	doors_clogged	sorters_clogged	combined_utilization	conveyor_throughput
E01	20	12	30	400	73%	86%	158	2	4	1	78%	2095
E02	20	12	30	475	74%	85%	161	2	5	1	78%	2056
E03	20	12	60	400	64%	84%	192	12	5	3	72%	1724
E04	20	12	60	475	63%	85%	192	12	5	4	71%	1724
E05	20	16	30	400	74%	79%	136	2	1	0	76%	2434
E06	20	16	30	475	74%	79%	135	2	1	0	76%	2452
E07	20	16	60	400	56%	76%	170	12	2	0	65%	1947
E08	20	16	60	475	65%	76%	170	11	5	3	70%	1947
E09	20	20	30	400	73%	63%	133	2	1	0	68%	2489
E10	20	20	30	475	72%	63%	136	2	0	0	68%	2434
E11	20	20	60	400	55%	62%	167	11	1	0	59%	1982
E12	20	20	60	475	59%	72%	153	9	2	0	66%	2164
E13	26	12	30	400	62%	85%	157	5	5	3	69%	2108
E14	26	12	30	475	67%	84%	162	6	6	4	72%	2043
E15	26	12	60	400	43%	82%	196	12	4	3	55%	1689
E16	26	12	60	475	46%	85%	188	11	5	4	58%	1761
E17	26	16	30	400	62%	80%	134	5	3	0	69%	2470
E18	26	16	30	475	66%	77%	142	5	5	1	70%	2331
E19	26	16	60	400	43%	80%	164	14	3	0	57%	2018
E20	26	16	60	475	48%	77%	168	13	3	1	59%	1970
E21	26	20	30	400	58%	68%	127	5	1	0	62%	2606
E22	26	20	30	475	63%	72%	124	4	1	0	67%	2670
E23	26	20	60	400	41%	61%	169	12	1	0	50%	1959
E24	26	20	60	475	43%	66%	160	13	2	0	53%	2069
E25	32	12	30	400	46%	85%	161	9	5	4	57%	2056
E26	32	12	30	475	54%	85%	159	6	5	4	62%	2082
E27	32	12	60	400	38%	87%	188	12	5	4	51%	1761
E28	32	12	60	475	37%	86%	188	12	6	4	50%	1761
E29	32	16	30	400	48%	80%	133	7	2	0	59%	2489
E30	32	16	30	475	52%	77%	140	6	5	2	60%	2364
E31	32	16	60	400	37%	80%	164	15	4	1	51%	2018
E32	32	16	60	475	39%	79%	166	12	5	3	52%	1994
E33	32	20	30	400	48%	68%	128	9	1	0	56%	2586
E34	32	20	30	475	53%	73%	123	7	2	0	61%	2691
E35	32	20	60	400	36%	66%	159	14	2	0	48%	2082
E36	32	20	60	475	38%	70%	155	13	2	0	50%	2136

5.2 Various Simulation Issues

The Company provided feedback on the model behavior at various stages of the development. The final simulation model was validated by FedEx after the recommended adjustments were implemented and multiple tests on different picking schedules provided estimated total times similar to real-time operations.

The experiments were performed on an Intel(R) Core(TM) i5-8265U CPU @ 1.60Ghz with 8G of RAM. The time needed to perform any one of the 36 experiments on this computer extends between 125 and 237 minutes. Simcad Pro includes an integrated random number generator functionality and cannot be setup manually (Simulation Software | Simcad Pro, n.d.). Therefore, each replication of the same experimental setting provides slightly different outcomes.

5.3 Analysis of Findings

Since meeting shipping deadlines in warehouse operations is at utmost importance, the 'throughput' is considered to be a key performance indicator in zone picking systems operations (van der Gaast et al., 2018). As mechanical equipments are being used (conveyors and sorters), the throughput may be affected by the man-machine balance (Gong and de Koster, 2011).

5.3.1 Operational Recommendations Based on Simulation Findings.

While the combined labor utilization is a percentage based on the two types of resource utilization, the conveyor throughput represents the number of items circulating in the model per hour during the selected cycle. If the Company focus would be to reduce the clogging at all points, the most appropriate choice should be the experimental setting of E10, as the only clogging observed is at two picking levels. In this experiment there are 20 pickers and 20 loaders, while the accumulation at the wedge is 30 minutes and the wedge speed is of 475 FPM. When the primary objective is to improve labor (pickers and loaders) productivity, the Company should adopt the experimental setting of E02 with 78% combined utilization of resources. This experiment uses 20 pickers, 12 loaders, and 30 minutes accumulation at wedge, while the wedge speed is at 475 FPM. If the overall objective is to improve the conveyor throughput, the management should implement the experimental setting of E34 with a conveyor throughput of 2,691 items per hour. This experimental setting uses 32 pickers, 20 loaders, and a wedge speed of 475 FPM, while the accumulation period is 30 minutes.

Finally, in line with the goals set by the Company, the measures obtained for experiment E20 (the baseline) can be improved as follows:

- to reduce the flow interruptions by 50%; as the baseline outcome is of 13 picking levels clogged, 3 doors clogged and 1 sorter clogged, the selected experimental setting should have clogging at no more than 6 picking levels, 1 door and no sorter.
- to improve the pick modules / conveyable loaders combination productivity by 5%; as the baseline outcome is of 59% combined utilization, the selected experiment should have no less than 64% combined utilization.
- to improve the throughput cubage by 10%; as the baseline has a conveyor throughput of 1,970 items per hour, the selected experiment should have a conveyor throughput of no less then 2,167 items per hour (as we use the same picking schedule, the percentage of increasing the conveyor throughput expressed in items per hour is assumed to be equal with the percentage of increasing the conveyor throughput expressed in cubic feet).

We filtered the findings presented in Table 4 and identified five possible experimental settings that satisfy all the three objectives. These five experiments are listed in Table 5. We recommend using the experimental setting of E05 as it generates economies by using less electricity and providing less maintenance due to lower wedge speed and by using fewer human resources at the picking modules and at the shipping doors. It is not surprising to observe that each of these five experimental settings consider a wedge accumulation period of 30 minutes. Therefore, the Company should focus on improving the bulk trailer loading operations by implementing bulk pre-picking activities.

Table 5

Experimental settings that provide results in line with the company's goals

Experiments	Parameters				Primary Measures						Derived Secondary Measures	
	pickers	loaders	acc_time	wedge_speed	picker_utilization	loader_utilization	estimated_total_time	picking_levels_clogged	doors_clogged	sorters_clogged	combined_utilization	conveyor_throughput
E05	20	16	30	400	74%	79%	136	2	1	0	76%	2434
E06	20	16	30	475	74%	79%	135	2	1	0	76%	2452
E09	20	20	30	400	73%	63%	133	2	1	0	68%	2489
E10	20	20	30	475	72%	63%	136	2	0	0	68%	2434
E22	26	20	30	475	63%	72%	124	4	1	0	67%	2670

5.3.2 Comparisons of Experiments that Yield Similar Findings.

a) Similar picker utilization

Although it is expected that a higher number of pickers would decrease picker utilization, the interaction with a lower period of accumulation at the wedge provides the same picker utilization for experiments E04 and E22. When only the number of loaders is altered as in the case of experiments E01 and E09, the picker utilization is the same, which leads us to assume that the number of loaders does not influence picker utilization. More loaders in experiment E09 compared to experiment E01 provides less loader utilization, less estimated total time, less doors clogged and less sorters clogged. While experiments E27 and E36 consider the same number of pickers and same wedge accumulation period, the wedge speed is different, therefore we can assume that the wedge speed is not influencing the picker utilization.

b) Similar loader utilization

With only the number of loaders being the same while comparing experimental settings of E01 and E28, we can assume that only this factor is influencing the loaders utilization. Less wedge accumulation time for E01 provides less doors clogged and less sorters clogged. As E28 uses more pickers and longer accumulation period, its pickers utilization is lower, the estimated total time is longer and the picking levels clogging is higher.

When only the number of pickers changes between two experiments, as in E21 and E33, we can observe that the number of pickers has no effect on loader utilization. Experiments E07 and E08 yield the same loader utilization while the difference between the two experiments is the wedge speed. Therefore, we can infer that wedge speed has no influence on loader utilization. Moreover, experiments E18 and E20 use different accumulation speeds, which also shows no effect of wedge speed on loader utilization. As a general observation, any two experiments that have equal loader utilization are using the same number of loaders. The best example to support this is provided through experiments E02, E04, E13, E16, E25 and E26 that use 12 loaders each and yield an 85% loader utilization.

c) Similar estimated total time

When we compare experiments E03 and E04, the only difference being the wedge speed, we observe that the outcomes are similar for these experiments. Therefore, we can assume that the wedge speed does not influence the estimated total time. On the other hand, considering two experiments with only the number of pickers being different between these experiments, as in E19 and E31, although we may believe that a higher number of pickers would decrease the estimated total time, we observe that there is no effect of the number of pickers on estimated total time. As E19 is using a lower number of pickers, their utilization is higher and there is a slightly lower clogging level in the three categories comparing to E31. We can observe by comparing experiments E05 and E10 that a higher number of loaders does not reduce the estimated total time. This is due to the constraint of maximum two loaders per shipping door. Comparing experiments E26 and E35, we can see that while the number of pickers is the same in these two experiments, the advantage of a lower accumulation period in E26 is offset by the lower number of loaders compared to E35. In this context, E26 presents superior labor utilization. E35 presents a higher number of picking levels clogged due to higher accumulation period and a lower number of doors and sorters clogged due to higher number of loaders compared to E26.

5.3.3 Statistical Analyses

A factorial ANOVA was conducted using JASP 0.14.1 to compare the main effects of number of pickers, number of loaders, period of accumulation at the wedge and speed of the wedge and their interactions effect on the picker utilization, loader utilization and estimated total time. A multinomial logistic regression was conducted using IBM SPSS Statistics 25 to compare the main effects of number of pickers, number of loaders, period of accumulation and speed of the wedge and their interactions effect on number of picking levels clogged, number of shipping doors clogged and number of sorters clogged.

5.3.3.1 Factorial ANOVA

A four-way analysis of variance was conducted on the influence of the four independent variables (number of pickers, number of loaders, period of accumulation at the wedge and speed of the wedge) on each of three primary dependent variables (picker utilization, loader utilization and estimated total time). The number of pickers included three levels (20, 26, 32), the number of loaders consisted of three levels (12, 16, 20), the period of accumulation at the wedge included two levels (30 minutes, 60 minutes) and the speed of the wedge consisted of two levels (400 FPM, 475 FPM). We used a level of significance of 0.05 for the evaluation of the statistical relationships.

i. Analysis of effects on picker utilization

The four-way interaction effect on picker utilization could not be computed due to the low number of experiments, as indicated by the following note.

> The following problem(s) occurred while running the analysis:
>
> - Number of observations is < 2 in picker_utilization after grouping on pickers, loaders, acc_time, wedge_speed

The three-way interaction between number of pickers, number of loaders and accumulation time could not be computed due to the variance in picker utilization becoming zero, as indicated by the following note.

> The following problem(s) occurred while running the analysis:
>
> - The variance in picker_utilization is equal to 0 after grouping on pickers, loaders, acc_time

After removing the problematic interactions, we obtained the ANOVA table presented in Table 6.

