CONFERENCE PAPER 6

2nd International Conference on Asphalt 4.0

Towards a digital twin architecture for the hot-mixed-asphalt production process

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Towards a digital twin architecture for the hot-mixed-asphalt production process

ABSTRACT

To address the scarcity of digital twin (DT)-based solutions in the asphalt pavement sector, Padecasa is developing a digital solution for improving the efficiency of the hot mix asphalt (HMA) production process of its plants. This DT will be used as an adaptive planning support system capable of optimizing plant operation, as well as site demand and transportation scheduling. As a part of this solution, a preliminary version of the virtual model representing the physical system had to be obtained, which posed several modeling challenges arising from the nature of the system's scope.

To overcome these issues, a Twin model architecture integrating several modeling techniques is proposed. In this architecture, agent-based simulation (ABS) is used to provide an intuitive and scalable structure to the simulation model, and include the communication system in which the interaction between agents occurs. As to the physical production processes, they have been modeled by means of discrete event simulation (DES), while system dynamics (SD) is used to represent the continuous variables. Finally, data-based models (DBM) have been used in these cases in which building knowledge-based models entailed great difficulty.

In this communication, the overall architecture of the proposed HMA production Twin model is presented, as well as examples of how the integration of the abovementioned modeling approaches allowed the overcoming of the problems identified. As a result, the proposed Twin model is capable of simulating the production process of a whole journey based on the information contained in the working orders, and the environmental variables.

1. INTRODUCTION

Digital twins (DT) are simulation-based digital solutions that can help improve industrial processes, in terms of economic and environmental efficiency, which has led to the broad adoption of this technology by leading industrial companies. In the construction sector, however, its presence is still very limited due to the endemic difficulties of this sector in adopting technological advances. This lack of DT-based solutions is more acute even in the asphalt pavement sector, despite their potential for addressing critical challenges for this sector such as mitigating environmental impacts, reducing energy consumption, or improving the reliability and precision of life cycle analysis (LCA).

To fill this gap, and as a part of an industrial research project called *"Gemelo digital para la producción y el diseño de mezclas bituminosas"*, Padecasa is developing a DT-based solution for improving the efficiency of the hot mix asphalt (HMA) production process of its plants. In this communication, we present a preliminary version of the Twin model, i.e. the virtual model representing the physical twin, which is capable of simulating the production process and forecasting results. This Twin model is intended to be used as the simulation model of an adaptive planning support system capable of optimizing plant operation, and site demand/transportation scheduling. To meet this requirement a relevant issue should be addressed: the heterogeneity of elements within the required system's scope.

Regarding this issue, the DT system boundaries had to include plant functioning and operation, site demand and transportation of HMA, and supply logistics. This scope, however, poses some conditions over the simulation model. For example, the dynamics of the HMA production process and the plant functioning depend on both discrete variables, such as the selected production rate or the input of a production order, and dynamic variables such as the ambient temperature or the humidity of the aggregates, especially in the case of RA aggregates. Other variables depend on both events and time, such as the fuel tank level which depends on the selected burner power, which is an event, and the time elapsed since that power was selected. This entails important modeling implications since the former can be tackled by discrete events simulation (DES) models but the latter changes over time and should be continuously evaluated, which the DES approach cannot satisfactorily provide. In contrast, the system dynamics technique is suitable for the modeling of contextual/exogenous time-dependent aspects.

In addition, in the process of HMA production and delivery, several participants are involved: site managers, plant operators, and suppliers. These interact through the communication system to articulate the production and logistics processes and, as a consequence, the modeling of the communication system, in accordance with the organizational structure, is also required. This communication framework focuses on individuals rather than processes, and neither the DES nor the SD approaches are well-suited to represent them. Instead, agent-based simulation (ABS), which allows the modeling of complex interacting objects, and therefore allows structuring the whole system's scope around these key participants, should be used.

Finally, some key aspects are difficult to evaluate exclusively based on DES rules. For example, the temperature of the aggregates at the exit of the dryer, which depends on several endogenous and exogenous factors, is very difficult to model as a process of heat transference. Instead, we addressed this problem via data-based prediction. By using the data provided by Padecasa's SENSASFALT monitoring system, it was possible to build data-based (DB) sub-models that evaluated these aspects. In consequence, the virtual model of the DT was conceived as a hybrid DES-SD-ABS-DB model to provide simulation results considering the whole system's scope.

