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A SIMULATION-BASED TDABC MODEL TO MANAGE SUPPLY CHAIN COSTING: A CASE STUDY

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ABSTRACT

Effective management of supply chain costing is crucial for decision-making during times of disruption. It provides accurate cost indicators, enabling organizations to adapt to the risks of disruptions and mitigate their adverse effects. The supply chain costing literature has shown that traditional cost accounting approaches are inadequate in addressing the dynamic and complex nature of supply chain performance and the nonlinear behavior of the involved processes. Consequently, this paper presents a simulation-based supply chain costing framework that integrates discrete event simulation and time-driven activity-based costing to explore the dynamics of management accounting tools in a real context with all their complexities and interdependencies. The framework will be applied to the logistics function of an automotive supply chain to demonstrate the applicability of a static versus a dynamic time-driven activity-based costing model. The suitability of the models is based on their ability to reflect the real operational performance of the supply chain and suggest ways to improve it.

1 INTRODUCTION

Global supply chains have been severely disrupted in recent years due to various factors, including climate change, the COVID-19 pandemic, and the Russian-Ukrainian conflict. These disruptions have tested the efficiency and resilience of supply chains (SC) and highlighted the need for quick adaptability. In attempting to balance resilience and cost efficiency, decision-makers need a deep understanding of supply chain costing. SC costing is a significant indicator of the effectiveness of core activities, operational efficiency, and resource management, and it is often an important factor in making informed decisions.

Logistics costs are a crucial component of supply chain management (SCM) and play a significant role in managing and controlling SC efficiency (Smith and Srinivas 2019). However, reports indicated that logistics sectors' profit margins are declining due to disruptions, increasing labor and operational expenses, and the complexity of last-mile deliveries (Paxton 2022). As a result, decision-makers seek advanced cost management techniques that can reflect the complexity and dynamic nature of logistics during disruptions.

Current costing models are limited in depicting supply chain costs and operational performance in a fast, dynamic, and complex context. Integrating management science with cost accounting approaches is necessary to overcome this challenge. Process simulation is a powerful tool that can effectively model the dynamic behavior of supply chains and understand the interconnectivity between actors at the intra- and inter-organizational levels (Jahangirian et al. 2010). Although simulation-based management accounting studies are still in their infancy stage, they can be used to explore the dynamics of management accounting tools in a real context with all their complexities and interdependencies.

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This paper introduces an integrated cost management framework combining two approaches: Discrete Event Simulation (DES) and Time-Driven Activity-Based Costing (TDABC). The framework improves decision-makers' comprehension of logistics and transportation performance during disruptions, enables them to evaluate future scenarios, and facilitates their assessment of strategies and decisions that involve substantial investments.

2 LITERATURE REVIEW

The SC encompasses the upstream and downstream flow of materials, information, and capital. As stated by Chopra (2019), SCM is the management of the surpluses and deficits of these flows along each transaction point of the SC system, from the source of raw material through to consumption and any associated return logistics. A resilient SC needs to balance resilience capabilities with cost efficiencies. The visibility and control of material, information and capital surpluses and deficits are critical in achieving this, with capital or cost often seen as the low-hanging fruit, especially from the perspectives of logistics cost drivers.

TDABC was developed to address activity-based costing (ABC) shortcomings, namely, resistance to change, time consumption for data gathering to feed ABC implementation, measurement errors, the lack of detail to capture some complexities, the lack of coordination between the ABC system in different departments, and the difficulty in updating the system or bring any modification (Kaplan and Anderson 2007). The technique is based on the calculation of two main parameters: capacity cost rate and time equations. The first calculates the cost per time of supplying the capacity and capacity usage; the second describes the process based on the total time spent per each process by assigning resources costs to the activities and transactions performed.

