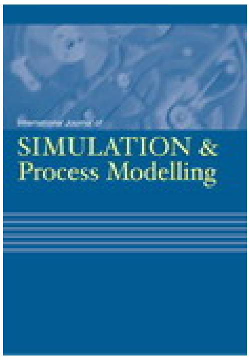

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Estimation of the service level in a materials analysis laboratory

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Abstract: This work introduces a materials laboratory for civil engineering where the time required to perform each test is not deterministic, likewise the overall performance of this laboratory varies over the time. The process begins by filling out an application and ends with the results report delivery. This article aims to provide the evaluation, analysis and improvement purposes of the service level of the laboratory. First performance indicators were defined and then the simulation model was generated and implemented to estimate the resulting values of the process; next, the system's operations were simulated, different scenarios were assessed, and the service level achieved was calculated. Considering outcomes from simulation process, the system was evaluated and analysed against the overall equipment effectiveness, thus the model provides a decision support tool to identify different configurations to achieve service level expected. Based on the obtained data, service level and key performance indicators were calculated for future scenarios.

Keywords: key performance indicators; KPIs; simulation; work orders; materials laboratory; performance.

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1 Introduction

The present work is developed for a laboratory that was created between the 1950 and 1960, the objective of this laboratory has been supporting the professional education of civil engineers. From 1970 it has offered to offer specialised services in the analysis of construction materials, and nowadays it has six kinds of services which focus on hydraulic concrete (HC), steel, asphalt concrete, construction elements (CE), geotechnics and topography; tests performed during the completion of the work, allow to know the physical properties of the materials that are analysed, these tests follow the standards required in Mexico, by mention NMX-C-416-2003 'Building Industry – Sampling of Earth Structures and Testing Method' and NMX-C-083-ONNCCE-2014 'Building Industry – Concrete – Determination of Compresive Strength of Specimen – Test Method'.

Worth to mention that all the offered services are duly certified, according with the construction regulations of Mexico City (Construction Regulations for the Federal District, 2019) including the obligations of constructors: "hire laboratories certified and/or accredited by authorised entities to carry out the tests established in the standards to guarantee the quality of the materials". From a managerial perspective, since its creation up today, according to the laboratory managers, they have worked without using performance indicators, so the strategic and operational decisions are made just by the experience of managers with the goal of accomplish required services. In Section 3.1 this paper proposes a set of indicators that seeks to help to recognise the status of the laboratory.

Based on the above, in terms of management and decision support tools, the laboratory has not taken a systematic approach to measure and review its performance and thus has not yet been assessed and identified bottleneck resources, hence the present work seeks to provide insights into the past performance and by means of using discrete event simulation aims to enable an iterative process for future improvement in combination with other methodologies such theory of restrictions (TOCs), as described by Tuğçe et al. (2014).

The measurement of performance in the processes or operations achieved by a company, allows to know if they are being carried out according to the expected performance level. The key performance indicators (KPIs) are widely used metrics to determine the fulfilment of the activities in a company. Belvárdi et al. (2012) mention that some studies show that the best approach to control the administration of supply chains is based on the Balanced Scorecard methodology, which aims to provide a monitoring system for the companies, through the analysis of a multidimensional panorama of the KPIs. Toor and Ogunlana (2009) consider that the KPIs are useful, since they allow comparing the current performance against the expected one in terms of effectiveness, efficiency and quality. Likewise, the KPIs allow evaluating the performance of all the parties involved in the chain. Morales et al. (2013) suggest a systematic approach for supply chain, where different aspects must be distinguished: from the supply chain it is necessary to delimit the system with respect to its environment, in this way the bases and the types of relationships between the links can be built, likewise, they help to determine the structure of the relationships and the existing organisation between the elements of supply, manufacturing and delivery. The authors mention that the performance measures for the supply chain must look at complexity, respond to changes in inputs, correctly represent the interests of customers and administration in the system, be programmable in process simulators, as well as demonstrate the differentiation and comparison between results under different scenarios. Sellitto et al. (2015) through the Supply Chain Reference Operators (SCOR) offers a framework where evaluation of reliability, responsiveness, agility, and costs is enabled.

The KPIs must represent the needs and objectives of the company, and at the same time they must be oriented to the mission and vision, as Shahin and Mahbod (2006) indicate that these reflect and are derived from the objectives of the organisation. Likewise, each indicator must be based on criteria that allow its subsequent analysis. Kikolski (2019) mentions that the key indicators are used to measure the basic parameters that characterise the operation of an organisation. Morales et al. (2013) extend these ideas considering the indicators as a set of variables that always warns about problems in the operation before the system reaches a critical point without solution. Palma (2014) considers that the metrics used in level one of the SCOR models are KPIs and their function is to measure and express the general performance of a specific characteristic. Gunasekaran et al. (2004) mention that the measurement of the performance of supply chains can be carried out at three levels: strategic, operational and tactical, likewise, the metrics used to measure performance and improvement at each level must truly capture the essence organisational performance. Lavy et al. (2014) define that the chosen KPI must be the most relevant to the organisation's objectives and must be calculated, analysed and evaluated so that future performance is acceptable at the lowest cost.

When carrying out a project, it is necessary to evaluate the performance achieved during its progress, so it is necessary to establish indicators that determine whether the performance is at the desired level. Ogunsanmi (2013) mentions that KPIs can be used to identify strengths and weaknesses in projects shared between the public and private sectors, as well as being useful tools for project performance management. Ugwu and Haupt (2005) refer to the fact that when developing effective strategies for sustainable construction environments, it is necessary to consider three key elements:

1 a clear formulation and establishment of objectives

2 identifying and evaluating alternatives in quantitative and/or qualitative terms

3 an effective implementation of the selected alternative.

Therefore, to develop the second point, it is necessary to establish KPIs that allow evaluating those alternatives that are established in both terms. Likewise Jahangirian et al. (2016) consider that in order to achieve successful simulation projects, it is necessary to propose a framework that includes KPIs, since they are linked to a set of critical success factors, through a measure of project success.