Table 6

ANOVA table on picker utilization

ANOVA - picker_utilization ▼

Cases	Sum of Squares	df	Mean Square	F	p
pickers	0.3201	2	0.1600	636.6409	< .001
loaders	0.0039	2	0.0020	7.8343	0.0131
acc_time	0.1995	1	0.1995	793.6354	< .001
wedge_speed	0.0087	1	0.0087	34.6519	< .001
pickers ✻ loaders	0.0020	4	0.0005	2.0331	0.1824
pickers ✻ acc_time	0.0076	2	0.0038	15.1602	0.0019
pickers ✻ wedge_speed	0.0006	2	0.0003	1.2376	0.3402
loaders ✻ acc_time	0.0004	2	0.0002	0.8729	0.4540
loaders ✻ wedge_speed	0.0004	2	0.0002	0.7403	0.5070
acc_time ✻ wedge_speed	0.0001	1	0.0001	0.3978	0.5458
pickers ✻ loaders ✻ wedge_speed	0.0007	4	0.0002	0.7403	0.5903
pickers ✻ acc_time ✻ wedge_speed	0.0029	2	0.0014	5.7017	0.0289
loaders ✻ acc_time ✻ wedge_speed	0.0018	2	0.0009	3.6796	0.0736
Residuals	0.0020	8	0.0003		

Note. Type III Sum of Squares

The main effect for number of pickers yielded an F ratio of $F(2, 8) = 636.6$, $p < .001$, indicating a significant effect for the levels of this independent variable.

The main effect for number of loaders yielded an F ratio of $F(2, 8) = 7.8$, $p = .0131$, indicating a significant effect for the levels of this independent variable.

The main effect for period of accumulation yielded an F ratio of $F(1, 8) = 793.6$, $p < .001$, indicating a significant effect for the levels of this independent variable.

The main effect for the speed of the wedge yielded an F ratio of $F(1, 8) = 34.6$, $p < .001$, indicating a significant effect for the levels of this independent variable.

The interaction effect of number of pickers and number of loaders is not significant, as $F(4, 8) = 2.0$, $p > .05$.

The interaction effect of number of pickers and accumulation time is significant, as $F(2, 8) = 15.2$, $p = .0019$.

The interaction effect of number of pickers and wedge speed is not significant, as $F(2, 8) = 1.2$, $p > .05$.

The interaction effect of number of loaders and accumulation time is not significant, as $F(2, 8) = 0.9$, $p > .05$.

The interaction effect of number of loaders and wedge speed is not significant, as $F(2, 8) = 0.7$, $p > .05$.

The interaction effect of accumulation time and wedge speed is not significant, as $F(1, 8) = 0.4$, $p > .05$.

The interaction effect of number of pickers, number of loaders and wedge speed is not significant, as $F(4, 8) = 0.7$, $p > .05$.

The interaction effect of number of pickers, accumulation time and wedge speed is significant, as $F(2, 8) = 5.7$, $p = .0289$.

The interaction effect of number of loaders, accumulation time and wedge speed is not significant, as $F(2, 8) = 3.7$, $p > .05$.

ii. Analysis of effects on loader utilization

The four-way interaction effect on loader utilization could not be computed due to the low number of experiments, as indicated by the following note.

> The following problem(s) occurred while running the analysis:
>
> - Number of observations is < 2 in loader_utilization after grouping on pickers, loaders, acc_time, wedge_speed

The three-way interaction between number of pickers, number of loaders and wedge speed could not be computed due to the variance in loader utilization becoming zero, as indicated by the following note.

The following problem(s) occurred while running the analysis:

- The variance in loader_utilization is equal to 0 after grouping on pickers, loaders, wedge_speed

The three-way interaction between number of pickers, number of loaders and accumulation time could not be computed due to the variance in loader utilization becoming zero, as indicated by the following note.

The following problem(s) occurred while running the analysis:

- The variance in loader_utilization is equal to 0 after grouping on pickers, loaders, acc_time

After removing the problematic interactions, we obtained the ANOVA table presented in Table 7.

Table 7

ANOVA table on loader utilization

ANOVA - loader_utilization ▼

Cases	Sum of Squares	df	Mean Square	F	p
pickers	0.0030	2	0.0015	2.3903	0.1337
loaders	0.1971	2	0.0986	156.1893	< .001
acc_time	0.0006	1	0.0006	0.9905	0.3393
wedge_speed	0.0010	1	0.0010	1.5891	0.2314
pickers ∗ loaders	0.0017	4	0.0004	0.6801	0.6189
pickers ∗ acc_time	0.0012	2	0.0006	0.9905	0.3998
pickers ∗ wedge_speed	0.0002	2	8.6111e −5	0.1365	0.8738
loaders ∗ acc_time	0.0003	2	0.0002	0.2773	0.7625
loaders ∗ wedge_speed	0.0064	2	0.0032	5.0492	0.0256
acc_time ∗ wedge_speed	0.0008	1	0.0008	1.2722	0.2814
pickers ∗ acc_time ∗ wedge_speed	0.0006	2	0.0003	0.4798	0.6303
loaders ∗ acc_time ∗ wedge_speed	0.0003	2	0.0001	0.2157	0.8090
Residuals	0.0076	12	0.0006		

Note. Type III Sum of Squares

The main effect for number of pickers yielded an F ratio of $F(2, 12) = 2.4$, $p > .05$, indicating that the effect for this variable was not significant at different levels.

The main effect for number of loaders yielded an F ratio of $F(2, 12) = 156.2$, $p < .001$, indicating a significant effect for the levels of this independent variable.

The main effect for period of accumulation yielded an F ratio of $F(1, 12) = 1.0$, $p > .05$, indicating that the effect for this variable was not significant at different levels.

The main effect for the speed of the wedge yielded an F ratio of $F(1, 12) = 1.6$, $p > .05$, indicating that the effect for this variable was not significant at different levels.

The interaction effect of number of pickers and number of loaders is not significant, as $F(4, 12) = 0.7$, $p > .05$.

The interaction effect of number of pickers and accumulation time is not significant, as $F(2, 12) = 1.0$, $p > .05$.

The interaction effect of number of pickers and wedge speed is not significant, as $F(2, 12) = 0.1$, $p > .05$.

The interaction effect of number of loaders and accumulation time is not significant, as $F(2, 12) = 0.3$, $p > .05$.

The interaction effect of number of loaders and wedge speed is significant, as $F(2, 12) = 5.0$, $p = .0256$.

The interaction effect of accumulation time and wedge speed is not significant, as $F(1, 12) = 1.3$, $p > .05$.

The interaction effect of number of pickers, accumulation time and wedge speed is not significant, as $F(2, 12) = 0.5$, $p > .05$.

The interaction effect of number of loaders, accumulation time and wedge speed is not significant, as $F(2, 12) = 0.2$, $p > .05$.

iii. Analysis of effects on estimated total time

The four-way interaction effect on estimated total time could not be computed due to the low number of experiments, as indicated by the following note.

> The following problem(s) occurred while running the analysis:
>
> - Number of observations is < 2 in estimated_time after grouping on pickers, loaders, acc_time, wedge_speed

The three-way interaction between number of pickers, number of loaders and wedge speed could not be computed due to the variance in estimated total time becoming zero, as indicated by the following note.

> The following problem(s) occurred while running the analysis:
>
> - The variance in estimated_total_time is equal to 0 after grouping on pickers, loaders, acc_time

After removing the problematic interactions, we obtained the ANOVA table presented in Table 8.

Table 8

ANOVA table on estimated total time

ANOVA - estimated_total_time ▼

Cases	Sum of Squares	df	Mean Square	F	p
pickers	66.5000	2	33.2500	1.6264	0.2555
loaders	6154.6667	2	3077.3333	150.5217	< .001
acc_time	8711.1111	1	8711.1111	426.0870	< .001
wedge_speed	5.4444	1	5.4444	0.2663	0.6198
pickers ✻ loaders	23.3333	4	5.8333	0.2853	0.8795
pickers ✻ acc_time	22.3889	2	11.1944	0.5476	0.5986
pickers ✻ wedge_speed	2.3889	2	1.1944	0.0584	0.9436
loaders ✻ acc_time	4.2222	2	2.1111	0.1033	0.9031
loaders ✻ wedge_speed	113.5556	2	56.7778	2.7772	0.1214
acc_time ✻ wedge_speed	53.7778	1	53.7778	2.6304	0.1435
pickers ✻ loaders ✻ wedge_speed	27.1111	4	6.7778	0.3315	0.8494
pickers ✻ acc_time ✻ wedge_speed	20.7222	2	10.3611	0.5068	0.6205
loaders ✻ acc_time ✻ wedge_speed	8.2222	2	4.1111	0.2011	0.8219
Residuals	163.5556	8	20.4444		

Note. Type III Sum of Squares

The main effect for number of pickers yielded an F ratio of $F(2, 8) = 1.6$, $p > .05$, indicating that the effect for this variable was not significant at different levels.

The main effect for number of loaders yielded an F ratio of $F(2, 8) = 150.5$, $p < .001$, indicating a significant effect for the levels of this independent variable.

The main effect for period of accumulation yielded an F ratio of $F(1, 8) = 426.1$, $p < .001$, indicating a significant effect for the levels of this independent variable.

The main effect for the speed of the wedge yielded an F ratio of $F(1, 8) = 0.3$, $p > .05$, indicating that the effect for this variable was not significant at different levels.

The interaction effect of number of pickers and number of loaders is not significant, as $F(4, 8) = 0.3$, $p > .05$.

The interaction effect of number of pickers and accumulation time is not significant, as $F(2, 8) = 0.5$, $p > .05$.

The interaction effect of number of pickers and wedge speed is not significant, as $F(2, 8) = 0.1$, $p > .05$.

The interaction effect of number of loaders and accumulation time is not significant, as $F(2, 8) = 0.1$, $p > .05$.

The interaction effect of number of loaders and wedge speed is not significant, as $F(2, 8) = 2.8$, $p > .05$.

The interaction effect of accumulation time and wedge speed is not significant, as $F(1, 8) = 2.6$, $p > .05$.

The interaction effect of number of pickers, number of loaders and wedge speed is not significant, as $F(4, 8) = 0.3$, $p > .05$.

The interaction effect of number of pickers, accumulation time and wedge speed is not significant, as $F(2, 8) = 0.5$, $p > .05$.

The interaction effect of number of loaders, accumulation time and wedge speed is not significant, as $F(2, 8) = 0.2$, $p > .05$.

5.3.3.2 Multinomial Logistic Regression

A multinomial logistic regression was conducted on the influence of the four independent variables (number of pickers, number of loaders, period of accumulation at the wedge and speed of the wedge) on each of three primary dependent variables (number of picking levels clogged, number of shipping doors clogged and number of sorters clogged). The number of pickers included three levels (20, 26, 32), the number of loaders consisted of three levels (12, 16, 20), the period of accumulation at the wedge included two levels (30 minutes, 60 minutes) and the speed of the wedge consisted of two levels (400 FPM, 475 FPM). We used a level of significance of 0.05 for the evaluation of the statistical relationships.

i. Analysis of effects on number of picking levels clogged

The picking levels clogged dependent variable outcomes were grouped into three levels: low (for 2 to 6 picking levels clogged), moderate (for 7 to 11 picking levels clogged), and high (for 12 to 15 picking levels clogged).

We can observe in Table 9 the proportion of experiments falling in each level of the dependent variable (picking levels clogged). The model fitting information in Table 10 indicates a significant improvement in fit of the final model over the null model for Chi-Square = 65.6 at $p < .001$.

Table 9

Case processing summary for picking levels clogged dependent variable

Case Processing Summary

		N	Marginal Percentage
Picking levels clogged	Low (2-6)	14	38.9%
	Moderate (7-11)	8	22.2%
	High (12-15)	14	38.9%
Valid		36	100.0%
Missing		0	
Total		36	
Subpopulation		36[a]	

a. The dependent variable has only one value observed in 36 (100.0%) subpopulations.