Over the last decade, TDABC has received more attention in academic literature, and its application has covered different sectors such as; hospitality, financial services, libraries, and manufacturing (Al-Halabi and Al-Mnadheh 2017; Bagherpour 2015; Gregório et al. 2016; Pernot et al. 2007; Vedernikova 2023; Yonpae and Sungwoo 2019), with a strong focus in healthcare (Khan et. al 2019; Azevedo 2020). However, less applications are reported in logistics despite evident opportunities in the field. Siguenza-Guzman et al. (2013) demonstrated that the technique captured the complexity of logistics operations and showed how the cost calculation was simplified by reducing the number of activities from 330 under ABC to 106 under TDABC. An application by Everaert et al. (2008) demonstrated how the traditional ABC misallocated 55 % of the indirect costs compared to TDABC. Another application of TDABC in distribution centers was made by Afonso and Santana (2016), considering two capacity rates. TDABC provides a perspective of resource consumption by each product category and type of freight (according to a radius). The calculation provides information on unused capacity and unprofitable products by comparing the cost to the sale. Like other costing methodologies, TDABC modeling is not stochastic and does not capture the uncertain and volatile nature of supply chain systems very well. Integrating TDABC with simulation modeling complements the capacity and time equation calculations with the dynamic, high variation of a real-world system.

SC costing and simulation modeling is a well published field, with many applications from retail distribution costing (Cooper et al. 2014), game theory-based coordination costing (Liu et al. 2008) and knowledge retention costing (Crowe et al. 2015). Interestingly, unlike its predecessor ABC, where application with simulation is common, especially in manufacturing, (Beck and Nowak 2000; Takakuwa 1997), the body of literature that combined TDABC and simulation is scarce. The few accessible articles available are confined to the healthcare sector (Bagherpour 2015; Dooley et al. 2022; Nagra et al. 2022).

3 METHODOLOGY

The methodology of this article develops an integrated costing framework based on the application of TDABC and DES, following a three-phase approach applied to a case study (Figure 1).

- Phase 1: *Understanding the context* of application within the selected case study. Through qualitative and quantitative data, collected from observations and interviews resulting in process map flows and conceptual models.
- Phase 2: *Application of the TDABC*, by following the implementation framework of TDABC that consists of identifying resource expenses within the studied department and their time drivers, calculating the capacity cost rates, and developing the subsequent time equations.
- Phase 3: *Integration of TDABC-DES*, once the system is understood, the simulation model translates the system configuration into a dynamic tool, based on the process mapping and the conceptual models of Phase 1. The developed time equation in Phase 2 will be enhanced to capture the dynamic nature of the process and will be inputted into the simulation. Similarly, the capacity cost will provide the foundations for key performance indicator (KPIs) calculations based on the time and cost of the studied processes, enabling the assessment of the operational performance of the studied SC.