In order to establish KPIs, it should not be assumed that all the indicators are applicable to the same projects or companies, they should not be seen as 'one size fits all' approach, depending on the needs of the project or the industry, and in conjunction with the mission, established vision and objectives, different KPIs would be relevant or not to determine different aspects of interest. Rondini et al. (2017) mention that companies are migrating from focusing on products, towards a service offer system, in this change they face complexity and dynamism according to customer preferences, so the key indicators should go in the same direction. Kang et al. (2016) make a detailed description of these metrics used in their research, they consider support elements such as time, quantity, and maintenance; then the relationships between each element that will serve to measure specific aspects within the system is established. When it is required to analyse and optimise operations in an emergency department, two aspects are important, being the KPIs and the improvement options that are desired to be considered in a study (Vanbrabant et al., 2019).

To replicate or emulate the behaviour of a system through the operations carried out by a company, it is necessary to use process simulation techniques. Gómez et al. (2015) refer that simulation can be used to solve real problems, through the analysis and description of the behaviour of the system. Likewise Rouzafzoon (2016) recreated the services offered in a hospital, considering that for the measurement of the performance and the results in the simulation model it is necessary to establish KPIs, the author considers the level of service and resource utilisation as a critical aspect in hospital administration and healthcare service provision (Heshmat et al., 2022; Venkatesan et al., 2023). For Cheaitou et al. (2020), emergency services in hospitals, have been growing, so users or patients have experienced a longer waiting time to receive service and then through simulation modelling, it can be used to identify factors that have a significant impact on length of stay of patients in the emergency department.

Janssens (2010) considers that in a hospital, it is important the methods to manage the demand for laboratory tests, since they require them to feed a computer system. According to Wert et al. (2023) computerised simulation can be used to model production processes and predict performance metrics that are important for the purposes of planning production strategies.

To reproduce the way in which a company is operating, it is necessary to describe all the procedures that are carried out, from the request for a service or the contracting to produce a product, Sánchez et al. (2015) consider that to develop the simulation process, the real structure of the production process must be taken into account as an input, in this way, all those procedures involved must be detailed to meet the requirements of the clients.

As various authors display, in the case of a laboratory, inputs are required to recreate the system, therefore, for a material testing laboratory, all inputs to the system should be considered, such as: the amount of pre-orders to be elaborate, the number of work orders (WOs) to fulfil and all the inputs necessary to meet the requirements of the laboratory demand.

For all this, it is necessary to have extensive knowledge of the processes, for example, what step is necessary to carry out to transform a pre-order into the result of a requested test, as well as the time it takes to prepare the test, and finally to know the outputs of the real system: percentage of WOs, level of service, work in process, among others. Likewise, it is important to properly characterise all these variables since they will allow establishing the bases to develop the simulation model with the use of software tools and establish scenarios of interest. Running the model and their inputs for those scenarios helps to the identify the most efficient way to manage laboratory resources in the face of different demand conditions, decisions that would be made based on the generation of KPIs in each scenario evaluated like García Orozco et al. (2022) make an estimation through KPIs to reduce the inactivity time in the delivery of automotive prototypes.

The remaining sections of this paper are structured as follows. In Section 2, the methodology applied to address the case study is described; Section 3 explains the case study, as well as the necessary elements to establish the KPIs and the simulation model; Section 4 shows the results obtained, Section 5 discusses the main findings and conclusions. Finally, future research lines are discussed in Section 6.

2 Description of the methodology

Simulation tools allow recreating the behaviour of the activities carried out by a company, Gómez et al. (2015) consider that through simulation scenarios of complex systems can be developed to understand their behaviour. Likewise García Orozco et al. (2022) consider that simulation is an important tool to identify the causes and quantify the effects on process' performance. Simulation models according to Morales et al. (2013) are composed of a set of representations, expressed as mathematical, logical, or symbolic relationships, between the entities that interact in the system, since through simulation it is possible to identify fundamental aspects in the operation of companies. Sánchez et al. (2015) consider that the application of this tool offers an alternative to get an accurate view of the critical points that production processes may have and to propose solutions that increase efficiency and reduce the execution time of different activities.

Table 1 Variable classification

Variable type	*Description*
Of level	They represent accumulations of the system, they are normally the most important variables and show the situation of the model at each instant, each level variable is associated with one or several flow variables
Flow	They determine the variation of the levels, collect the actions resulting from the decisions made in the system, determining the variations of the levels
Auxiliaries	They are parameters that allow a better visualisation of the aspects that condition the behaviour of the flows

Source: Modified from Campuzano et al. (2010) and Andrés aet al. (2016)

To establish the necessary bases for the development of a simulation model, Andrés et al. (2016) consider necessary to differentiate three types of variables within the system. Table 1 shows this variables' classification.

The implemented methodology follows the steps proposed by Banks (1998) in a simulation study:

1 data collection, categorisation and analysis
2 description of support elements
3 establishment of KPIs
4 development of operational processes
5 development of the simulation model
6 verification and validation of the simulation model.

In the first step, all the data related to the attention to WOs from the laboratory of the case study are collected, as Petrovic (2019) mentions, the demand for service is usually expressed through statistical data, later in the description of the elements support details are those that are likely to be counted, such as the number of WOs, confirmed WOs, confirmation time, etc. For the establishment of KPIs it is necessary to describe the relationship between the support elements and based on this, establish the indicators that allow knowing the current situation of the mentioned laboratory.

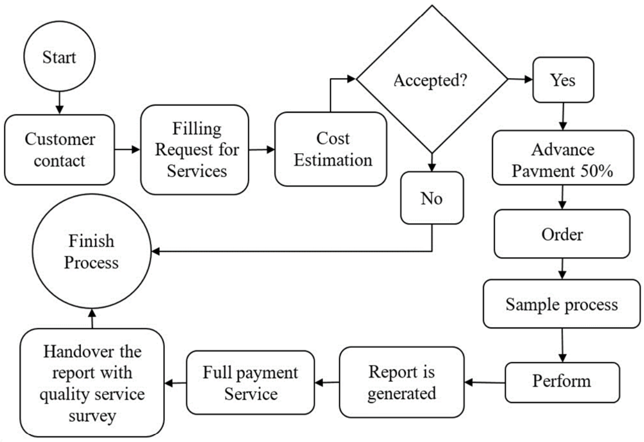
Then, for the development of the operational processes, a discovery phase is performed by using flow diagrams and general description of the activities involved, as well as the time it takes to complete the WOs. Finally, for the development of the simulation model, besides the ability of coding or implementing the logic using software tools, it is necessary to have the bases mentioned before, as Mohsen et al. (2021) consider, to carry out the simulation study, knowledge of the operations that are performed are required, such as that they can establish the parameters that allow estimating the required level of the KPIs.