As a result, the preliminary DT can simulate a whole journey of HMA production across the whole system's scope. This enables the development, in a subsequent stage, of an adaptive planning support system within the DT that affords an initial production plan and continued support across the journey's uncertainties.

This paper focuses on presenting the architecture of the proposed Twin model, and illustrating how the abovementioned challenges have been addressed by means of a hybrid model integrating DES with DS and ABS, coupled with DBM. The remainder of this work is structured as follows: Sections 2 and 3 provide an overview of the proposed DT and Twin Model architectures at a high level, while section 4 illustrates how the integration of approaches contributed to overcoming modeling problems. In section 5, the input and output information required for and provided by the simulation is mentioned. Finally, section 6 presents the conclusion, limitations, and next lines of work.

2. PROPOSED DT ARCHITECTURE

2.1 Objective

The main objective for the proposed DT is to help improve the overall production process performance via operations planning and scheduling with near real-time decision-making capacity. For this scheduling, it should be able to simulate different process setups and scheduling alternatives under different scenarios, provide a set of compromise solutions based on environmental, product performance, and economic cost, and finally, facilitate the selection of the best solution.

In addition, the DT must comply with the following requirements:

- Helps gain insight into how the processes work, revealing its dynamics and sensitivity to exogenous parameters such as environmental aspects or restrictions in logistics.

- Allows to observe and supervise the resources that are used or the sequences of activities involved in the operation.
- Allows past situations to be analyzed to identify the origin of problems.
- And last, but not least, it can be used to train personnel throughout the entire life cycle of the plant.

2.2 System scope

Life cycle analysis (LCA) and life cycle cost (LCC) are useful approaches for estimating both production process efficiency and cost, and are intended to be implemented in the DT for obtaining key performance indicators (KPIs). One key issue in the development of an LCA model is the definition of the system's boundaries, which have to include plant functioning and operation, site demand and transportation of HMA, supply logistics, and the communication between involved agents (Figure 1).

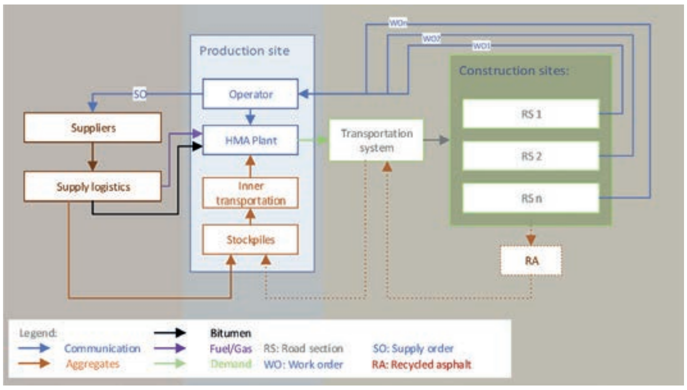


Figure 1. System scope.

2.3 Functional unit

Another important issue for proper LCA modelling is the selection of the functional unit. A functional unit refers to the product, service, or system whose impacts, are calculated by a life-cycle assessment (LCA), and could be chosen based on different criteria (Furberg et al, 2022).

In our case, the LCA will be used for measuring the performance of the production process, and therefore, a performance functional unit was selected as the type of functional unit.

On the other hand, it is important that the functional unit be physically traceable, at least until it enters the construction site. This discards generic functional entities such as Tn of produced HMA of a given type since it is not possible to trace it. The traceable units in HMA production are delivery notes, which represent all the HMA in each truck that entered the construction site from the production site, and in batch plant, the mixes, which are the HMA each time discharged from the mixer to the truck. These latter, however, are traceable only during the production process, since once discharged in the truck, they cannot be separated from each other and get mixed to form a delivery note. In consequence, the delivery note was selected as the functional unit for performance evaluation, while mixes should also be represented in the virtual model.

2.4 Proposed DT architecture

Following previous work that has been found relevant to this work (de Prada et al, 2022; Latsou et al, 2023), the DT is structured in three main layers (Figure 2):

2.4.1 Data acquisition and storage

This layer is used to capture data measured directly by sensors, actuators or controllers, or obtained from enterprise manufacturing systems. Once the data is acquired and stored in a data base, data processing, including filtering process, artificial intelligence-based processing and data analytics, is used to transform the data into information. In this work, this layer is composed of the devices, database, and information processes developed by Padecasa with the SENSASFALT project, and is not described in this work.