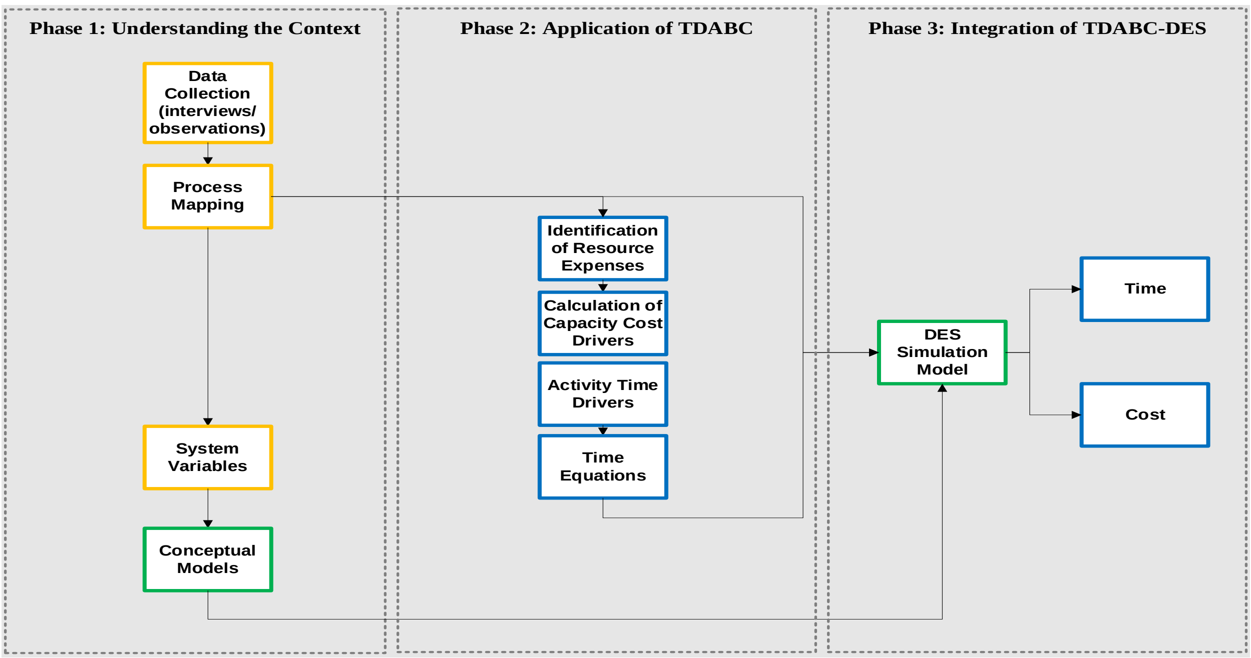

Figure 1: Three-phase approach methodology.

4 CASE STUDY

4.1 Problem Statement

The case study company is a manufacturing company that operates in the automotive sector in Morocco. The company will be referred to as XYZ for confidentiality reasons. The activity of XYZ is dedicated to the sewing and cutting of car seat covers intended exclusively for export to Europe, with a portion intended for the local original equipment manufacturer (OEM). To assess the capabilities of TDABC in evaluating operational performance, the technique is applied to the logistics activities of the case study. The inbound logistics activities within XYZ can be summarized in the four main processes: the reception of goods (components, textile rolls, and chemical products), quality inspection, put-away, storage and picking. After the picking process, production begins through the activities of cutting, sewing, foaming, and filling. If all quality tests are fulfilled, the finished products are ready for dispatch.

4.2 Phase 1: Understanding the Context

Several interviews were conducted with different stakeholders to understand the SC context and illustrate the SC configuration. To allow system improvement, a deep understanding of the actual configuration was needed through process mapping such as material and information flow analysis and diagram (MIFA) and MIFD. These detailed process maps were based on the generic source/deliver make-to-order structures of the supply chain operations reference (SCOR) model (APICS 2017), as illustrated in Figure 2.

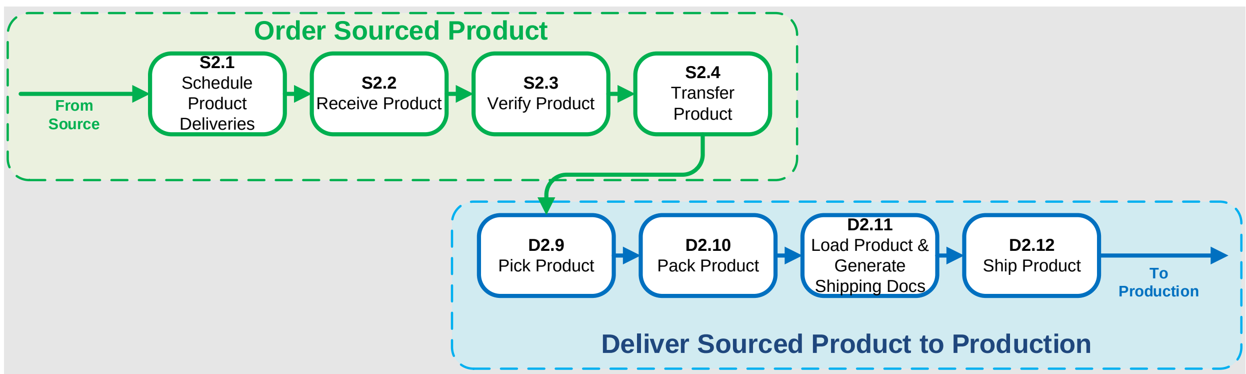

Figure 2: Basic process flow of the SC activities within XYZ.