3 Application of the methodology

Carrying out tests it is necessary to rely on specialised laboratories in different areas, according to Krivickas and Krivickas (2007) and referred to by Mahmoud et al. (2019), laboratories can be classified into three types: practical laboratories, simulation laboratories, and remote laboratories. In the case of our study, a practical laboratory was considered, since tests of different construction materials are performed there, likewise, Mahmoud et al. (2019) refer that KPIs can be used for the design, evaluation, and management of laboratory facilities. The general objective of the present work fits with an application for evaluation purposes.

As mentioned before, this laboratory carries out the analysis of construction materials, the available tests comprise the following: HC, steel (ST), asphalt concrete (ACN), CE, geotechnics (GT), topography (TOP) and multiple (MULTI); through these tests it is possible to measure the physical properties of the materials in question, the way in which an WOs is treated is shown in Figure 1.

Figure 1 Processing of OR



Source: Own elaboration

According to Figure 1, it begins with the filling out of a service request to make a quote, if the clients accept the pre-order, it is considered as 'confirmed' and it becomes a WOs, then, from this moment the service time starts and once the last test is done the time it takes for a WOs to be completed stops. Due to the nature of the laboratory, the time in which the report is generated is not considered, since it is prepared once the tests are finished and is delivered at the time of the settlement of the services.

Figure 2 shows the general operation of the laboratory.

Figure 2 General laboratory operation

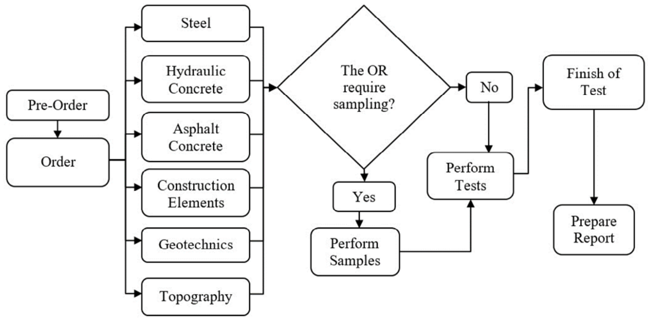


Figure 2 begins with the quotes received, however, only a percentage of these become WOs, according to the preference of the clients, any of the 6 mentioned services can be chosen, likewise, according to the type of service of the WOs this will require sampling and different tests will be performed.

The historical figures obtained about the pre-orders and WOs requested by clients from 2014 to 2019 are presented in Table 2 and Table 3.

Figure 3 shows the distribution of requests for each of the services, based on service request information from 2014–2019.

From Table 2 and in Figure 3, it can be seen that there is a very clear preference for geotechnical (GT) and concrete (HC) services, and a very sparse demand among the rest of the services from the catalogue offered by laboratory. The percentages obtained will serve as a basis for establishing the distribution of the type of service requested for quotes.

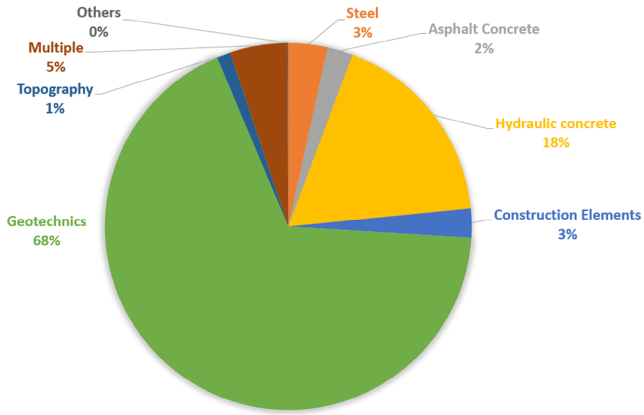
Table 2 Average preference percentage of requests by service from 2014–2019

Month	*ST*	*ACN*	*HC*	*CE*	*GT*	*TOP*	*MULTI*	*Others*	*Total*
Jan	3.1%	0.0%	18.4%	1.00%	73.5%	2.0%	2.0%	0.0%	100%
Feb	5.9%	0.0%	14.7%	2.90%	69.6%	2.0%	4.9%	0.0%	100%
Mar	0.0%	0.0%	17.1%	4.90%	62.2%	3.6%	12.2%	0.0%	100%
Apr	14.4%	1.7%	20.3%	3.40%	53.4%	1.7%	5.1%	0.0%	100%
May	0.0%	4.3%	18.3%	2.20%	71.0%	0.0%	3.2%	1.0%	100%
Jun	2.0%	4.6%	15.9%	1.30%	71.5%	0.7%	4.0%	0.0%	100%
Jul	0.0%	4.0%	20.0%	0.00%	70.0%	0.0%	6.0%	0.0%	100%
Aug	1.2%	3.3%	13.3%	2.20%	70.0%	1.1%	8.9%	0.0%	100%
Sep	1.2%	1.2%	25.9%	1.10%	70.6%	0.0%	0.0%	0.0%	100%
Oct	3.3%	1.0%	17.8%	5.60%	65.6%	1.1%	5.6%	0.0%	100%
Nov	3.2%	0.0%	19.4%	3.20%	67.7%	1.7%	4.8%	0.0%	100%
Dec	2.0%	8.0%	12.0%	2.00%	70.0%	0.0%	6.0%	0.0%	100%