Table 10

Model fitting information for picking levels clogged dependent variable

Model Fitting Information

	Model Fitting Criteria			Likelihood Ratio Tests		
Model	AIC	BIC	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	80.955	84.122	76.955			
Final	31.388	47.224	11.388	65.567	8	.000

The likelihood ratio tests in Table 11 show that there is a statistically significant relationship between the dependent variable and the independent variable ‘pickers’ ($p < .001$), the independent variable ‘accumulation time’ ($p < .001$) and the independent variable ‘wedge speed’ ($p = .015$). Further, in Table 12, we can see that the independent variable ’wedge speed’ is significant in distinguishing moderate level of the dependent variable from low level of the dependent variable ($p < .001$). Also, the independent variables ‘accumulation time’ and ’wedge speed’ are significant in distinguishing high level of the dependent variable from low level of the dependent variable ($p < .001$). An increase of the accumulation time at wedge increases the probability of picking levels clogged to be on ‘high’ level (as Exp(B) = 2863.428). An increase of the wedge speed will decrease the probability of picking levels clogged to be on ‘moderate’ level (as Exp(B) = .491) or on ‘high’ level (as Exp(B) = .477).

Table 11

Likelihood ratio tests for picking levels clogged dependent variable

Likelihood Ratio Tests

	Model Fitting Criteria			Likelihood Ratio Tests		
Effect	AIC of Reduced Model	BIC of Reduced Model	-2 Log Likelihood of Reduced Model	Chi-Square	df	Sig.
Intercept	37.233	49.901	21.233	9.845	2	.007
Pickers	50.419	63.087	34.419	23.030	2	.000
Loaders	32.011	44.680	16.011	4.623	2	.099
Accumulation Time (min.)	88.418	101.086	72.418	61.029	2	.000
Wedge Speed (FPM)	35.809	48.477	19.809	8.421	2	.015

The chi-square statistic is the difference in -2 log-likelihoods between the final model and a reduced model. The reduced model is formed by omitting an effect from the final model. The null hypothesis is that all parameters of that effect are 0.

Table 12

Parameter estimates for picking levels clogged dependent variable

Parameter Estimates

Picking levels clogged[a]		B	Std. Error	Wald	df	Sig.
Moderate (7-11)	Intercept	-425.594	8533.995	.002	1	.960
	Pickers	13.461	184.314	.005	1	.942
	Loaders	6.533	157.908	.002	1	.967
	Accumulation Time (min.)	7.184	79.458	.008	1	.928
	Wedge Speed (FPM)	-.712	.022	1018.244	1	.000
High (12-15)	Intercept	-464.670	5602.915	.007	1	.934
	Pickers	13.871	184.314	.006	1	.940
	Loaders	6.325	157.908	.002	1	.968
	Accumulation Time (min.)	7.960	.000	.	1	.
	Wedge Speed (FPM)	-.740	.000	.	1	.

Parameter Estimates

			95% Confidence Interval for Exp(B)	
Picking levels clogged[a]		Exp(B)	Lower Bound	Upper Bound
Moderate (7-11)	Intercept			
	Pickers	701627.798	9.077E-152	5.423E+162
	Loaders	687.436	2.666E-132	1.773E+137
	Accumulation Time (min.)	1318.321	3.056E-65	5.687E+70
	Wedge Speed (FPM)	.491	.470	.513
High (12-15)	Intercept			
	Pickers	1056997.593	1.368E-151	8.169E+162
	Loaders	558.456	2.164E-132	1.441E+137
	Accumulation Time (min.)	2863.428	2863.428	2863.428
	Wedge Speed (FPM)	.477	.477	.477

a. The reference category is: Low (2-6).

ii. Analysis of effects on number of shipping doors clogged

The shipping doors clogged dependent variable outcomes were grouped into three levels: none (for no shipping doors clogged), low (for 1 to 3 shipping doors clogged), and high (for 4 to 6 shipping doors clogged).

We can observe in Table 13 the proportion of experiments falling in each level of the dependent variable (shipping doors clogged). The model fitting information in Table 14 indicates a significant improvement in fit of the final model over the null model for Chi-Square = 48.4 at $p < .001$.

Table 13

Case processing summary for shipping doors clogged dependent variable

Case Processing Summary

		N	Marginal Percentage
Doors clogged	None (0)	1	2.8%
	Low (1-3)	18	50.0%
	High (4-6)	17	47.2%
Valid		36	100.0%
Missing		0	
Total		36	
Subpopulation		36[a]	

a. The dependent variable has only one value observed in 36 (100.0%) subpopulations.

Table 14

Model fitting information for shipping doors clogged dependent variable

Model Fitting Information

	Model Fitting Criteria			Likelihood Ratio Tests		
Model	AIC	BIC	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	61.631	64.798	57.631			
Final	29.273	45.109	9.273	48.357	8	.000

The likelihood ratio tests in Table 15 show that there is a statistically significant relationship between the dependent variable and the independent variable ‘pickers’ ($p = .028$), the independent variable ‘loaders’ ($p < .001$) and the independent variable ‘wedge speed’ ($p = .027$). Further, in Table 16 we can see that the independent variable ’wedge speed’ is significant in distinguishing low level of the dependent variable from ‘none’ level of the dependent variable ($p < .001$). Also, the independent variable ’wedge speed’ is significant in distinguishing high level of the dependent variable from ‘none’ level of the dependent variable (p < .001). An increase of the wedge speed will decrease the probability of shipping doors clogged to be on ‘low’ level (as Exp(B) = .680) or on ‘high’ level (as Exp(B) = .713).

Table 15

Likelihood ratio tests for shipping doors clogged dependent variable

Likelihood Ratio Tests

	Model Fitting Criteria			Likelihood Ratio Tests		
Effect	AIC of Reduced Model	BIC of Reduced Model	-2 Log Likelihood of Reduced Model	Chi-Square	df	Sig.
Intercept	25.442	38.110	9.442[a]	.168	2	.919
Pickers	32.395	45.063	16.395	7.122	2	.028
Loaders	66.520	79.188	50.520	41.247	2	.000
Accumulation Time (min.)	28.688	41.356	12.688[a]	3.414	2	.181
Wedge Speed (FPM)	32.493	45.161	16.493	7.219	2	.027

The chi-square statistic is the difference in -2 log-likelihoods between the final model and a reduced model. The reduced model is formed by omitting an effect from the final model. The null hypothesis is that all parameters of that effect are 0.

a. Unexpected singularities in the Hessian matrix are encountered. This indicates that either some predictor variables should be excluded or some categories should be merged.

Table 16

Parameter estimates for shipping doors clogged dependent variable

Parameter Estimates

Doors clogged[a]		B	Std. Error	Wald	df	Sig.
Low (1-3)	Intercept	186.058	7519.651	.001	1	.980
	Pickers	4.675	253.015	.000	1	.985
	Loaders	-6.949	373.318	.000	1	.985
	Accumulation Time (min.)	.964	69.613	.000	1	.989
	Wedge Speed (FPM)	-.386	.029	175.328	1	.000
High (4-6)	Intercept	231.731	8382.787	.001	1	.978
	Pickers	4.998	253.015	.000	1	.984
	Loaders	-11.785	439.300	.001	1	.979
	Accumulation Time (min.)	1.008	69.613	.000	1	.988
	Wedge Speed (FPM)	-.339	.000	.	1	.

Parameter Estimates

			95% Confidence Interval for Exp(B)	
Doors clogged[a]		Exp(B)	Lower Bound	Upper Bound
Low (1-3)	Intercept			
	Pickers	107.206	4.611E-214	2.493E+217
	Loaders	.001	.000	[b]
	Accumulation Time (min.)	2.621	1.457E-59	4.713E+59
	Wedge Speed (FPM)	.680	.642	.720
High (4-6)	Intercept			
	Pickers	148.089	6.368E-214	3.444E+217
	Loaders	7.615E-6	.000	[b]
	Accumulation Time (min.)	2.739	1.523E-59	4.926E+59
	Wedge Speed (FPM)	.713	.713	.713

a. The reference category is: None (0).

b. Floating point overflow occurred while computing this statistic. Its value is therefore set to system missing.

iii. Analysis of effects on number of sorters clogged

The sorters clogged dependent variable outcomes were grouped into three levels: none (for no sorters clogged), low (for 1 to 2 sorters clogged), and high (for 3 to 4 sorters clogged).

We can observe in Table 17 the proportion of experiments falling in each level of the dependent variable (sorters clogged). The model fitting information in Table 18 indicates a significant improvement in fit of the final model over the null model for Chi-Square = 62.3 at $p < .001$.

Table 17

Case processing summary for sorters clogged dependent variable

Case Processing Summary

		N	Marginal Percentage
Sorters clogged	None (0)	18	50.0%
	Low (1-2)	6	16.7%
	High (3-4)	12	33.3%
Valid		36	100.0%
Missing		0	
Total		36	
Subpopulation		36[a]	

a. The dependent variable has only one value observed in 36 (100.0%) subpopulations.

Table 18

Model fitting information for sorters clogged dependent variable

Model Fitting Information

Model	Model Fitting Criteria			Likelihood Ratio Tests		
	AIC	BIC	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	76.821	79.988	72.821			
Final	30.554	46.389	10.554	62.267	8	.000

The likelihood ratio tests in Table 19 show that there is a statistically significant relationship between the dependent variable and the independent variable ‘pickers’ ($p = .008$), the independent variable ‘loaders’ ($p < .001$), the independent variable ‘accumulation time’ ($p = .002$) and the independent variable ‘wedge speed’ ($p = .001$). Further, in Table 20 we can see that the independent variable ’wedge speed’ is significant in distinguishing low level of the dependent variable from ‘none’ level of the dependent variable ($p < .001$). Also, the independent variable

’wedge speed’ is significant in distinguishing high level of the dependent variable from ‘none’ level of the dependent variable (p < .001). An increase of the wedge speed will increase the probability of sorters clogged to be on ‘low’ level (as Exp(B) = 2.082) or on ‘high’ level (as Exp(B) = 2.132).

Table 19

Likelihood ratio tests for sorters clogged dependent variable

Likelihood Ratio Tests

	Model Fitting Criteria			Likelihood Ratio Tests	
Effect	AIC of Reduced Model	BIC of Reduced Model	-2 Log Likelihood of Reduced Model	Chi-Square	df
Intercept	26.648	39.316	10.648[a]	.094	2
Pickers	36.334	49.003	20.334	9.781	2
Loaders	83.739	96.407	67.739	57.185	2
Accumulation Time (min.)	38.647	51.315	22.647	12.093	2
Wedge Speed (FPM)	40.510	53.178	24.510	13.956	2

Likelihood Ratio Tests

	Likelihood Ratio Tests
Effect	Sig.
Intercept	.954
Pickers	.008
Loaders	.000
Accumulation Time (min.)	.002
Wedge Speed (FPM)	.001

The chi-square statistic is the difference in -2 log-likelihoods between the final model and a reduced model. The reduced model is formed by omitting an effect from the final model. The null hypothesis is that all parameters of that effect are 0.

a. Unexpected singularities in the Hessian matrix are encountered. This indicates that either some predictor variables should be excluded or some categories should be merged.