4.3 Phase 2: Application of the TDABC

The application of TDABC relies predominantly on the calculation of two parameters: the capacity cost rate and time equation. Rahoui et al. (2021) provide a detailed calculation of the capacity rates and the elaboration of the time equations used this case study.

4.3.1 Capacity Cost Rate

The first step in implementing TDABC is calculating the capacity cost rate by dividing the total aggregated department costs over the total capacity supplied (Table 1).

$$\textbf{Capacity cost rate} = \frac{cost\ of\ capacity\ supplied}{practical\ capacity\ of\ resources\ supplied}$$

The *cost of capacity supplied* is calculated by summing the cost of all the resources used in the logistics department or process, including personnel, supervision, occupancy, equipment, and technology. The logistics costs are summing up to 5165808.03 Moroccan Dirham (MAD).

The *practical capacity* at XYZ is calculated by defining the total time available for employees to operate the work, i.e., multiplying daily working hours by the total number of employees in each process and the number of working days per year (Kaplan and Anderson 2007; Somapa et al. 2012).

Following the recommendations of Kaplan and Anderson (2007) for the calculation of practical capacity, and after concerting with the managers, this capacity was estimated at 80 % of the nominal capacity. The 20 % accounts for restroom and cigarette breaks, as well as prayer time.

4.3.2 Time Equations

Linear models are used to develop the equation for each process, as suggested by Afonso and Santana (2016) and Kaplan and Anderson (2007). Based on the process maps and the interviews, the equations were elaborated, taking into consideration the time drivers of each process (Everaert et al. 2008). The time measurements were taken from direct observations, where the activities were stop-watch timed. If available from the ERP system, the information was taken directly from the system to avoid the bias of time estimation and time estimation errors. 30 observations were taken for each sub-activity when possible. Table 2 presents the equations for the four processes.

Table 1: Capacity cost rate calculation.

Operators	morning shift	afternoon shift	night shift
Operators (Reception & Put-away)	32 h	32 h	8 h
Quality reception	16 h	16 h	8 h
Picking	56 h	48 h	16 h
Total worked hours/day	216 h		
Total worked days	300		
Nominal capacity in hours	76032		
Practical capacity in min	3649536		
Capacity cost rate	**1.54 MAD/min**	92.7 MAD/h	

Table 2: Time equations of the logistics processes.

Process	Time equations
Reception	$1+ 14.17+ 10.15X_4+ 90\, X_5+ 2.36X_8X_9+ 2.74*3\, X_6+ 1.15X_1X_{10}+ 0.66\, X_2X_{11}+ 0.63\, X_{12}\, X_{13} +1.63X_3\, X_{22} +3.87X_1X_{10}+ 1.04X_2X_{11} +0.12\, X_2X_{13} + 5\, X_7$
Quality inspection	$1+ 2.41X_{14}\,(X_{23}X15X_1+ X_{24}X_{15}X_2) + 3.01X_1\, X_{14}\, X_{16} + 5.63X_2\, X_{14}\, X_{16} + 15* 2X_{17}\,(X_1+X_2) +705X_{15}X_1+ 12X_{15}\, X_2 + 135X_1X_{15} + 10X_2X_{15} + 15X_{15}$
Put-away	$5 + 1.51X_1X_{18}+ 5.17\, X_{25}X_1\, X_{10}+ 0.76X_2X_{19} + 1.02X_3X_{20} + 0.94X_1 +\alpha 3$
Picking	$0.25+ 2X_1+ 0.82X_2 + 0.22X_1 + 0.\, 22X_2 + 2.49X_1X_{21} + 0.86X_2X_{21}$

where:

X_1: 1 if it's a component, 0 otherwise.
X_2: 1 if it's a textile roll, 0 otherwise.
X_3: 1 if it's a chemical product, 0 otherwise.
X_4:1 if documents are conform, 0 otherwise
X_5: report to the management
X_6:1 if truck if double-deck, 0 otherwise
X_7:1 if the textile roll is coming with missing barcode
X_8: number of lines in each manifest
X_9: number of manifests per truck
X_{10}: number of pallets (component)
X_{11}: number of rolls pallet
X_{12}: 1 if rolls are handled manually
X_{13}: number of textile rolls to be handled manually
X_{14}: 1 if the supplier is problematic, 0 otherwise
X_{15}: number/ quantity of the components in the batch
X_{16}: duration to check sample from the batch
X_{17}: 1 if sample is not conform, 0 otherwise
X_{18}: 1 if bin location is empty, 0 otherwise
X_{19}: number of rolls
X_{20}: number of containers of chemical products
X_{21}: is the distance travelled
X_{23}: the number of problematic components
X_{24}: the number of problematic rolls
X_{25}: number of boxes in a pallet
$\boldsymbol{\alpha 3}$: Number of the component to put back to the truck receiving area (TRA)

4.4 Phase 3: Integration of TDABC-DES

4.4.1 Model Boundaries

Through the aid of TDABC, a simulation model was developed to assess the performance of the inbound logistics company within a dynamic complex manufacturing context. The dynamic model would account for the uncertainty and complexity that fails to be captured by the sole application of TDABC. Therefore, the simulation model integration increases the robustness of the TDABC model and improves process performance through four major axes:

1. Improve the time equations, as seen in TDABC the time is developed using the average values of the 30 observations, instead, the average will be replaced by their probability distribution function.
2. Capture the dynamic nature of the system: the TDABC-DES model avoids isolating events with deterministic parameters (example of the reception of one truck) and captures the uncertainty and variability of activities.
3. Override the TDABC assumption that resources are available, and allocate the resource according to their availability to execute the tasks.
4. Assess the accuracy of the current configuration through the calculation of the TDABC-based operational KPIs: time of activities and their subsequent cost.

4.4.2 Data Collection

In addition to the data collected to elaborate the time equations, additional data were needed to develop the simulation model (Table 3).

Table 3: Additional data required for the simulation model.

Area	Data required	
Reception	The mix of components in the truck N of pallets of components N of textile rolls & chemical barrels Time to unput manifest Time to scan materials	Truck arrival rate Trip Time from Entry to Loading bay Truck Unloading Time Checking time % of conforming docs
Quality inspection	Percentage of problematic suppliers Non-conformity rate of suppliers Isolation time Sorting time	Time to check conformity for the 3 materials Response time of management when problem is reported
Put away	Time to store pallets, Chemicals & textile (in racks and for picking) Review resource assignment for storage (forklift vs transporters)	Probability of empty bin available Number of cells available
Sorting	Sorting policy	Stock capacity/ inventory turn
Picking	Frequency of replenishment Picking schedule	Resources
Warehouse layout	Interchangeability of the resources across different processes	

4.4.3 Simulation Modelling

The simulation model was developed in Anylogic software V8. The flexibility enabled by the Java-based software allowed the integration of the time equations and customization of events to reflect real-life situations. To ensure the model functioned as expected, some assumptions needed to be made:

1. The raw material mix in the truck is represented by 60 % textiles, 39 % components and 1 % chemical products. This is justified by actual stocks, where XYZ had an overstock of chemical products. Textile rolls constitute the majority of the sourced raw material. While the number of components and rolls could be equal, components are represented by pallets, while rolls are wrapped individually or rarely shipped in pallets when the needed lengths are small.
2. 30 % and 25 % of the received textile and components respectively will undergo a quality check.
3. There are six unloading bays, but two are used for the dispatch, so for the inbound logistics activities, four bays are assumed to be available.
4. Once the suppliers replace the non-conforming material, the new shipment is assumed automatically to be quality conforming.

5 RESULTS

5.1 Discrete Event Simulation Initial Results

The model was validated using a three phased approach, the first approach consisted of validating conceptual model and process flows with warehouse and logistics managers. In the second phase, a decomposition method was followed by verifying each group of blocks separately, using the software built-in code debugger. The third approach observed the model behavior under known and defined input parameters, comparing statistically the results of the models against the real outputs (e.g., the total number of trucks received, the number of conforming components).