Table 3 Total pre-orders, orders and confirmation percentage from 2014 to 2019

Month	*Year*																	
	2014			*2015*			*2016*			*2017*			*2018*			*2019*		
	PRE	*OR*	*CNR*	*PRE*	*OR*	*CNR*	*PRE*	*OR*	*CNR*	*PRE*	*OR*	*CNR*	*PRE*	*OR*	*CNR*	*PRE*	*OR*	*CNR*
Jan	33	14	42.42	23	11	47.83	15	10	66.67	15	7	46.67	13	5	38.46	16	7	43.75
Feb	22	10	45.45	12	12	100.0	31	11	35.48	20	5	25.00	27	7	25.93	18	10	55.56
Mar	23	11	47.83	18	6	33.33	16	8	50.00	17	7	41.18	4	2	50.00	19	6	31.58
Apr	25	12	48.00	30	7	23.33	19	12	63.16	20	8	40.00	27	8	29.63	26	16	61.54
May	18	7	38.89	17	8	47.06	20	11	55.00	26	14	53.85	26	8	30.77	13	4	30.77
Jun	22	9	40.91	36	10	27.78	57	12	21.05	22	11	50.00	23	8	34.78	17	6	35.29
Jul	9	5	55.56	12	11	91.67	10	4	40.00	10	5	50.00	9	6	66.67	11	3	27.27
Aug	16	6	37.50	23	10	43.48	21	13	61.90	16	10	62.50	14	4	28.57	19	10	52.63
Sep	17	4	23.53	13	8	61.54	28	10	35.71	15	4	26.67	18	2	11.11	20	10	50.00
Oct	23	15	65.22	26	9	34.62	16	11	68.75	12	2	16.67	21	6	28.57	15	7	46.67
Nov	18	9	50.00	15	7	46.67	8	4	50.00	12	1	8.33	15	1	6.67	16	8	50.00
Dec	7	4	57.14	15	10	66.67	10	4	40.00	12	2	16.67	4	3	75.00	7	3	42.86
Total	233	106	45.49	240	109	45.42	251	110	43.82	197	76	38.58	201	60	29.85	197	90	45.69

Figure 3 Service request average preference percentage since 2014–2019 (see online version for colours)



Source: Own elaboration

The categorisation of the data was carried out as follows:

1 quote request date

2 type of service

3 WO confirmation date

4 description of the requested service

5 WO delivery date.

With this information it is possible to know the date on which a pre-order was requested and the time it takes for the client to confirm (OR date), the types of orders and the description of the services requested by the clients, allows estimate the time necessary to treat the OR; in summary, all the required system inputs can be determined.

3.1 *Establishment of the KPIs*

To determine if the service level reached the set goal, Table 4 shows the established KPIs.

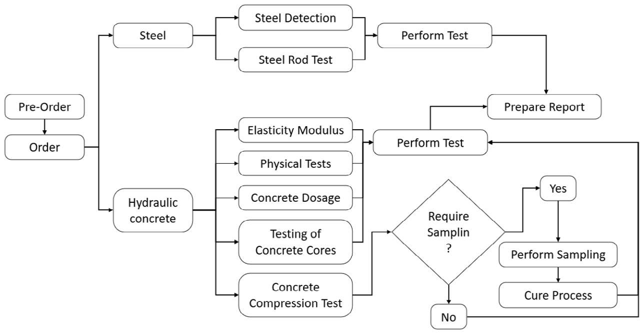
Table 4 Key performance indicators

KPI	*Calculation*
Service confirmation rate (1)	SCR = Confirmed PRE by Service / PRE Received by Service
Orders to be confirmed (2)	OTBC = Total Amount of Orders To Confirm
Percentage of orders to confirm (3)	POTC = Orders To Be Confirm / PRE Received
Total confirmation percentage (4)	TCP = Confirmed PRE / PRE Received
Completed orders (5)	CO = Total Amount of Completed Orders
Orders in service (6)	OIS = Total Amount of Orders In Service
Percentage of completed orders (7)	PCO = Completed Orders / Total Entered Orders
Work in process (WIP) (8)	WIP = Orders in Working Process / Total Entered Orders

3.2 *Development of operational processes*

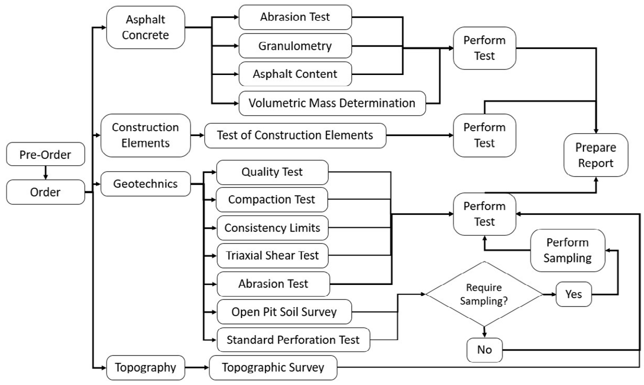
To develop the simulation model, it is necessary to describe the actual process followed by the laboratory. Figure 4 and Figure 5 show the process.

Figure 4 Procedures for services of ST and HC



Source: Own elaboration

Figure 5 Procedures for ACN, CE, GT and Topography services



Source: Own elaboration

From Figure 4, the process begins by receiving the pre-order, which is not necessarily the same on a daily basis, likewise, a percentage of these quotes is confirmed, which proceeds to become a WO, for example, in Table 2 for the month of April there is a probability of almost 53.4% that a client chooses an GT budget, and according to Table 3 that it is confirmed on average of 44.27%.

The way in which WOs are treated is considering the discipline of first-in-first-out waiting lines (FIFO); that is, the first WOs that enter the laboratory must be the first to be completed, however, the completion time of the tests is variable and this means that, for the finished WOs (delivery of the report) this behaviour is not observed (i.e. the report of one order requested earlier can be delivered after a later one).

For four types of service, from the seven offered, sampling on field is needed, this is the movement of employees to the site of construction work is required to extract samples of material; for the other cases, clients bring their samples, so this time is considered accordingly in the duration to perform these tests.

Once all the tests have been completed, the results are recorded in the logbooks, then the client reports are prepared. Lastly, the client is asked to evaluate the services with the application of a quality survey, then the report is delivered and the process ends.

To replicate the behaviour of the laboratory through a simulation model, it was necessary to determine the properties of the real system, which were previously established, and for the implementation of the model, must be allowed change the values of the system during the simulation process (Chase et al., 2009).

For the development of the simulation model, it was necessary to use computational tools that recreated the way in which the laboratory processes the WOs, it was chosen the JaamSim software, since it offers the necessary resources for the implementation of the model and run of scenarios with different parameters. To carry out the simulation, a personal computer with an Intel Core i3 processor, 4.0 GB RAM memory and a 64-bit operating system was used.

3.2.1 Probability distribution considered for the simulation model

After analysing the data statistically and by using the software Stat::Fit® and Minitab®, the following probability distributions were determined, which are mentioned below, also in Table 5 the parameters of the probability distribution of confirmation by type of service by month are shown.

- average probability distribution of service preference
- average probability distribution of the amount of arrival of pre-orders
- probability distribution of average time elapsed between pre-orders
- probability distribution for confirmation of the type of service
- probability distribution of the average delay time for confirmation of a pre-orders
- probability distribution for test type selection
- probability distribution for average service times.