Table 20

Parameter estimates for sorters clogged dependent variable

Parameter Estimates

Sorters clogged[a]		B	Std. Error	Wald	df	Sig.
Low (1-2)	Intercept	-148.268	4220.261	.001	1	.972
	Pickers	4.513	93.518	.002	1	.962
	Loaders	-20.724	302.259	.005	1	.945
	Accumulation Time (min.)	.923	28.316	.001	1	.974
	Wedge Speed (FPM)	.733	.023	974.493	1	.000
High (3-4)	Intercept	-125.108	4861.900	.001	1	.979
	Pickers	4.747	93.518	.003	1	.960
	Loaders	-25.315	427.101	.004	1	.953
	Accumulation Time (min.)	1.476	49.199	.001	1	.976
	Wedge Speed (FPM)	.757	.000	.	1	.

Parameter Estimates

			95% Confidence Interval for Exp(B)	
Sorters clogged[a]		Exp(B)	Lower Bound	Upper Bound
Low (1-2)	Intercept			
	Pickers	91.214	2.275E-78	3.657E+81
	Loaders	9.996E-10	5.208E-267	1.919E+248
	Accumulation Time (min.)	2.516	1.988E-24	3183799650159098 600000000.000
	Wedge Speed (FPM)	2.082	1.989	2.180
High (3-4)	Intercept			
	Pickers	115.252	2.875E-78	4.621E+81
	Loaders	1.014E-11	.000	[b]
	Accumulation Time (min.)	4.377	5.796E-42	3.306E+42
	Wedge Speed (FPM)	2.132	2.132	2.132

a. The reference category is: None (0).

b. Floating point overflow occurred while computing this statistic. Its value is therefore set to system missing.

5.3.3.3 Summary of Statistical Analyses

The analysis of variance on picker utilization showed statistically significant effects for all the main effects, for the interaction of number of pickers and accumulation time at wedge and for the interaction of number of pickers, accumulation time at wedge and wedge speed. The analysis of variance on loader utilization showed statistically significant effects for the main effect of number of loaders and for the interaction of number of loaders and wedge speed. The analysis of variance on estimated total time showed statistically significant effects for the main effects of number of loaders and accumulation time at the wedge. The three multinomial logistic regression analyses of effects on number of picking levels clogged, on number of shipping doors clogged and on number of sorters clogged revealed that there are statistically significant relationships between all the dependent variables and all the independent variables, except for the relationships between ‘loaders’ with ‘picking levels clogged’ and ‘accumulation time’ with ‘shipping doors clogged’. Moreover, an increase of the accumulation time at wedge increases the probability of picking levels clogged to be on ‘high’ level (as Exp(B) = 2863.428) and an increase of the wedge speed will increase the probability of sorters clogged to be on ‘low’ level (as Exp(B) = 2.082) or on ‘high’ level (as Exp(B) = 2.132). The summary of the statistical analyses is presented in Table 21.

Table 21

Summary of statistical analyses

Statistical analysis	Dependent variable	Statistically significant effects / relationships
Analysis of variance	picker utilization	pickers
		loaders
		accumulation time
		wedge speed
		pickers * accumulation time
		pickers * accumulation time * wedge speed
	loader utilization	loaders
		loaders * wedge speed
	estimated total time	loaders
		accumulation time
Multinomial logistic regression analysis	picking levels clogged	pickers
		accumulation time
		wedge speed
	shipping doors clogged	pickers
		loaders
		wedge speed
	sorters clogged	pickers
		loaders
		accumulation time
		wedge speed

If the Company focus would be to improve picker utilization, the most appropriate choice is a combination of low number of pickers, high number of loaders, low accumulation time and high wedge speed. This corresponds to the experimental setting of E10 which consists of 20 pickers and 20 loaders, while the accumulation at the wedge is 30 minutes and the wedge speed is of 475 FPM. When the primary objective is to improve loader utilization, the Company should adopt a combination of low number of loaders and high wedge speed. There are six experimental settings (E02, E04, E14, E16, E26 and E28) that satisfy these requirements (12 loaders and wedge speed of 475 FPM) which yield a minimum of 84% loader utilization. If the overall objective is to improve the estimated total time, the management should adopt high number of loaders and low accumulation time at the wedge. There are six experimental settings (E09, E10, E21, E22, E33 and E34) that satisfy these requirements (20 loaders and accumulation time at the wedge of 30 minutes) which yield a maximum of 136 minutes of estimated total time. Finally, to reduce the odds of clogging, the Company should use the lower speed of 400 FPM at the wedge and should improve the bulk trailer loading operations by implementing bulk pre-picking activities.

5.4 Simulation Model Implementation

We prepared a user guide for the simulation model so that an operator would be able to simulate a chosen cycle. This user guide is presented in Appendix C.

There are several reasons for which this simulation model should be used at strategic level rather than operational level:

- Preparation of the input data is long because of the necessary manipulation of the data file.
- Data import is time consuming as it needs to be performed individually for each pick level.

- Accurately forecasting the start of pre-picking and of actual cycle start (resulting the wedge accumulation time) is difficult, if not almost impossible.
- The operator should invest time to observe the events during simulation.
- Model execution time duration is as long as real time operations or even longer.
- Testing different options would multiply the time necessary for this activity.

Preparing and importing the data and executing the simulation model only for one time requires around four hours of work. Therefore, rather than to perform these simulations on a daily basis, it is more important to understand the effects of altering different parameters in the simulation model. This can be achieved through comparison of simulation outcome with real-life operations outcome. The conclusions drawn after the analysis of different experiments should constitute the base for future operational decisions.

In terms of simulation outcome, it is important to note that the picker utilization should be estimated when the last item was picked, not at the end of simulation. Similarly, in order to obtain a reliable loader utilization outcome, the loaders should be assigned a work schedule that starts at the end of the accumulation period at the wedge.

Chapter 6: Conclusion and Future Research Directions

The performance of any supply chain is affected, among other factors, by the efficiency of the operations performed at their warehouses / DCs. This is why simulation / optimization tools are necessary in the design phase of such facilities or to evaluate and improve their operations. Our applied research work analyzes the conveyor operations of the FedEx distribution centre located at Coteau-du-Lac, Quebec. Through the simulation model developed, we provide managerial insights based on the findings of 36 simulation experiments, according to the experimentations established through varying the selected levels of four parameters. The managerial insights are argued by taking into account the goals set by the Company. All the experiments are based on a single real-life cycle. Each experiment is a variation of the parameters of cycle 7 of November 10, 2020. The validated experiment E20 is a replication of the real-life setting and is used as a baseline for the managerial insights.

The analyses of variance revealed that all the independent variables present statistically significant effects on picker utilization, while for loader utilization, only the number of loaders presents statistically significant effect and for estimated total time, only the number of loaders and wedge speed variables present statistically significant effects. The multinomial logistic regression analyses showed that the higher speed of the wedge increases the odds of sorters clogging. To reduce the odds of clogging, the Company should use the lower speed of 400 FPM at the wedge and should improve the bulk trailer loading operations by implementing bulk pre-picking activities. We recommend using the experimental setting of E05 (20 pickers, 16 loaders, 30 minutes of accumulation time at the wedge and a speed of 400 FPM at the wedge) as it complies with the goals set by the Company. Moreover, this setting generates economies by using less electricity and providing less maintenance due to lower wedge speed and by using fewer human resources at the picking modules and at the shipping doors. This can be achieved only by improving the bulk trailer loading operations.

Because of the complexity of the simulation model and the number of objects circulating in the model at any given point in time, the time necessary to perform the simulation for an experimental setting is similar to the time of real time operations (if not somewhat longer for certain experiments). Therefore, we were able to analyze a limited number of experiments and we focused on the parameters and their levels that seemed to be the most important to the Company. More research is necessary to ameliorate the knowledge on the conveyor system dynamics, therefore future studies should include more factors and/or levels. Also, our findings need to be further validated by using different picking schedules. Without much effort, our simulation model can be adapted to account for those aspects not included in this investigation, as other possible levels of resources, accumulation times and wedge speed, or the allocation of a specific number of resources for each picking area and each shipping door.

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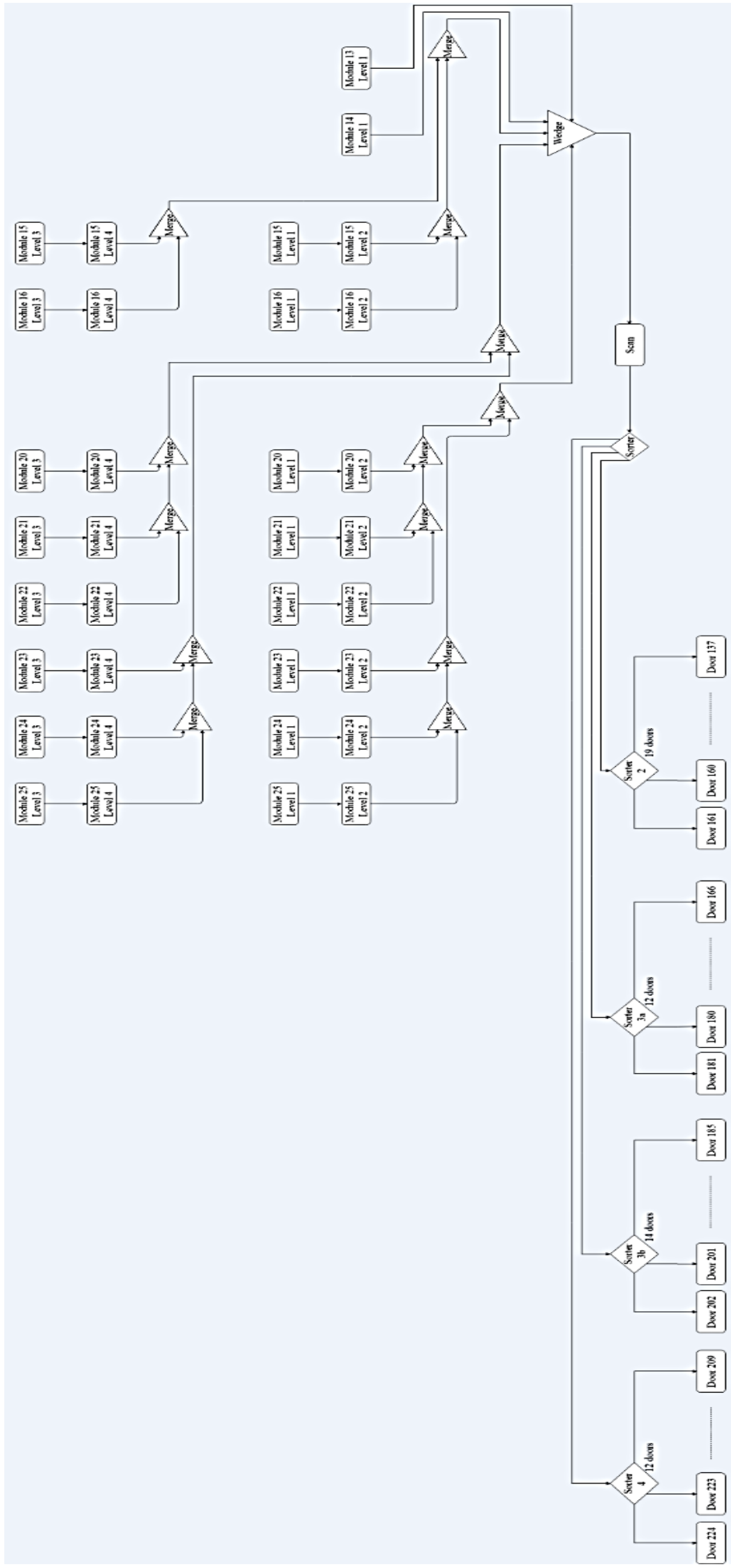
Appendix A: Process Flow Diagram for the Conveyor Operations