After validating the model, the simulation was run for a period of three months to make sure that the model reached a steady-state behavior. It was observed that the model was steady after one week. Since the data generated from 3 months of model time needed a large computer capacity and the model was steady after one week, the model time was set to one month. Table 4 presents the results from 25 runs based on the unloading time for bays and dock-to-stock KPIs.

Table 4: Summary of 25 runs TDABC-DES Reception times results.

Process	Min Time	Avg Time	Max Time	Standard Deviation
Reception Time (dock-to-stock)	13.76 h	19.49 h	30.75 h	3.65
Unloading Time B1	3.58 h	4.38 h	5.25 h	0.38
Unloading Time B2	24.97 h	46.46 h	75.12 h	12.00

Two important KPIs for the reception process are the unloading times for Bay 1 and Bay 2, and the total reception time. The simulation shows that the average duration of the process is 19.49 h. The calculated KPIs were compared to real life observations and actual company KPIs to validate the model and its ability to represent real life scenarios. Depending on the particular real-life scenario, trucks were received within an interval of 8 up to 24 h. This duration is accounting for the reception with no issues, but also considering scenarios with unexpected reception issues such as missing documents and references received without labels (Barcodes).

The unloading time and dock-to-stock for the first loading bay is estimated to 4.38 h. However, for the other docks, the lead-time is much longer since priority is given to the first dock, and there are not enough resources to proceed with the unloading of more than a truck at a time. For instance, for the second dock the average lead time is 46 h; according to the practitioners, this is closer to the lower bound of inefficient unloading operations. A similar process was followed to validate the other logistics processes, where the total process time was compared to the real process time when available.

5.2 Comparison of TDABC and TDABC-DES Results

The purpose of TDABC-based models is to calculate the process times and costs which are not always available or obtained through the ERP system. A comparison of the overall process results to KPIs is intricate, so expert advice was needed to comment on the result and their proximity to real world results. In addition to the advice, observations made by the modeler, who shadowed the operators over a 3-month period, allowed them to comment on the results.

To compare the results between the application of TDABC and TDABC-DES, a two-week period is considered to reduce the error and the inference of randomness and noise effect on the results when comparing deterministic and stochastic techniques. The values obtained from the simulation model and TDABC will be compared to the real system values for data and model validation.

Table 5 provides the results of TDABC application, calculating the average process time over a two-week period, when:

1. There is a normal reception with no reported issue, the average is 31.14 h.
2. When 25 % of the received trucks over the period have missing documentation that blocks the continuity of the operation, the average reception time is 46.13 h.
3. When 10 % of the received textile rolls arrived with missing labels for the RFID reader-, the average is 37.47 h.

By calculating the average of the three case scenarios, the reception time is estimated by the TDABC model to be 38.24 h. In contrast with the DES-based TDABC, the average reception time when considering different scenarios is 19.72 h. This latter result is closer to the benchmark that is based on the observations of the modeler and the expert advice and operators' testimonies. The components' put-away results show that the time process estimation is underestimated through the static application of TDABC, where the time equations ignore the delay times due to a lack of resources, or the resources are involved in other activities. However, for the textile rolls, the period is overestimated through the TDABC as compared to the DES-based TDABC. The mathematical model is not acknowledging when resources are becoming available to proceed with the assigned activities. Static TDABC also ignores when activities run in parallel, since every sub-activity of the process is added to the time equation.

The picking process is slightly different from the previous processes as it is not directly linked to incoming deliveries. Its frequency is fixed, and any variance stems from the distance travelled. The distance can be divided into three segments: close (for less than 10 meters), medium (between 10 and 50 meters), and far (for more than 100 meters).

There is a noticeable difference in the average times for the picking process between the static and dynamic TDABC. Whilst the interpretation of the results for this process is particular, it can be explained by simulation-based results that represent a one-off picking activity, in contrast with the static TDABC whose results represent the cumulative time of picking operations.