2.4.2 Twin model and adaptation module

This layer embodies a set of models and comprises the virtual twin. It also includes the adaptation module, which affords simulation parameters adjustment, validation, identification, etc., for updating the virtual twin in near real-time. This layer is almost fully developed and will be further described in this work.

2.4.3 Decision-making, visualization, and interaction

The top layer includes tools for decision-making, typically optimization methods based on the simulation results provided by layer 2. It also enables interaction between the DT and the users, facilitating visual analytics and an interface for the DT management. The development of this layer will be addressed in the near future and will be presented in subsequent work.

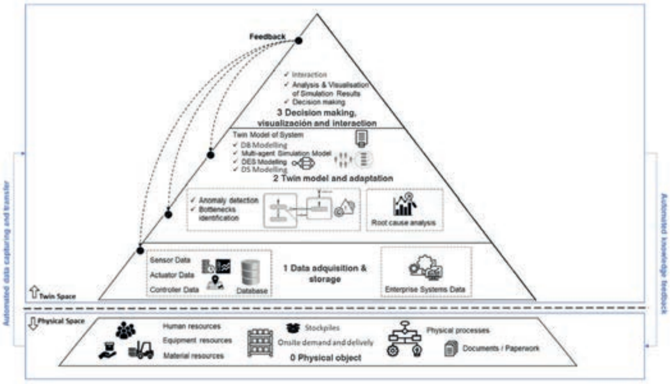


Figure 2. Digital twin architecture, based on de Prada et al, 2022, and Latsou et al, 2023.

3. TWIN MODEL ARCHITECTURE

3.1 Overview

Typically, plant production processes are modeled as a DES, which is a modeling method quite resembling the workflows usually employed to describe industrial processes. However, the HMA production process includes elements of different dynamics and types of interaction, such as the HMA production plant and the construction site, which would be counterintuitive and difficult to include in an overall DES model. Besides, there is a broad range of different scenarios under real-world conditions, since each journey the production site would have to attend a different number of different construction sites each of which with different demands in terms of scheduling, type of product and quantity demanded. Building an overall model accounting for all possible combinations would lead to high inefficiency, rendering this effort useless as a simulation engine of an optimization method, which is the intended use of the Twin model. To solve this problem, the proposed architecture implements agent-based simulation, which helps structure the system's scope into a decentralized system of agents, which can be programmatically scaled up at model startup, and facilitates the modeling of their interactions based on state workflows. Following this reasoning, the next Twin model overall architecture is proposed:

- Physical processes agent. This is the main layer of the Twin model, and includes all processes to transform physical objects (entities) such as aggregates, filler, bitumen, etc., into mixes and delivery orders of HMA, and the logistics for their transportation to or from the construction site.
- Plant logic agent, which basically represents the plant's PLC logic. This agent interacts with the physical process agent to actuate the plant processes modeled in the physical process agent.
- Operator logic agent, embodying the task performed and decisions made by the operator to govern the production process. This agent interacts with the plan logic agent to input the information required for HMA production, and with the physical process agent to oversee the plant functioning. Il also interacts with the supplier agent, to whom it will send supply orders.
- Construction site logic agent, which is a very simplistic model of the onsite HMA demand dynamics. This agent interacts with the Operator logic by sending to it work orders referring to the product specifications and quantity of the HMA being demanded.
- Supplier logic agent, which is a very simplistic model of the supply chain dynamics. This agent interacts with the Operator logic by supplying the production site with the

materials requested by the Operator via supply order.

3.2 Physical processes agent

This agent consists of a DES model of a transformation process through which the raw materials (aggregates, bitumen, and filler) are transformed into HMA, and then delivered at the construction site to be transformed into asphalt pavement. It also includes a reference to the service life of this pavement, including its eventual reuse to be once more used to pave the same road. The process starts with the delivery of the raw materials, and finishes at the end of the service life of the pavement produced with the recycling of the raw materials. Overall, the production process cab be grouped in two stages:

- Predosing stage, which includes the feeding of the dryer with aggregates, their drying, their classification and storage in the hoppers of the tower, and the filtering of the dust during the drying process.
- Dosing stage, which includes the dose of materials, their mixing, and the discharge of the resulting product into the transports to the construction site.

Besides, the model includes the Delivery and Service Subsystems, which represent the subsequent processes after the Dosing stage. To model this. the proposed architecture is structured into 5 sequential subsystems, which are briefly described below.