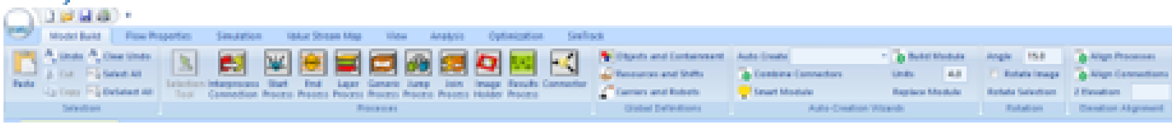


Appendix B: Observations on Experiments

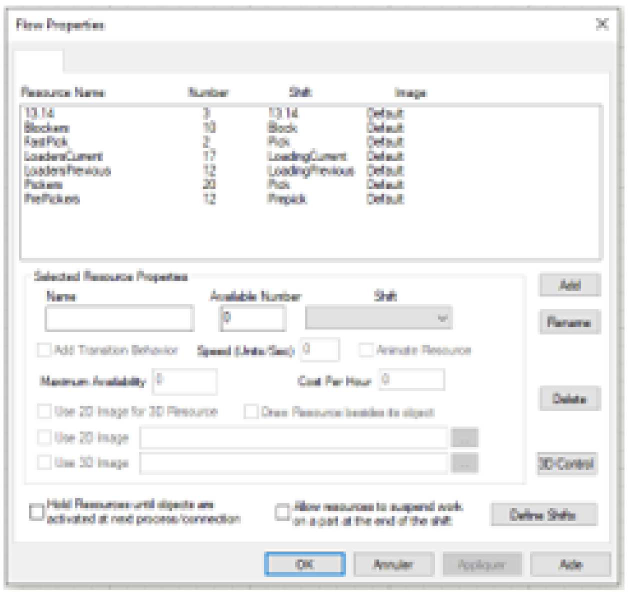
Experiment	Observations		
	Picking levels clogging start time	Doors clogging start time	Sorters clogging start time
E01	141 at 1h12; 131 at 1h14	220 at 0h48; 202 at 0h54; 148 at 1h19; 181 at 1h30	S4 at 1h33
E02	141 at 1h13; 131 at 1h25	220 at 0h51; 202 at 0h52; 148 at 1h17; 196 at 1h24; 181 at 1h31	S4 at 1h37
E03	141, 202, 204, 212, 222, 224, 232, 234, 242 and 244 at 1h07; 223 at 1h16; 131 at 1h20	220 at 1h17; 181 at 1h25; 148 at 1h27; 202 at 1h38; 196 at 1h39	S4 at 1h47; S1 at 2h00; S3 at 2h06
E04	141, 202, 204, 212, 222, 224, 232, 234, 242 and 244 at 1h09; 223 at 1h14; 131 at 1h19	181 at 1h17; 220 at 1h19; 148 at 1h22; 202 and 171 at 1h25	S4 and S1 at 1h40; S3 and S2 at 1h43
E05	141 at 1h11; 131 at 1h16	148 at 1h30	
E06	141 at 1h12; 131 at 1h28	148 at 1h25	
E07	141, 202, 212, 214, 224, 232, 234, 242 and 244 at 1h07; 222 at 1h10; 223 at 1h13; 131 at 1h15	148 at 1h33; 220 at 1h48	
E08	141, 202, 212, 222, 224, 232, 234, 242 and 244 at 1h07; 223 at 1h13; 131 at 1h17	220 at 1h21; 148 at 1h27; 202 and 181 at 1h38; 196 at 1h43	S4 at 1h58; S1 at 1h59; S3 at 2h06
E09	141 at 1h22; 131 at 1h26	148 at 1h36	
E10	141 at 1h11; 131 at 1h12		
E11	204, 212, 234, 242 and 244 at 1h07; 141, 222, 224 at 1h09; 202 at 1h10; 131 at 1h14; 223 at 1h17	148 at 1h37	
E12	141, 212, 224, 232, 234, 242 and 244 at 1h10; 222 at 1h13; 131 at 1h26	148 at 1h25; 220 at 1h45	
E13	242 at 0h54; 224 and 244 at 0h55; 141 at 0h56; 131 at 0h59	220 at 0h49; 202 at 0h55; 148 at 1h12; 181 at 1h14; 196 at 1h15	S4 and S3 at 1h26; S1 at 1h38
E14	141 and 242 at 0h51; 222 at 0h53; 244 at 0h56; 131 and 224 at 1h07	220 at 0h47; 202 at 0h53; 148 at 0h55; 196 at 1h02; 171 at 1h04; 181 at 1h07	S4 at 1h13; S3 at 1h21; S1 at 1h25; S2 at 1h28
E15	202, 204, 212, 222, 234, 242 and 244 at 0h50; 131, 141 at 0h51; 224 at 0h54; 203 and 223 at 0h59	220 at 1h23; 148 at 1h25; 181 at 1h34; 196 at 1h42	S1 at 1h51; S4 at 1h53; S3 at 2h14
E16	131, 202, 204, 212, 234, 242 and 244 at 1h51; 141, 222, 224 at 0h53; 223 at 1h02	220 and 181 at 1h20; 196 at 1h23; 148 at 1h24; 202 at 1h41	S4 and S1 at 1h45; S3 at 1h50; S2 at 2h05
E17	242 at 0h50; 141, 224 and 244 at 0h52; 131 at 1h01	148 at 1h12; 181 at 1h24; 220 at 1h32	
E18	202 at 0h52; 141 and 222 at 0h53; 244 at 0h59; 131 at 1h10	220 at 0h50; 202 and 148 at 1h05; 181 at 1h15; 196 at 1h25	S4 at 1h30
E19	152, 202, 204, 212, 232, 234 and 242 at 0h46; 131 and 244 at 0h49; 141, 203, 222 at 0h51; 224 at 0h56; 223 at 1h03	148 at 1h35; 220 at 2h11; 196 at 2h20	
E20	131, 202, 204, 212, 214, 234, 242 and 244 at 0h49; 141, 203, 222, 224 at 0h51; 223 at 0h59	220 at 1h22; 148 at 1h27; 181 at 1h36	S4 at 2h01
E21	242 and 244 at 0h53; 141 at 0h54; 224 at 0h55; 131 at 1h08	148 at 1h37	
E22	242 at 0h42; 141 at 0h56; 244 at 1h03; 131 at 1h10	148 at 1h20	
E23	141, 152, 202, 204, 222, 234, 242 and 244 at 0h48; 131, 212 at 0h50; 224 at 0h52; 223 at 0h59	148 at 1h35	
E24	202, 204, 232, 234, 242 and 244 at 0h50; 131, 141, 212, 222, 224 and 234 at 0h52; 223 at 1h02	148 at 1h25; 220 at 1h55	
E25	141, 202, 222, 232 234, 242 and 244 at 0h42; 131 and 224 at 0h49	220 at 0h50; 148 at 1h01; 181 at 1h02; 196 at 1h10; 202 at 1h11	S4 at 1h20; S1 at 1h28; S3 at 1h38; S2 at 1h41
E26	234 and 242 at 0h43; 141 at 0h44; 244 at 0h46; 131 at 0h50; 224 at 0h53	220 at 0h45; 202 at 0h53; 181 at 0h56; 148 at 0h57; 196 at 1h00	S4 at 1h03; S3 at 1h16; S1 at 1h19; S2 at 1h33
E27	131, 141, 202, 204, 212, 234, 242 and 244 at 0h39; 224 at 0h43; 222 and 223 at 0h48; 203 at 0h50	220 at 1h18; 181 at 1h20; 196 at 1h22; 148 at 1h24; 214 at 1h31	S4 at 1h36; S3 at 1h42; S1 at 1h44; S2 at 1h58
E28	202, 204, 212, 234, 242 and 244 at 0h39; 131, 141 at 0h41; 222 and 224 at 0h44; 223 at 0h51; 203 at 0h55	220 at 1h20; 181 at 1h21; 196 at 1h23; 148 at 1h24; 202 at 1h32; 214 at 1h37	S4 at 1h39; S3 at 1h43; S1 at 1h55; S2 at 1h57
E29	242 and 234 at 0h41; 141 at 0h42; 244 at 0h44; 222 and 224 at 0h47; 131 at 1h01	148 at 1h04; 220 at 1h24	
E30	141, 222, 242 and 244 at 0h44; 234 at 0h48; 131 at 0h57	220 and 148 at 1h00; 202 and 181 at 1h15; 196 at 1h20	S4 and S1 at 1h33
E31	131, 141, 152, 202, 204, 212, 214, 224, 232, 234, 242 and 244 at 0h39; 222 at 0h47; 203 and 223 at 0h50	148 at 1h40; 220 at 1h49; 202 and 196 at 2h10	S4 at 2h11
E32	202, 203, 204, 212, 234, 242 and 244 at 0h41; 131 at 0h43; 141, 222 at 0h45; 224 at 0h47; 223 at 0h49	181 at 1h18; 220 and 148 at 1h19; 196 at 1h27; 202 at 1h30	S4 at 1h40; S1 at 1h42; S3 at 1h50
E33	212, 232, 234, 242 and 244 at 0h40; 141 at 0h42; 224 at 0h46; 222 at 0h49; 131 at 1h03	148 at 1h08	
E34	141 and 242 at 0h41; 224 and 244 at 0h43; 222 at 0h44; 234 at 0h49; 131 at 1h04	148 at 1h05; 220 at 1h35	
E35	141, 152, 202, 204, 212, 234 and 242 at 0h38; 131, 203, 204, 222, 224 and 244 at 0h41; 223 at 0h50	148 at 1h27; 220 at 1h58	
E36	131, 141, 202, 203, 204, 212, 234, 242 and 244 at 0h40; 222, 224 at 0h43; 223 at 0h49; 243 at 1h15	148 and 220 at 1h30	

Appendix C: User Guide for Simulation

1) Resources and shifts definition



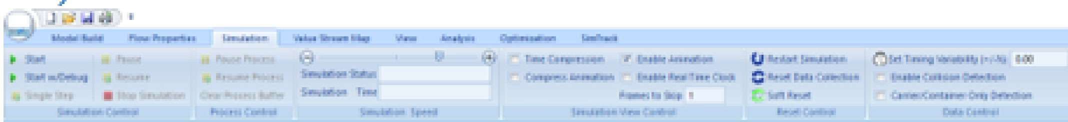
To create or modify resources: Model Build → Global Definitions → Resources and Shifts.



Click on Define Shifts to create or modify any shift definition.

Appendix C (continued)

2) Simulation controls

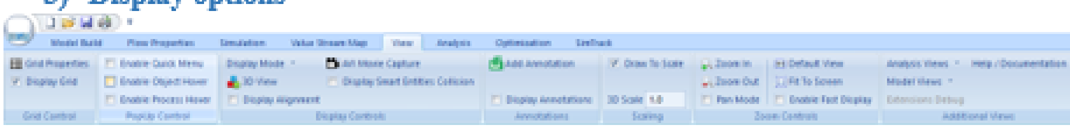


For simulation controls: Simulation → Simulation Control: Start, Pause, Resume, Stop Simulation.

To set simulation speed: Simulation → Simulation Speed.

For model animation: Simulation → Simulation View Control: Enable Animation (remove the check mark to increase simulation speed).