With such a difference in the results, where the static TDABC tends to underestimate or overestimate the durations of different processes as compared to the DES-based TDABC, it is challenging to draw a conclusion about the strength of the models. However, by comparing the results from both models to a real case scenario that had the same input parameters, it becomes clearer which model presents realistic results that reflect the real-world system.

Table 5: Comparison processes results with TDABC and DES-based TDABC.

Scenario	Process	Static TDABC	DES-TDABC	Benchmark
	Reception			
S1	Normal delivery	31.14 h	19.72 h	8 to 24 h
S2	Delivery with missing documents	46.13 h		
S3	Delivery with missing barcodes	37.47 h		
	Average	38.24 h		
	Quality inspection			
S4	Quality inspection of components with no issue	4.56 h	13.08 h	2 to 48 h
S5	Quality inspection of problematic references	65.82 h	40.19 h	
	Average of quality inspection for components	35.19 h	26.63 h	
S6	Quality inspection of rolls	15.79 h	12.34 h	36 to 70 h
S7	Quality inspection of problematic rolls	54.02 h	116.03 h	
	Average of quality inspection of rolls	34.90 h	64.18 h	
	Put-away			
S8	Put away component with no return to TRA zone	27.22 h	60.96 h	24 to 72h
S9	Put-away components with return to TRA	27.96 h		
	Average Put away components	27.59 h		
	Average Put away of rolls	20.30 h	44.58 h	24 to 36 h
	Picking			
S10	Picking components close	18.98 h	1.38 h	10 min to 1h
S11	Picking components Medium	19.56 h		
S12	Picking components far	20.28 h		
	Average picking components	19.60 h		
	Average Picking of rolls	6 h	0.23 h	20 min to 35min

In terms of costs, process costs are obtained by multiplying process durations by capacity cost rate (see Figure 4). The TDABC overestimates the cost of the reception, the quality inspection of components and the picking for both components and rolls and underestimates the cost of quality inspection for rolls and put-away process. The misallocation of process costs is directly attributed to the process time calculations seen in Figure 3.

Figure 4 shows that the total difference between logistics activity cost can amount to 12785.18 MAD, based on the two models. The contrast arises from the difference calculated for each process duration and can be minimized using a more accurate model that reflects as closely as possible the real world activity and the logistical performance.

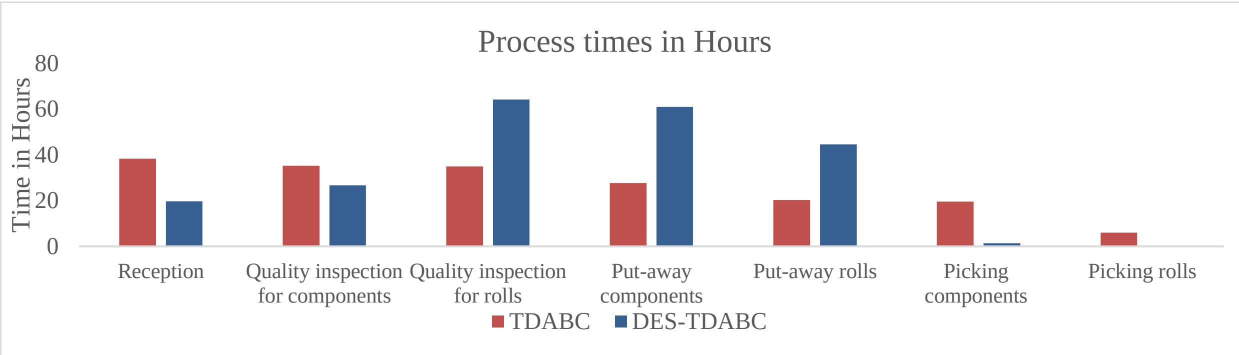

Figure 3: Comparison of the process time calculation via TDABC and TDABC-DES.