3.2.1 Dryer feeding subsystem

In this subsystem, the aggregates enter the production plant and are conveyed to the dryer, where they loss their humidity and reach the required temperature. To model this, "Ari" entities representing 10kg of aggregates are created with the following properties, which are assigned as the entity completes the production process:

- o prAriGradClas: Gradation class
- o prNatId: Code of the nature of the aggregate
- o prDensi: Bulk density in kg/cm3
- o vaPe: Weight, varies during the drying process
- o vaHum: Humidity, varies during the drying process
- o vaTa: Temperature, varies during the drying, hot storage, mixing, and delivery processes.

3.2.2 Drying and heating subsystem

In this subsystem, the heating of aggregates takes place as the aggregates pass through the drum. This in turn generates dust, which is recovered by the dedusting unit and sent to the recovered filler silo. This subsystem also includes the possibility of aggregating cold RA at the exit of the dryer into the flow of heated aggregates. Then, the aggregates travel through the elevator to the tower, where they are classified into gradations and stored. More details on the modeling of this subsystem are given in section 4.2.

3.2.3 Tower screening and store hoppers subsystem

In this subsystem, the aggregates are classified by the screeners according to their gradation and transferred to the tower hoppers, where they remain until the Dosing stage. For this classification, the plant is provided with as many screens as gradations in which the aggregates should be classified. i.e., one screen per store hopper. However, the transition from each screen to its associated hopper is only partially reliable since material passing each screen would contain also aggregates of lower gradation, and since screens would be partially saturated during the screening, aggregates that should have fallen through a lower screen are displaced to others of higher grid spacing. In sum, aggregates of a given gradation may go to hoppers of higher gradation due to the physics of the screening process. To model this, both the probabilities of destination for each gradation, and the proportion of aggregates of each gradation in each hopper, have been empirically determined by Padecasa in the course of this research.

3.2.4 Tower dosing and mixing subsystem (batch plant)

In this subsystem, the following processes takes place:

- Weighting and mixing of aggregates from the storage hoppers. In this process, a certain number of "Ari" entities are picked up from the storage hoppers and mixed.
- Mixing of the other components. After the mixing time specified for the aggregates abovementioned, cold RA may be incorporated into the mixing process. Then, bitumen, and filler, are progressively weighted and incorporated into the mixer following the sequence and timing specified in the selected formula. At the end of this process a new Ama entity, which in batch plants, represents the mixes each time discharged from the mixer to the transport (section 2.3), is created with the following properties:
    - PrAmaID: Unique code of each amasada
    - prAlbaID: Unique code of the amasada to which the amasada belongs
    - prFormulaDosDId: Code of the dosing formula.
    - prFormulaIPreDosId: Code of the predosing formula used for the feeding with aggregates.
    - prTaSalida: Temperature of the product at the end of the process
    - prTaSalidaT: Theoretical temperature of the product at the end of the process
    - prPe: Weight of the amasada
    - prPeT: Theoretical weight of the amasada
    - prPeByComp: Weight of each component
    - prPeByCompT: Theoretical weight of each component
    - peTiMixT: Total time of mixing
    - peTiMixA: Time of mixing of the aggregates

3.2.5 Delivery and Service Subsystem

This subsystem embodies the following processes:

- Generation of the delivery note and dispatching. This has been modeled as the "CargaTteObra" batch object in which mixes are gathered until the delivery note is complete. The number of mixes required for each batch is automatically calculated by the model based on the batch weight and maximum mix weight input by the Operator (section 3.3). When the batch is complete, a new entity called "Albaran", representing the delivery note, is generated. This entity, in turn, contains all its associated Alba entities to keep record of them, in addition to the same properties of the "Ama3.2.5".
- Transportation of the HMA to the construction site. The first stop of the truck will be the platform scale, which is represented as a delay object designated as "Pesaje". Then, the trip continues towards the construction site.
- Transformation of the HMA into asphalt pavement. At its arrival to the construction site, the transport may have to wait before its load can be placed by the pavement team. Once the truck is downloaded, it will return for another delivery note or return to its initial location if the working order is finished.
- Service of the asphalt pavement and its recycling. By including the recycling process, it is possible to evaluate LCA and LCC along a wider time span than the first service life. This, however, remains at conceptual level and has not yet been developed into the simulation model.

3.3 Plant logic agent

This agent represents the plant's production logic embodied in the PLC, and it is used to establish and monitor the plant's current state by means of a statechart workflow (Figure 7).