Table 5 Parameter of the probability distribution confirmation by type of service per month

Probability percentage confirmation of pre-orders							
Month	*ST*	*ACN*	*HC*	*CE*	*GT*	*TOP*	*MULTI*
Jan	33.33	0.00	73.81	0.00	40.25	16.67	16.67
Feb	41.67	0.00	63.89	16.67	39.04	0.00	22.22
Mar	0.00	0.00	75.00	25.00	29.91	16.67	16.67
Apr	36.11	8.33	66.47	0.00	36.81	0.00	13.89
May	0.00	5.56	93.33	20.83	35.49	0.00	16.67
Jun	16.67	41.67	56.67	33.33	27.70	0.00	19.44
Jul	0.00	50.00	69.44	0.00	45.91	0.00	0.00
Aug	8.33	16.67	43.57	33.33	47.35	0.00	12.50
Sep	0.00	0.00	75.42	16.67	27.07	0.00	0.00
Oct	0.00	16.67	59.52	33.33	36.62	16.67	16.67
Nov	11.11	0.00	58.33	33.33	25.02	16.67	0.00
Dec	16.67	16.67	55.56	16.67	46.11	0.00	0.00

Table 6 Probability distribution of choice of tests by type of service

Type of test	*% Probability by test*
Steel	
Steel detection	35
Test steel rods	65
Quantity of steel rod samples	
1 Sample of steel rod	45
2 Samples of steel rod	10
3 Samples of steel rod	35
4 Samples of steel rod	10
Asphalt concrete	
Los Angeles abrasion test in stone materials	25
Granulometry	25
Asphalt content and granulometry	25
volumetric mass determination	25
Hidraulic concrete	
Elasticity modulus	5
Physics test	5
Concrete dosage	5
Testing of concrete cores	15
Concrete compression test	35
Testing of concrete samples	35
Construction elements	
Testing of construction elements	-
Geotechnics	
Open pit soil survey (OPSS)	43
Standard perforation test (SPT)	30
Quality test	3
Compaction test	4
Consistency limits	5
Triaxial shear test	10
Los Angeles abrasion test	3
Stone test	2
Test type of OPSS	
1 OPSS at 3 metres depth	25
2 OPSS at 3 metres depth	25
3 OPSS at 3 metres depth	25
1 OPSS at 4.5 metres depth	25
Test type of SPT	
1 SPT at 5 metres depth	17
1 SPT at 10 metres depth	17
1 SPT at 15 metres depth	16
2 SPT at 5 metres depth	17
2 SPT at 10 metres depth	17
2 SPT at 15 metres depth	16

3.2.2 Definition of variables

Level variables

These variables allow the WOs to be accumulated and only change according to the behaviour of the flow variables.

Some of these variables were considered within the model were:

- *pre-orders arrivals:* represents the number of pre-orders that arrive on a daily basis
- *WO without confirmation:* indicate the number of budgets that were not confirmed
- *WO to be confirmed:* indicate the number of pending quotes to be confirmed
- *WO treated:* is all the WO that were completed.

Flow variables

This type of variables determines the variation of the levels, likewise they collect the information that results from the actions taken within the system, for the development of the model the time necessary to perform the tests of the corresponding services is considered, the time of completion is considered in days. Table 7 shows the distributions that were established for the implementation of the simulation model.

Table 7 Distributions for the flow variables

Process	*Distribution*
Steel_Detection_Test	Uniform (1, 2)
Test of 1 Sample of Steel Rod	Uniform (1, 2)
Test of 2 Samples of Steel Rod	Triangular (1, 2, 3)
Test of 3 Samples of Steel Rod	Triangular (2, 2, 4)
Test of 4 Samples of Steel Rod	Triangular (2, 3, 5)
Los Angeles Abrasion Test of SM	Uniform (1, 2)
Granulometry	Triangular (1, 2, 4)
Content_Asphalt_and_Granulometry	Triangular (2, 3, 4)
Volumetric_Mass_Determination	Triangular (1, 1, 3)
Elasticity_Modulus	Constant (1)
Phisycs_Test	Triangular (2, 3, 5)
Concrete_Dosage	Triangular (3, 5, 8)
Test_of_Concrete_Cores	Triangular (4, 7, 10)
Casting_of_Concrete_ Specimens	Constant (28)
Testing_of_Concrete_Samples	Constant (1)
Testing_of_Construcution_Elements	Triangular (1, 2, 4)
1_OPSS_3m	Triangular (3, 4, 7)
2_OPSS_3m	Triangular (3, 4, 7)
3_OPSS_3m	Triangular (3, 5, 8)
7_OPSS_3m	Triangular (5, 8, 10)
1_OPSS_4_5m	Triangular (3, 4, 7)

Table 7 Distributions for the flow variables (continued)

Process	*Distribution*
1_SPT_5m	Triangular (3, 5, 7)
1_SPT_10m	Triangular (5, 7, 12)
1_SPT_15m	Triangular (7, 10, 14)
2_SPT_5m	Triangular (3, 5, 7)
3_SPT_30m	Triangular (21, 25, 30)
Quality_Test	Triangular (5, 7, 9)
Compaction	Triangular (3, 5, 7)
Consistency_Limits	Triangular (1, 2, 4)
Triaxial_Shear Test	Triangular (1, 3, 4)
Los_Angeles_Abrasion_Test	Triangular (1, 2, 4)
Stone_Test	Uniform (2, 4)
Topography	Triangular (2, 5, 8)

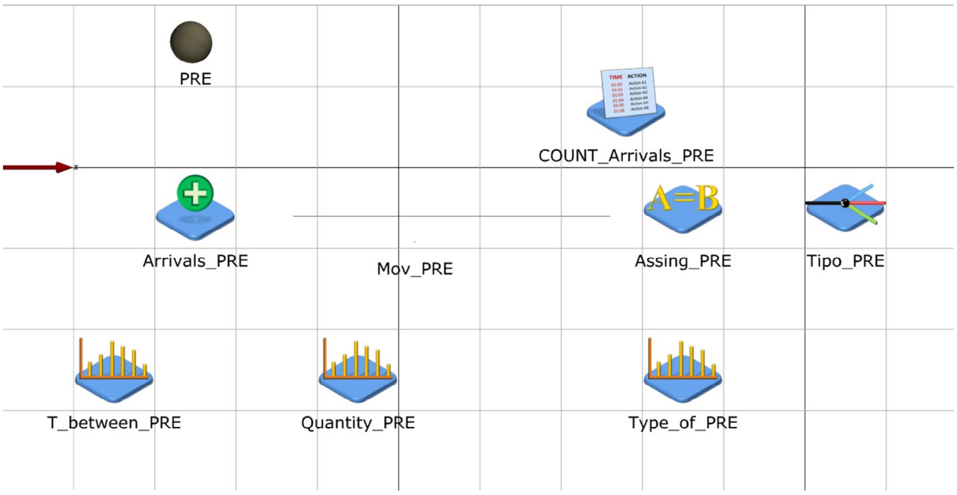
Auxiliary variables

For the case study, it was not necessary include this type of variables.