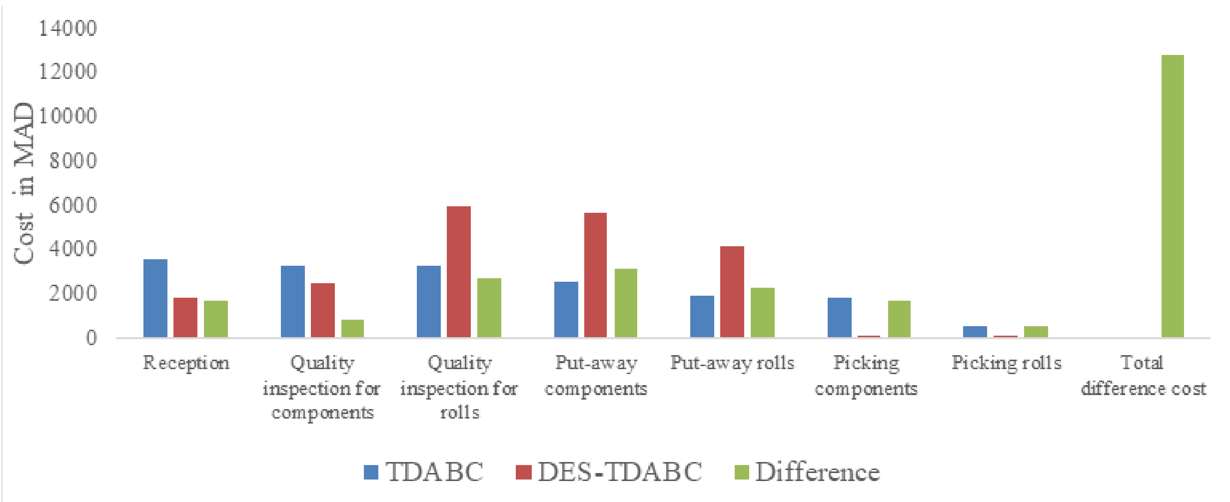

Figure 4: Comparison of processes cost (in MAD) under TDABC and DES-TDABC.

6 DISCUSSION AND CONCLUSION

The initial results of the application of static TDABC have determined that the technique is well suited for calculating the times in ideal scenarios and considering different time drivers. Although it allows accounting for different scenarios within the same process, it fails to consider the intricacy of the real-world case scenario, where multiple "what-ifs" are possible and the possibility of activities taking place in parallel. In fact, the comparison between the statistic TDABC and TDABC-DES results demonstrates that the capabilities of the technique are limited to situations with low variability.

The static TDABC application tends to misestimate the duration of activities compared to TDABC-DES. In the case of underestimation (e.g., quality inspection of problematic rolls, put-away of components and textile rolls) it can be explained by the lack of consideration of available resources. TDABC tacitly considers that resources are available all the time, whenever the activity event is triggered. In contrast, the DES-based TDABC accounts for the idle and waiting times when the activity starts. For instance, if two trucks are received on the same day, the dock-to-stock of the first delivery is 8 hours while for the second truck, the unload lasts for 19 hours since the resources are still engaged in the first truck, or the TRA area is full, so the put-away activity needs to start before proceeding with the unloading of the second truck, to avoid blocking the alleys. Another explanation for this underestimation is that the establishment of the time equations for each process assumes that each process is independent and linear. However, the processes are intertwined; for instance, the reception and quality inspection are dependent upon one another, as are the put-away, quality inspection and reception. In the case of overestimation (e.g., reception) the linear nature of equations doesn't capture the parallelism between activities and tend to add up all the terms that results in an overestimation of the duration. Furthermore, TDABC-DES input time equations based on the probability distributions for each subprocess instead of the adopted averages in TDABC, which limits the bias of outliers when calculating averages.

DES-based TDABC provides more realistic estimations since it accounts for the usual inconveniences, such as the reception of deliveries without appropriate documentation and missing labels at a random frequency that were set in the simulation modelling software. In fact, the simulation-based model allows accounting for the conventional uncertainties but also unconventional delays such as severe weather conditions, strikes and other unforeseeable conditions by introducing a random seed in the model parameters for that purpose. Besides integrating the uncertainty in the calculation, the simulation-based TDABC accounts for the resources deployed to execute the task, contrary to the static version, that does not include the number of resources while developing the time equations. Therefore, provides with a more realistic measure of performance.

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