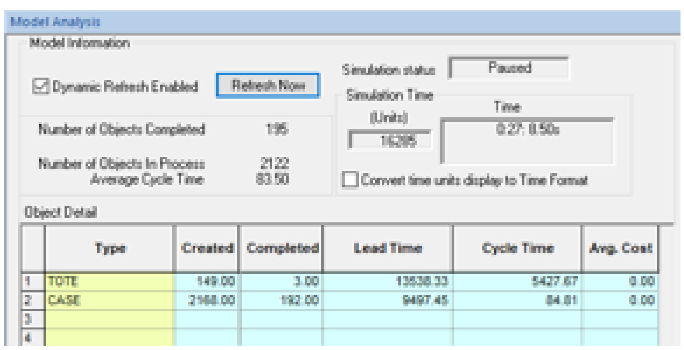
3) Display options



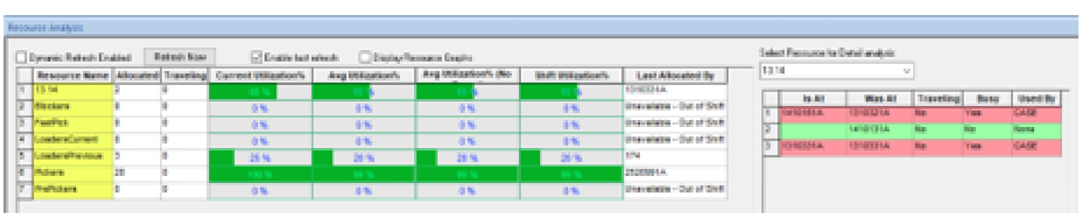
To record: View → Display Controls → AVI Movie Capture.

To see the picking levels signs: View → Annotations (check Display Annotations).

To observe statistics related to objects: View → Additional Views → Analysis Views → Model Analysis.



For resource analysis: View → Additional Views → Analysis Views → Resource Analysis.

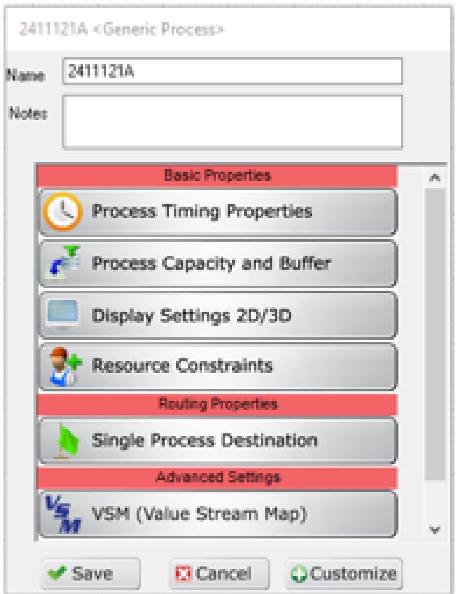


Check "Enable fast refresh" to observe utilisation as the simulation runs.

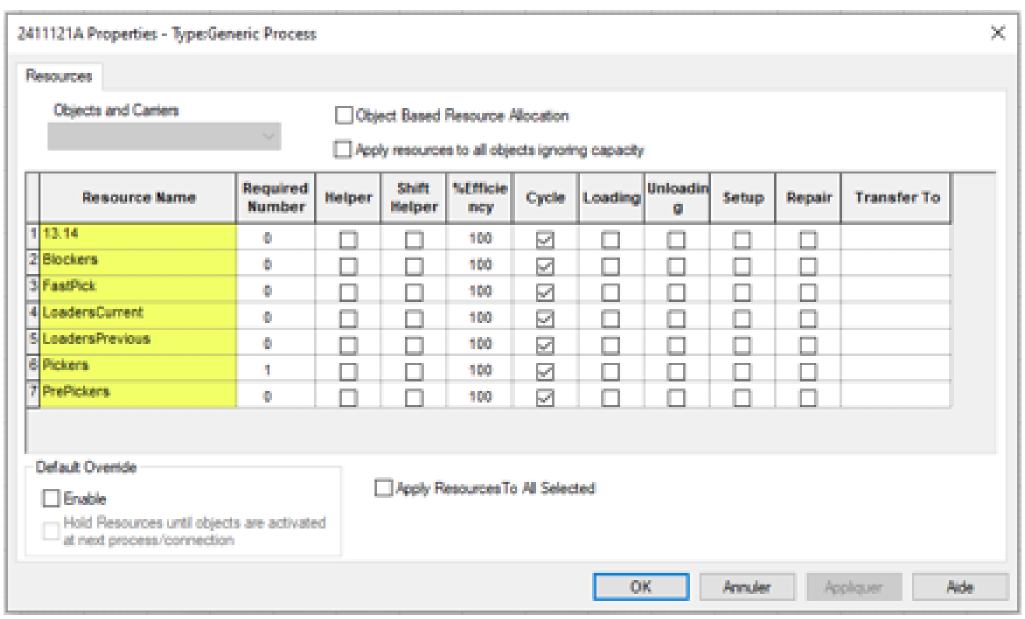
Appendix C (continued)

4) Picking resources assignment

a. Select all the picking locations that will use a certain resource.
b. Open any one of them.



c. Click on Resource Constraints.



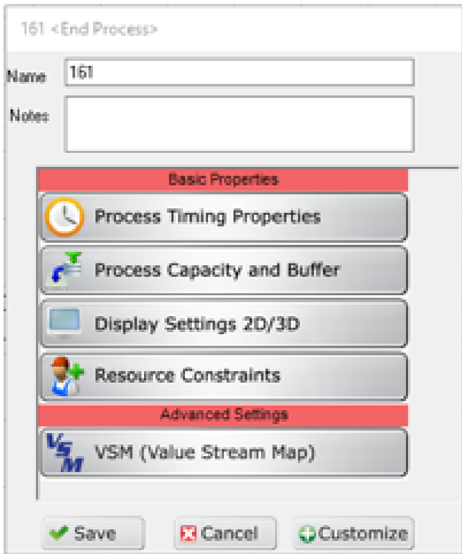
d. Modify Required Number as needed.
e. Check the Apply Resources To All Selected.
f. Click OK, followed by Save.

Appendix C (continued)

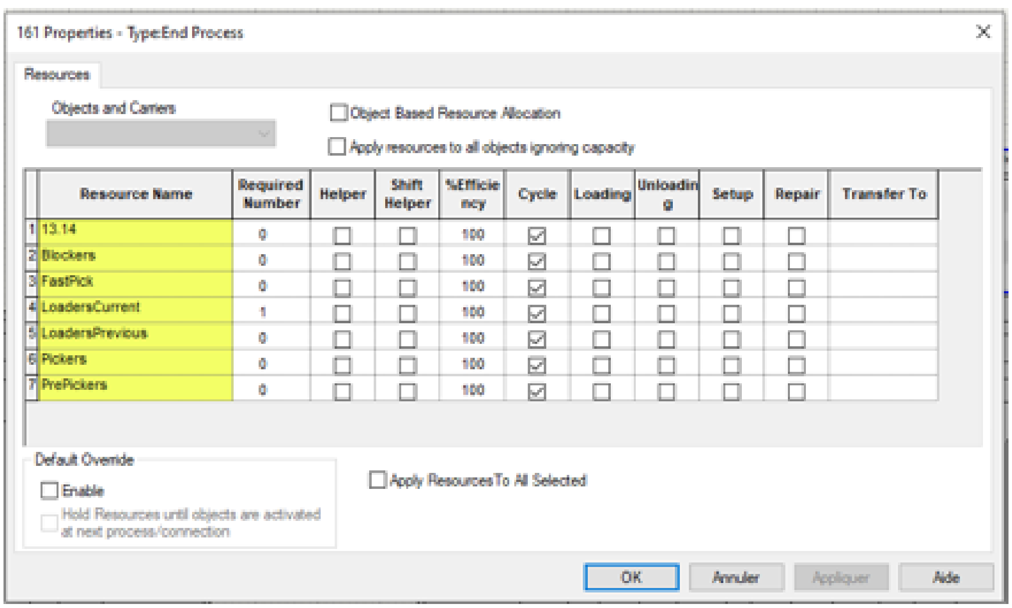
5) Loading resources assignment

a. Select all the shipping doors that will use a certain resource.

b. Open any one of them.



c. Click on Resource Constraints.



d. Modify Required Number as needed.

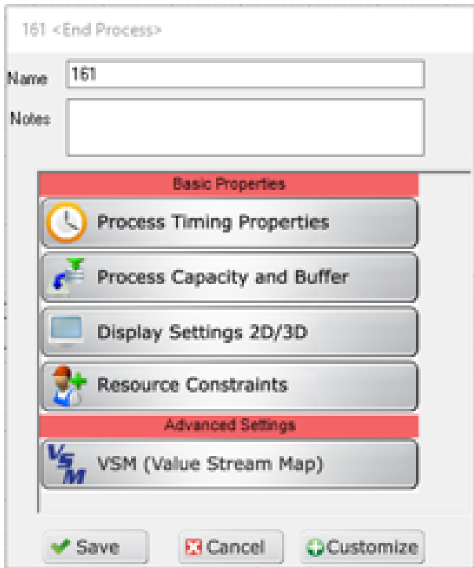
e. Check the Apply Resources To All Selected.

f. Click OK, followed by Save.

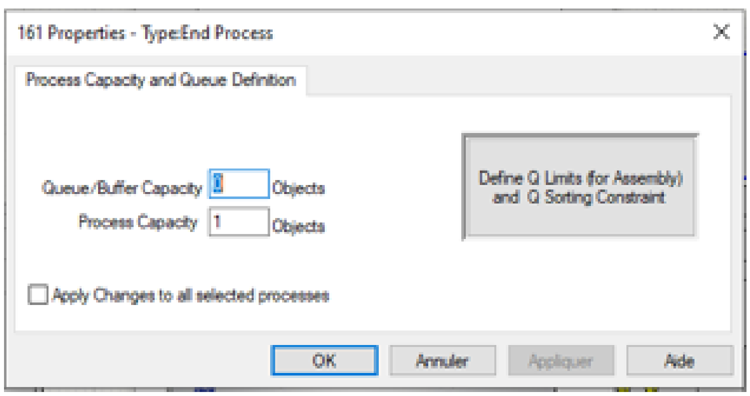
g. To modify the amount of resources used at each door, select the doors that use the same amount of resources.

Appendix C (continued)

h. Open any one of them.



i. Click on Process Capacity and Buffer.



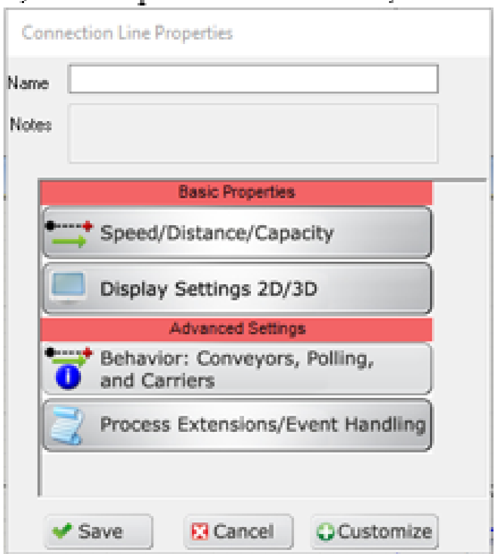
j. Modify Process Capacity to reflect the number of resources used.
k. Check the Apply Resources To All Selected.
l. Click OK, followed by Save.