3.3 Development of the simulation model in JaamSim

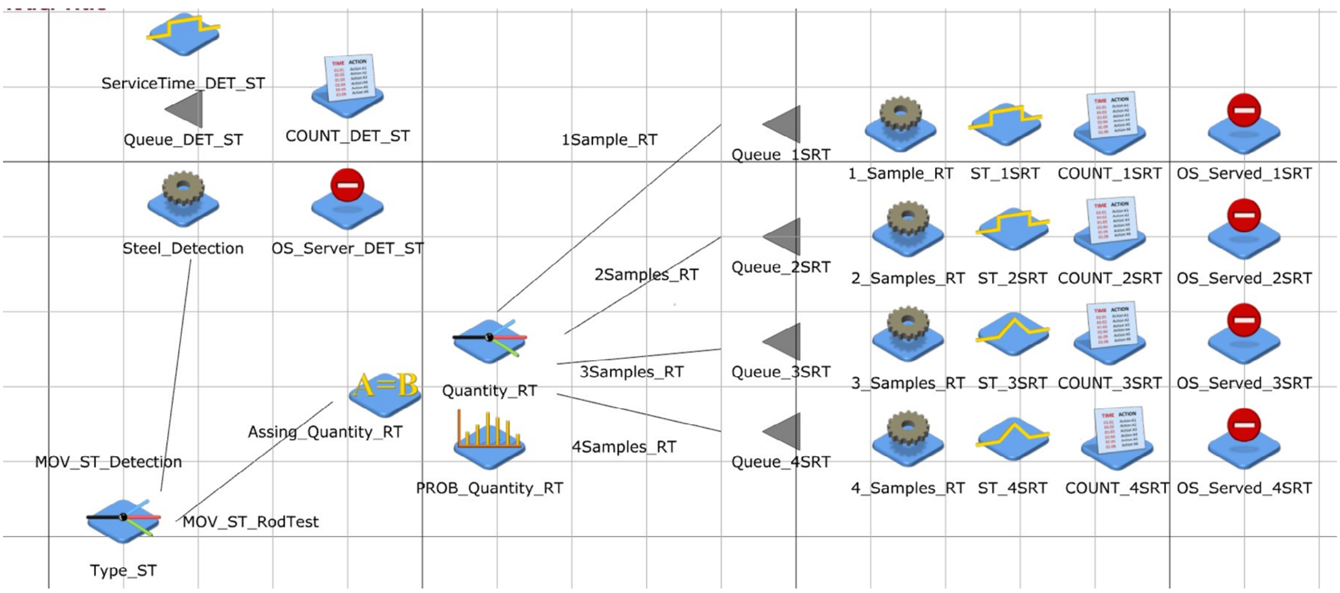
To replicate the behaviour of the operations of the tests carried out in the laboratory, it was decided to use the JaamSim software, which is a free and open source discrete event simulation software; the flows described in Figures 6 and 7 served as the conceptual basis for transferring all the relevant processes to the model implemented in this software.

Figure 6 Simulation model template for generating system inputs (see online version for colours)



Source: Own elaboration

Figure 7 Simulation model template for ST services (see online version for colours)



Source: Own elaboration

Figure 6 shows the process for the generation of entities (PRE), these are linked to two types of probabilities, the time between arrivals of each PRE and the probability of the amount of PRE that can arrive on daily basis. Then, the probability for the type of PRE corresponding to the service preference for each month is assigned.

Figure 7 shows the procedures for ST services, these are assigned a probability of confirmation and the distribution of time that a client takes to confirm and accept a quote, subsequently according to the probability of the type of test, the WOs are assigned to a 'service station', they also have a queue that considers the order to treat the WOs applying the FIFO policy, the first WO to enter must be the first to be completed. The test time process was established under the service time distribution, finally, all the WOs completed are counted.

3.4 *Model verification and validation*

It was verified that the simulation model was functional generating the required inputs, executing the processes and producing expected outputs according to the established parameters; in this way, it was evaluated each month comparing the preference of the service and the real data was verified against the simulated data. Table 8 shows the results of the validation for the month of January as an example, considering the entries generated. This validation was conducted for the remaining 11 months, however, for sake of space these are not included in this document.

Table 8 Verification of data generation with regarding preference for service (January)

Month	*Services*	*Real data*	*Simulated data*	*Absolute difference*
January	ST	3.64%	3.16%	0.48%
	AC	0.00%	0.00%	0.00%
	HC	19.37%	19.34%	0.03%
	CE	1.29%	0.93%	0.36%
	GT	72.17%	72.60%	0.43%
	TOP	2.02%	2.29%	0.28%
	MULTI	1.51%	1.67%	0.16%
		Variance		0.0004%

To verify the model, confidence intervals were calculated for the amount of PRE received for each type of service. To exemplify these data, the month of January is considered, the amount of PRE is in an interval of [2, 30] with a confidence level of $(1 - \alpha)\cdot 100 = 95\%$, only 4 data out of the 100 generated are out of range, in replicates 2, 8, 41 and 43, 37, 33, 39 were received and 32 PRE respectively. The confidence intervals for each type of service are listed below, considering a confidence level of 95%.

- number of PRE ST: Confidence interval [0, 2], data out of range: 3
- quantity of PRE ACN: according to the preference by type of service, this does not have representativeness, therefore, data for ACN were not generated
- number of PRE HC: Confidence interval [0, 8], data out of range: 5
- number of PRE CE: Confidence interval [0, 1], data out of range: 2
- number of PRE GT: Confidence interval [1, 22], data out of range: 5
- number of PRE TOP: Confidence interval [0, 2], data out of range: 5
- number of PRE MULTI: Confidence interval [0, 1], data out of range: 4.

4 Results

The execution of the model was conducted to verify the correct function of all the process, then the proposed KPIs were calculated, and the results are shown in Table 9.

For HC services, almost 61% confirmation is achieved in the PRE, of the 189 WO counted from the results of the replicates, 30 remain in the confirmation process, which represents 9.62%, and 93 WOs of the total PRE are rejected. 117 WOs are completed on time, which gives near to 61.90% of attention during the established period of time, on the other hand, 72 WOs are still in WIP, which indicates that the 38.1% are in process. In general, a TCP of 25.36% was achieved, this indicates that from the 1613 PRE generated, only 409 are confirmed.

This analysis was performed for the remaining 11 months; however, for sake of space these analyses are not included in this paper, likewise, from this process, scenarios were proposed to determine the behaviour of the seven services offered by the laboratory, through the analysis of the KPIs and the level of service obtained.

Four scenarios were considered, which exemplify situations in which the laboratory could take actions to predict the level of performance of the laboratory. The first scenario (Scenario 1), considers a 20% increase in the amount of PRE that the laboratory receives, the second (Scenario 2), deals with an increase in the confirmation rate of 20% of PRE, in the third (Scenario 3), reflect a 20% increase in the rate of attention to WOs, and the last (Scenario 4), includes the three scenarios before mentioned in one. Each of these scenarios is compared against the base situation or 'scenario 0', which corresponds to the simulation replicates considering the current conditions determined from the analysis of historical data.

The results obtained from the first scenario are shown in Tables 10 and 11.

Table 9 KPI obtained with the simulation model (January)

				January				
KPI/services	*ST*	*ACN*	*HC*	*CE*	*GT*	*TOP*	*MULTI*	*Total*
PRE	51	0	*312*	15	1171	37	27	1613
OR	11	0	*189*	0	197	2	10	409
NA	29	0	*93*	15	706	32	12	887
SCR	21.57%	0.00%	*60.58%*	0.00%	16.82%	5.41%	37.04%	
OTBC	11	0	*30*	0	268	3	5	317
POTC	21.57%	0.00%	*9.62%*	0.00%	22.89%	8.11%	18.52%	
APOTC				*19.65%*				
TCP				*25.36%*				
OS	11	0	*117*	0	164	2	8	302
OIS	0	0	*72*	0	33	0	2	107
POS	100.0%	0.0%	*61.9%*	0.00%	83.25%	100.00%	80.00%	73.83%
WIP	0.0%	0.0%	*38.1%*	0.00%	16.75%	0.00%	20.00%	26.17%

Table 10 Results obtained from scenario 1

Month/data	*January*		*February*		*March*	
	Scenario 0	*Scenario 1*	*Scenario 0*	*Scenario 1*	*Scenario 0*	*Scenario 1*
PRE	*16.13*	*19.05*	20.35	24.64	10.01	11.95
OR	*4.09*	*4.76*	4.44	4.63	2.27	2.66
NA	*8.87*	*10.58*	11.69	14.16	6.1	7.28
OTBC	*3.17*	*3.71*	4.22	5.85	1.64	2.01
OS	*3.02*	*3.31*	3.1	3.29	1.65	1.93
OIS	*1.07*	*1.45*	1.34	1.34	0.62	0.73

Table 11 KPIs obtained from scenario 1

KPI/month	*January*		*February*		*March*	
	Scenario 0	*Scenario 1*	*Scenario 0*	*Scenario 1*	*Scenario 0*	*Scenario 1*
TCP	*25.36%*	*24.99%*	21.82%	18.79%	22.68%	22.26%
POTC	*19.65%*	*19.48%*	20.74%	23.74%	16.38%	16.82%
POS	*73.84%*	*69.54%*	69.82%	71.06%	72.69%	72.56%
WIP	*26.16%*	*30.46%*	30.18%	28.94%	27.31%	27.44%

Table 12 Results obtained from scenario 2

Data/month	*January*		*February*		*March*	
	Scenario 0	*Scenario 2*	*Scenario 0*	*Scenario 2*	*Scenario 0*	*Scenario 2*
PRE	16.13	16.72	*20.35*	*19.6*	10.01	10.14
OR	4.09	5.03	*4.44*	*4.22*	2.27	3.07
NA	8.87	7.81	*11.69*	*9.92*	6.1	5.25
OTBC	3.17	3.88	*4.22*	*5.46*	1.64	1.82
OS	3.02	3.48	*3.1*	*2.93*	1.65	2.18
OIS	1.07	1.55	*1.34*	*1.29*	0.62	0.89

Table 13 KPIs obtained from scenario 2

KPI/month	*January*		*February*		*March*	
	Scenario 0	*Scenario 2*	*Scenario 0*	*Scenario 2*	*Scenario 0*	*Scenario 2*
TCP	25.36%	30.08%	21.82%	21.53%	22.68%	30.28%
POTC	19.65%	23.21%	20.74%	27.86%	16.38%	17.95%
POS	73.84%	69.18%	69.82%	69.43%	72.69%	71.01%
WIP	26.16%	30.82%	30.18%	30.57%	27.31%	28.99%

Table 14 Results obtained from scenario 3

Data/month	*January*		*February*		*March*	
	Scenario 0	*Scenario 3*	*Scenario 0*	*Scenario 3*	*Scenario 0*	*Scenario 3*
PRE	16.13	16.7	20.35	20.35	10.01	11.39
OR	4.09	4.27	4.44	3.85	2.27	2.82
NA	8.87	9.24	11.69	11.41	6.1	6.9
OTBC	3.17	3.19	4.22	5.09	1.64	1.67
OS	3.02	3.06	3.1	2.71	1.65	2.23
OIS	1.07	1.21	1.34	1.14	0.62	0.59

Table 15 KPI obtained from scenario 3

KPI/month	*January*		*February*		*March*	
	Scenario 0	*Scenario 3*	*Scenario 0*	*Stage 3*	*Stage 0*	*Stage 3*
TCP	25.36%	25.57%	21.82%	18.92%	22.68%	24.76%
POTC	19.65%	19.10%	20.74%	25.01%	16.38%	14.66%
POS	73.84%	71.66%	69.82%	70.39%	72.69%	79.08%
WIP	26.16%	28.34%	30.18%	29.61%	27.31%	20.92%