Appendix C (continued)

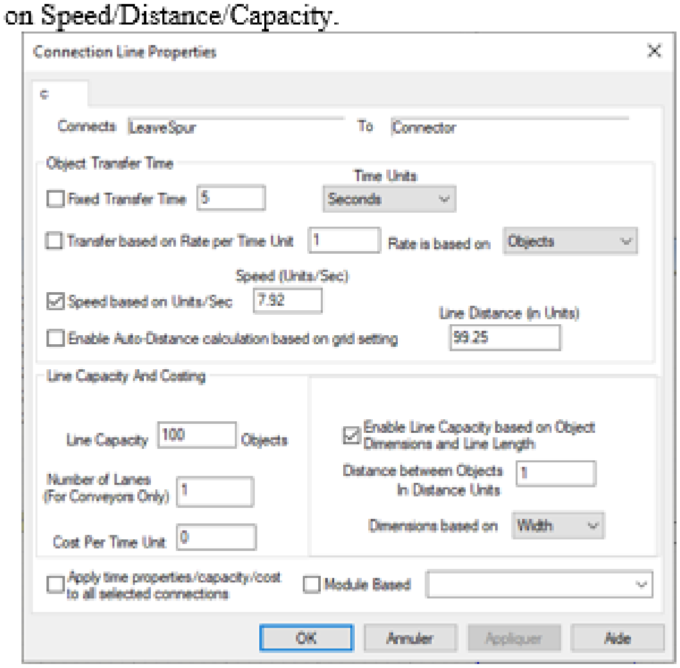
6) Updating characteristics of any conveyor segment

(This is particularly useful when the wedge speed needs to be modified. The wedge segments that can be modified are highlighted in orange.)

a. Apply this to each individual segment to avoid modifying characteristics for other segments, for example their line distance, which might be different for each segment.



b. Click on Speed/Distance/Capacity.

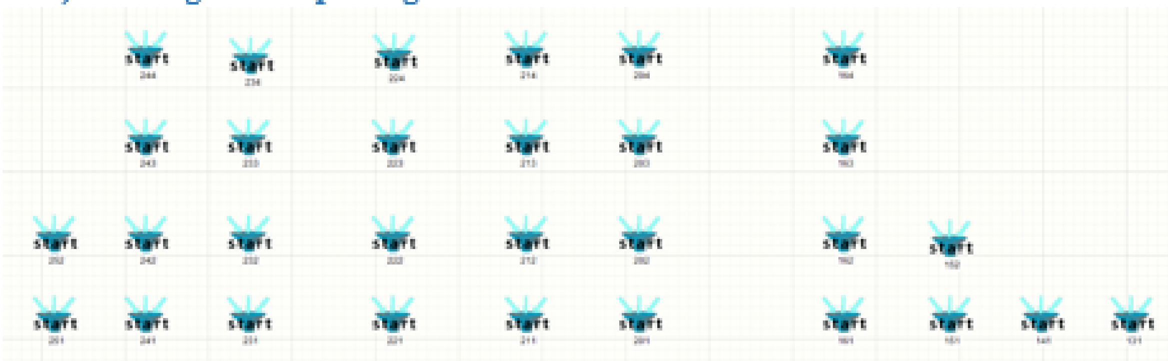


c. Modify the values of Speed or Line Distance as needed. The units are expressed in feet.

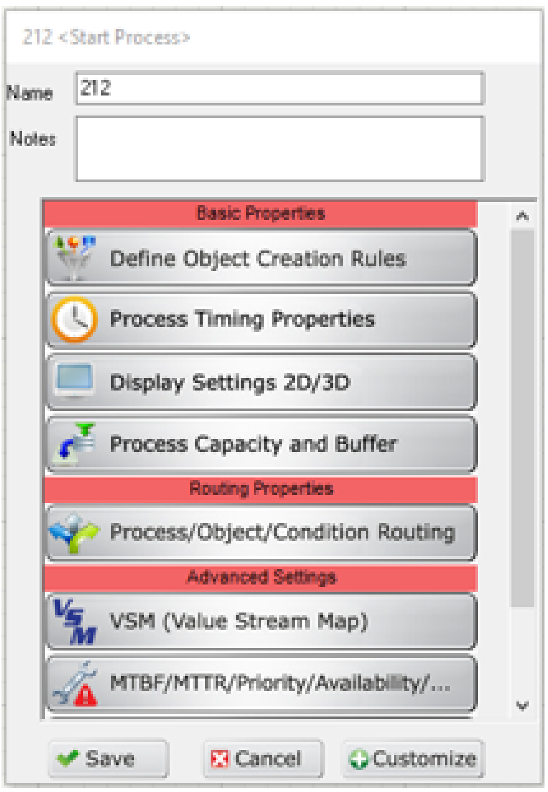
d. Click OK, then Save.

Appendix C (continued)

7) Picking data importing

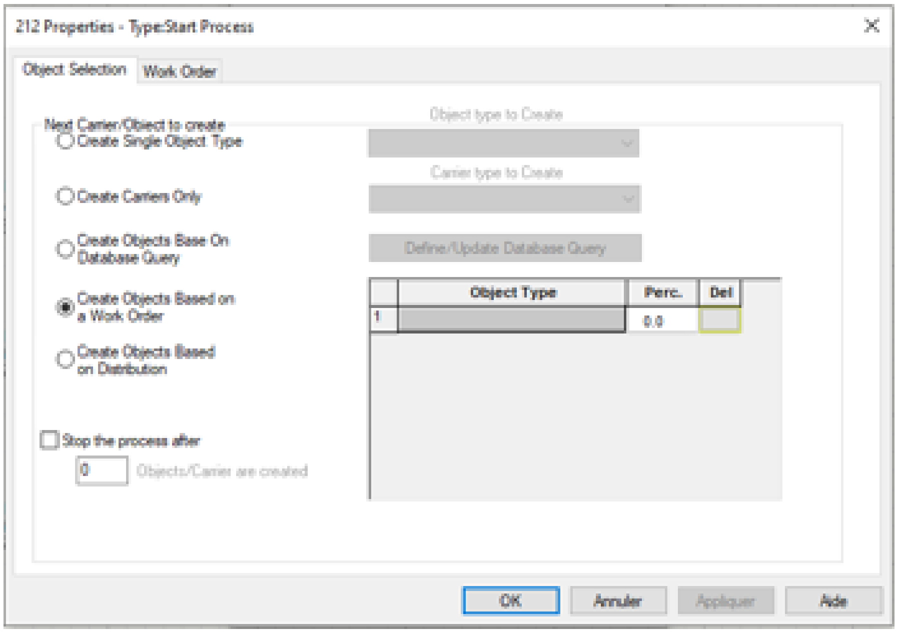


a. Select each Start process one by one. They correspond to the levels of the picking modules.

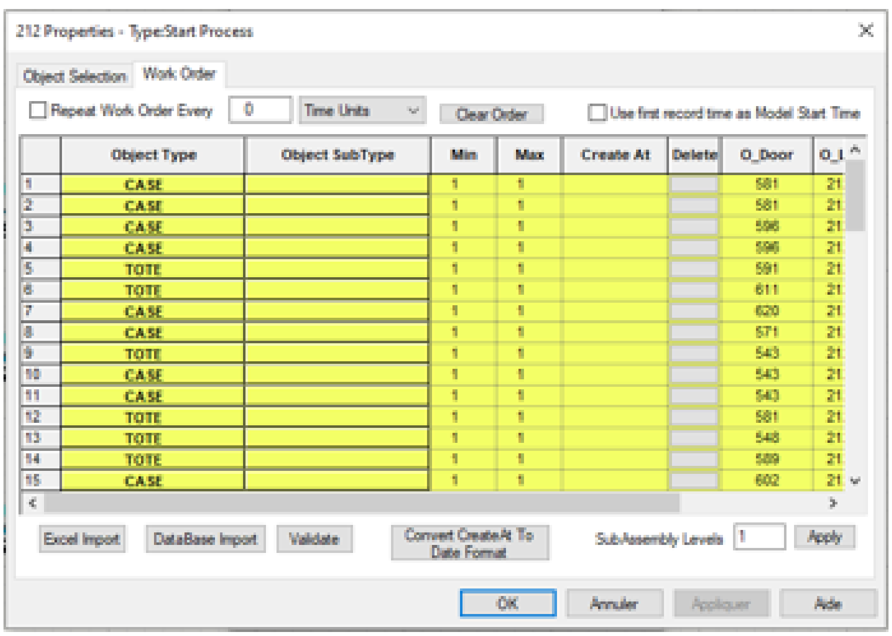


b. Click on Define Object Creation Rules.

Appendix C (continued)



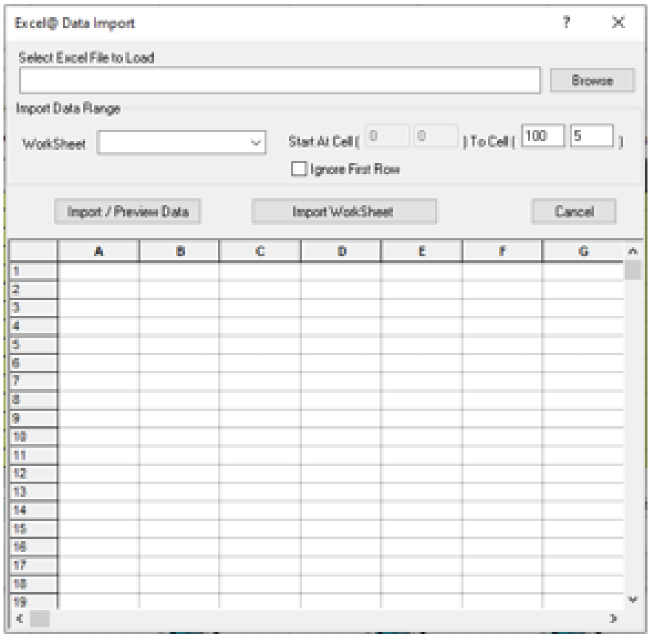
c. Select the Work Order tab.



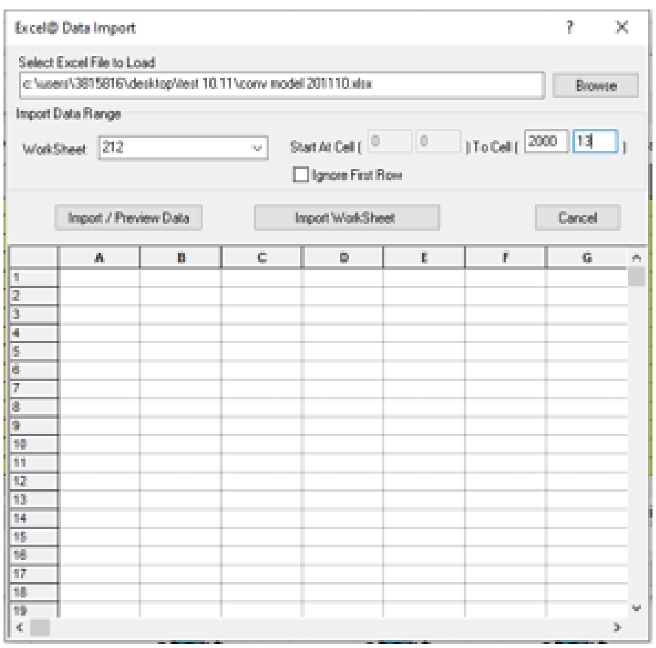
d. Click on Clear Order.

e. Click on Excel Import.

Appendix C (continued)



f. Click on Browse to select the file to import from.
g. Select the appropriate WorkSheet.
h. Fill in 2000 for the line numbers and 13 for the column numbers in the To Cell.

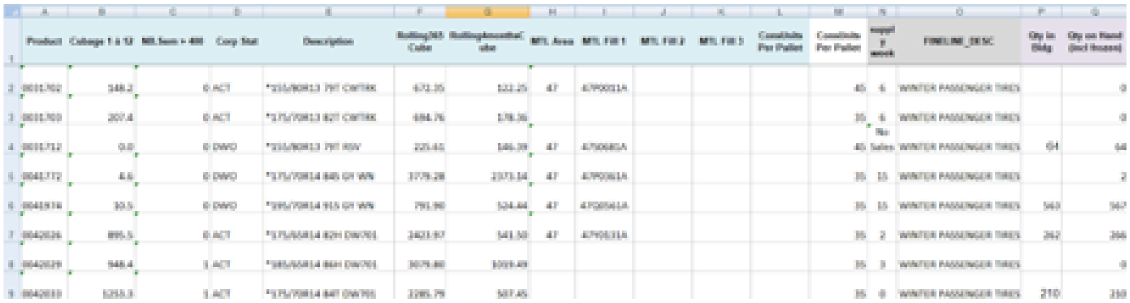


i. Click on Import WorkSheet.
j. Click OK, then Save.

Appendix C (continued)

8) "Global Rank Report MMDDYYYY.xlsx" file

Before preparing the input file, the "Global Rank Report MMDDYYYY.xlsx" file should be prepared following these steps:

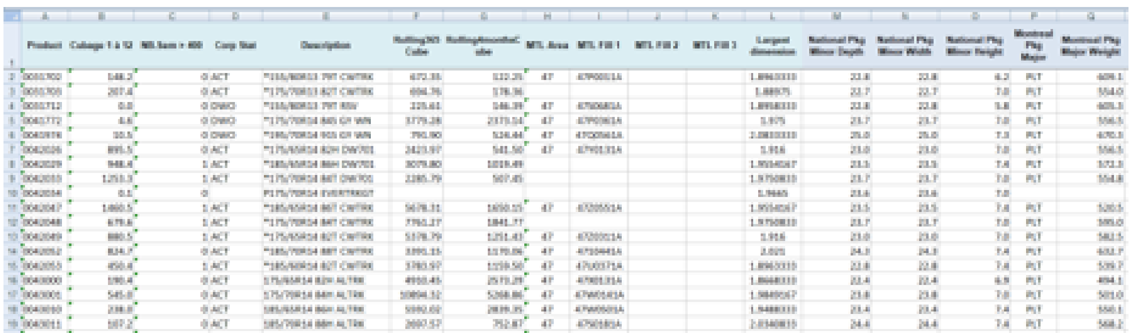


a. Remove all the columns from L to AS.

b. Insert before column L a new column called Largest Dimension.

c. In the new column select the largest dimension of each object based on National Pkg Minor columns and transform from inch to feet. Example:

=MAX(M2:O2)/12



Appendix C (continued)

9) Input data file

Steps to prepare the input data for the conveyor simulator, starting from the system extract file:

	A	B	C	D	E	F	G	H	I	J	K
1	CANADIAN TIRE CORPORATION										
2	Montreal DC										
3	OUTSTANDING ITEMS REPORT										
4	J Day: 314	Cycle: 07									
5	Work Area : ALL										
6	Shipping Unit Type: ALL										
7	Report printed at: 10-NOV-2020 07:47:45										
8	==============================										
9	Shipping Unit	SU Type	Status	Scan Lane	Store	Shipment	Workarea	Sector	Product	Location	
10	2102102451	CASE	ALLOCATED		602	21	290102	C-CASEFLOW	AREA_16_L1	423706	1612301
11	2102102471	CASE	ALLOCATED		602	21	290102	C-CASEFLOW	AREA_16_L1	396680	1613805
12	2102102456	CASE	ALLOCATED		602	21	290102	C-CASEFLOW	AREA_16_L1	633712	1612608
13	2102102457	CASE	ALLOCATED		602	21	290102	C-CASEFLOW	AREA_16_L1	633712	1612608
14	2102102491	CASE	ALLOCATED		602	21	290102	C-CASEFLOW	AREA_16_L1	642704	16160C8
15	2102102409	CASE	ALLOCATED		602	21	290102	C-CASEFLOW	AREA_16_L1	1500192	1611201
16	13502102487	CASE	ALLOCATED		589	135	290101	C-CASEFLOW	AREA_16_L1	426843	16150C1
17	13502102466	CASE	ALLOCATED		589	135	290101	C-CASEFLOW	AREA_16_L1	563739	1613748
18	13502102461	CASE	ALLOCATED		589	135	290101	C-CASEFLOW	AREA_16_L1	874234	1613246
19	13502102462	CASE	ALLOCATED		589	135	290101	C-CASEFLOW	AREA_16_L1	874234	1613246

a. Remove the information lines before the column headers (8 lines).
b. Remove the columns that are not necessary for this simulation model: Status, Scan Lane, Shipment, Workarea, Sector, Location.
c. Assign the name O_Location to the unnamed column.
d. Create 8 new columns with following headers: Object Subtype, Min, Max, Create at, Delete, O_ReleaseFrom, O_Sorter, O_Width.
e. Re-arrange columns in the following order: SU Type, Object Subtype, Min, Max, Create at, Delete, Store, O_Location, O_ReleaseFrom, O_Sorter, O_Width, Shipping Unit, Product.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	SU Type	Object Subtype	Min	Max	Create at	Delete	Store	O_Location	O_ReleaseFrom	O_Sorter	O_Width	Shipping Unit	Product
2	CASE						602	1612301				2102102451	AREA_16_L1
3	CASE						602	1613805				2102102471	AREA_16_L1
4	CASE						602	1612608				2102102456	AREA_16_L1
5	CASE						602	1612608				2102102457	AREA_16_L1
6	CASE						602	16160C8				2102102491	AREA_16_L1
7	CASE						602	1611201				2102102439	AREA_16_L1
8	CASE						589	16150C1				13502102487	AREA_16_L1
9	CASE						589	1613748				13502102466	AREA_16_L1
10	CASE						589	1613246				13502102461	AREA_16_L1
11	CASE						589	1613246				13502102462	AREA_16_L1
12	CASE						620	16110C3				17502102410	AREA_16_L1
13	CASE						620	1610503				17502102420	AREA_16_L1
14	CASE						620	1614183				17502102481	AREA_16_L1
15	CASE						620	1616208				17502102495	AREA_16_L1
16	CASE						620	1613583				17502102463	AREA_16_L1
17	CASE						620	1613583				17502102464	AREA_16_L1
18	CASE						620	16107C8				17502102434	AREA_16_L1
19	CASE						591	1610403				19002102418	AREA_16_L1

f. Assign value of 1 for every picking line in columns Min and Max
g. In O_Sorter column use VLOOKUP to determine the sorter for each line based on the value in Store column. The function should search the information in "Sorters with shipping doors.xlsx" file. Example:

=VLOOKUP(G2;'C:\Users\3815816\Desktop\Test 10.11\[sorters with shipping doors.xlsx]Feuil1'!$B$2:$C$58;2;FALSE).

h. In O_Width column use VLOOKUP to determine the largest dimension for each object based on the picking location in O_Location column. The function should search the information in "Global Rank Report MMDDYYYY.xlsx" file for the week corresponding to the cycle simulated. Example:

Appendix C (continued)

=VLOOKUP(H2;'C:\Users\3815816\Desktop\Test 10.11\[Global Rank Report 11042020.xlsx]Table'!$I:$L;4;)

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	SU Type	Object Subtype	Min	Max	Create at	Delete	Store	O_Location	O_ReleaseFrom	O_Sorter	O_Width	Shipping Unit	Product
2	CASE		1	1			602	1310021A		Sorter3	1.895833333	2102326733	AREA_13_L1
3	CASE		1	1			589	1310021A		Sorter3	1.895833333	13502326736	AREA_13_L1
4	CASE		1	1			589	1310021A		Sorter3	1.895833333	13502326737	AREA_13_L1
5	CASE		1	1			589	1310021A		Sorter3	1.895833333	13502326738	AREA_13_L1
6	CASE		1	1			589	1310021A		Sorter3	1.895833333	13502326739	AREA_13_L1
7	CASE		1	1			558	1310021A		Sorter1	1.895833333	19702326719	AREA_13_L1
8	CASE		1	1			558	1310021A		Sorter1	1.895833333	19702326721	AREA_13_L1
9	CASE		1	1			558	1310021A		Sorter1	1.895833333	19702326722	AREA_13_L1
10	CASE		1	1			558	1310021A		Sorter1	1.895833333	19702326723	AREA_13_L1
11	CASE		1	1			558	1310021A		Sorter1	1.895833333	19702326724	AREA_13_L1
12	CASE		1	1			558	1310021A		Sorter1	1.895833333	19702326725	AREA_13_L1
13	CASE		1	1			558	1310021A		Sorter1	1.895833333	19702326726	AREA_13_L1
14	CASE		1	1			558	1310021A		Sorter1	1.895833333	19702326742	AREA_13_L1
15	CASE		1	1			611	1310021A		Sorter4	1.895833333	19902326727	AREA_13_L1
16	CASE		1	1			570	1310021A		Sorter2	1.895833333	20802326735	AREA_13_L1
17	CASE		1	1			614	1310021A		Sorter4	1.895833333	26402326728	AREA_13_L1
18	CASE		1	1			614	1310021A		Sorter4	1.895833333	26402326729	AREA_13_L1
19	CASE		1	1			614	1310021A		Sorter4	1.895833333	26402326730	AREA_13_L1

i. Apply Filter on table headers.
j. Remove the picks from AREA_25_V if any in the Product column.
k. In SU Type column select TOTES only, then replace all values with "2" in O_Width column.
l. Select all items in SU Type column, then select #N/A in O_Width column. Replace all values with "1.67" in O_Width column.
m. Select all items in O_Width column. Sort from A to Z the O_Location column, then sort Smallest to Largest the Shipping Unit column.
n. Select TOTE only on SU Type column. For every shipping unit remove all lines except the last one.
o. Select all items in SU Type column, then sort from A to Z the O_Location column
p. Create worksheets for each pick module level and name them accordingly. Example: name the worksheet as "243" for module 24 level 3.
q. In the Product column select each area one by one and copy their content to their worksheet.

42	CASE		1	1			620	15151B6		Sorter4	1.870083333	17502328807	AREA_15_L1
43	CASE		1	1			614	15151B8		Sorter4	1.041666667	26402328808	AREA_15_L1
44	TOTE		1	1			602	15152A1		Sorter3	2	2102328801	AREA_15_L1
45	TOTE		1	1			614	15152B6		Sorter4	2	26402328753	AREA_15_L1
46	TOTE		1	1			591	15153C3		Sorter3	2	19002328794	AREA_15_L1
47	CASE		1	1			620	15154B3		Sorter4	1.67	17502328812	AREA_15_L1
48	CASE		1	1			620	15154B3		Sorter4	1.67	17502328813	AREA_15_L1
49	CASE		1	1			581	15154B8		Sorter2	0.708333333	25102328814	AREA_15_L1
50	CASE		1	1			581	15154B8		Sorter2	0.708333333	25102328815	AREA_15_L1
51	CASE		1	1			620	15154C8		Sorter4	1.375	17502328816	AREA_15_L1
52	TOTE		1	1			598	15156C3		Sorter3	2	39602328791	AREA_15_L1
53	TOTE		1	1			614	15158A1		Sorter4	2	26402328810	AREA_15_L1

Cycle 7 manipulated / 131 / 141 / 151 / 152 / 161 / 162 / 163 / 164 / 201 / 202 / 203 / 204 / 211 / 212 / 213 / 214 / 221

Ready