Table 16 Results obtained from scenario 4

Data/month	*January*		*February*		*March*	
	Scenario 0	*Scenario 4*	*Scenario 0*	*Scenario 4*	*Scenario 0*	*Scenario 4*
PRE	16.13	20.83	20.35	23.74	10.01	12.98
OR	4.09	5.91	4.44	5.33	2.27	3.71
NA	8.87	9.53	11.69	11.71	6.1	6.97
OTBC	3.17	5.39	4.22	6.7	1.64	2.3
OS	3.02	4.33	3.1	3.89	1.65	2.7
OIS	1.07	1.58	1.34	1.44	0.62	1.01

Table 17 KPI obtained from scenario 4

KPI/month	*January*		*February*		*March*	
	Scenario 0	*Scenario 4*	*Scenario 0*	*Scenario 4*	*Scenario 0*	*Scenario 4*
TCP	25.36%	28.37%	21.82%	22.45%	22.68%	28.58%
POTC	19.65%	25.88%	20.74%	28.22%	16.38%	17.72%
POS	73.84%	73.27%	69.82%	72.98%	72.69%	72.78%
WIP	26.16%	26.73%	30.18%	27.02%	27.31%	27.22%

For the month of January, on average, 19.05 PRE would be received, compared to the simulation considering the original parameters in which 16.13 arrived; this increased by 2.92, in addition 4.76 were confirmed; 0.67 more than in the scenario 0, which gives 24.99% confirmation, therefore, compared to the original model, similar results were achieved.

For the WOs that were confirmed in scenario 1 in the month of January, 3.31 of the 4.76 would be able to be treated, obtaining 69.54% of orders finished, leaving 1.45 to be completed, generating a WIP of 30.46%, compared to the same month of the scenario 0, the percentage of orders fulfilled decreases.

For scenario two, the results achieved are shown in Tables 12 and 13.

For the month of February, an average of 19.60 PRE was obtained, of which 4.22 were confirmed (WO), compared to Scenario 0, equivalent results were achieved, resulting in a TCP of 21.53%, of the total pre-orders 9.92, 1.77 would be rejected. Less PRE than in Scenario 0 for this month were generated; 5.46 PRE would remain in the confirmation process.

Of the 4.22 WOs, 2.93 are served, which yields 69.43% for the indicator of orders completed on time, achieving equivalent results compared to the Scenario 0, on the other hand, 1.29 WOs would remain in the service process, obtaining a WIP of 30.57 %.

The results of the Scenario 3 are shown in Table 14 and Table 15.

From the simulation of the third scenario for the month of March, an average of 11.39 PRE would be received, 1.38 more than in the Scenario 0, of these PRE 2.82 would be confirmed in WOs, which yields a TCP of 24.76%, 6.9 PRE would be rejected and 1.67 would remain in the confirmation process, of the total WOs 2.23 would be treated to on time during the evaluation period, which gives rise to a PCOs of 79.08%, which compared to the Scenario 0 would obtain approximately 7%. more than orders fulfilled, on the contrary, 0.59 orders would remain in WIP, which corresponds to 20.92%.

The results obtained in scenario 4 are shown in Table 16 and Table 17.

Based on this scenario for the month of January, an average of 20.83 PRE would be received, 4.70 more than in the Scenario 0; 5.91 PRE would be confirmed, which gives rise to a TCP of 28.37%, against, 9.53 PRE would be rejected and 5.39 would remain in the confirmation process. Of the 5.91 WOs, 4.33 would be able to be completed on time, obtaining 73.27% of orders served on time, in contrast 1.58 would be being processed, generating 26.73% of WIP.

5 Conclusions

This paper illustrates the development of a discrete event simulation model implemented in JaamSim, through which it is possible to replicate the behaviour of the processes of the seven services offered in the laboratory. This model has been verified and validated, also with the use of the KPIs proposed for the normal operation of the laboratory (Scenario 0) and later for four scenarios suggested.

With the calculation and evaluation of the KPIs, it was possible to determine the level of service achieved by the laboratory in the data analysis period (2014–2019), as well as for the four scenarios suggested. With these results, decisions and changes can be made to improve the indicators or reinforce the actions that achieve correct attention to WOs.

According to the outputs coming from the simulation of the historical data and later from proposed scenarios, 75.41% of orders are treated annually on time (PCO), thus 24.59% remain as work in process, comparing the overall equipment effectiveness mentioned by Morales et al. (2013) an acceptable result is achieved, however, this level of performance deserve attention to reach better results, this is to achieve 85% of OEE, therefore is important first maintain the KPI of PCO in 75% to later make the necessary improvements and increase the service level up to 85%.

In specific under scenario four, the performance in the processing of WOs would be improved, the amount of pre-orders would be increase, in the same way, the number of WOs would increase, making it possible to treat to a greater number of WOs during the a monthly period (30 days) through the evaluation of performance indicators, an improvement in the attention of the WOs, confirmation of the PRE and reduction of work-in-process, similarly, the number of rejected pre-orders would be reduced.

Each scenario allows the identification of different areas of opportunity, in cases where the number of WOs is increased without increasing the capacity to process them, the WOs simply remain in the confirmation process or in waiting line to be processed. In the case of increasing the service capacity, at this point more WOs can be completed, but the increase in the service rate is not fully exploited thus could not be a profitable scenario.

Therefore, a global improvement represents the best option, since a greater number of WOs is received and at the same time the capacity to treat them, thus maintaining the KPI of orders completed on time and reducing the WIP.

6 Future research

Through the evaluation of the performance achieved with the simulation study and compared against the OEE, is necessary establish a future line of research having the base line performance at 75.41% of PCO; TOCs may help to identify weak process on the structure, also this theory focuses on this points which are the bottlenecks for the entire industry as mentioned by Tuğçe aet al. (2014). Once these bottlenecks are detected, the variables of resources of the laboratory can be modified in the model to calculate the KPIs and look for best options and configurations to achieve the 85% of OEE which gives a ‘good’ level according to Morales et al. (2013) and the laboratory would become global class with good competitiveness.

Also, it would be insightful to re-model the actual simulation model, with the purpose of strengthening and detailing the processes carried out in this laboratory, aiming to identify potential bottlenecks in each workstation, just as mentioned by Renna (2019) with the centralised, distributed and proportional policies adjustments can be made to improve the performance under bottom-up approach.

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