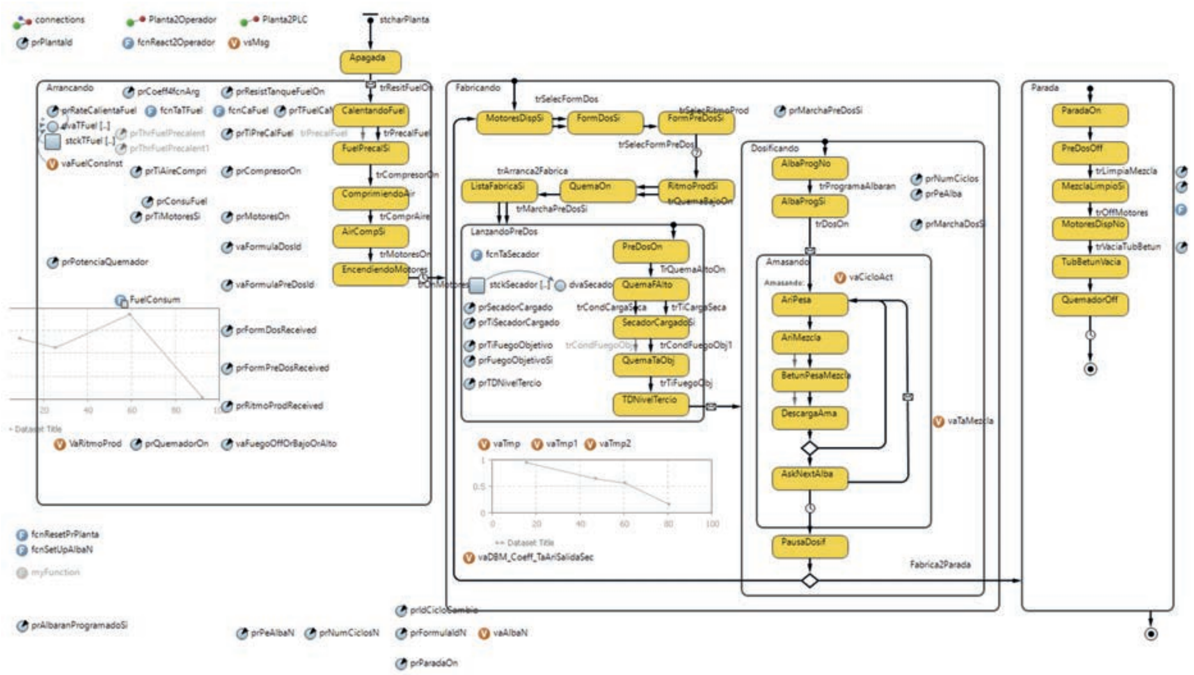


Figure 7. Statechart of the Plant agent.

As in the case of the Operator agent, there are three main states in which the plant may be, namely starting up, producing or stopping. Besides, once in any of these states, the agent may be in sub-states such as heating fuel in the case of the starting-up state, dosing in the case of the producing state, or cleaning the mixer in the stopping state. Within each state, the agent should perform some task before it can pass to the next state, which is modeled by means of transitions, in which the condition to transit from one state to the next is programmed.

3.4 Operator logic agent

This agent embodies the logic employed by the operator to manage the production plant based on the working orders communicated from the construction sites, and the production site's environment at each moment. These working orders have been modelled as the ProdOrder entities with the following properties:

- prOrdenTrabajoId: Unique code of each work order
- prTaEnObra and prTaEnObraT: Real and theoretical temperature that the product should have upon arriving the construction site
- prNoAlbasIn and prNoAlbasInT: Real and theoretical number of delivery notes to complete the working order
- prSelecRitmoProd: Estimated production rate
- prQProducTramo and prQDemandaTramoIni: Real and theoretical quantity of product to complete the working order
- prTiIniProd and prTiIniProdEst. Real and theoretical time at which production should start

With this information, the Operator is able to setup the Plant and produce the demanded HMA (Figure 3). This has been modeled as a state flowchart structured in the Starting up, Producing, and Stopping main states. This architecture allows the updating of the input parameters during the completion of working orders, at her beginning of each delivery note, to model the adjusting of the production rate, burner power or time of mixing, as the Operator identifies changes in key variables such as temperature in the production or the construction sites, which may affect the burner power, or in the time of mixing as a consequence of changes in the weight of each amasada.

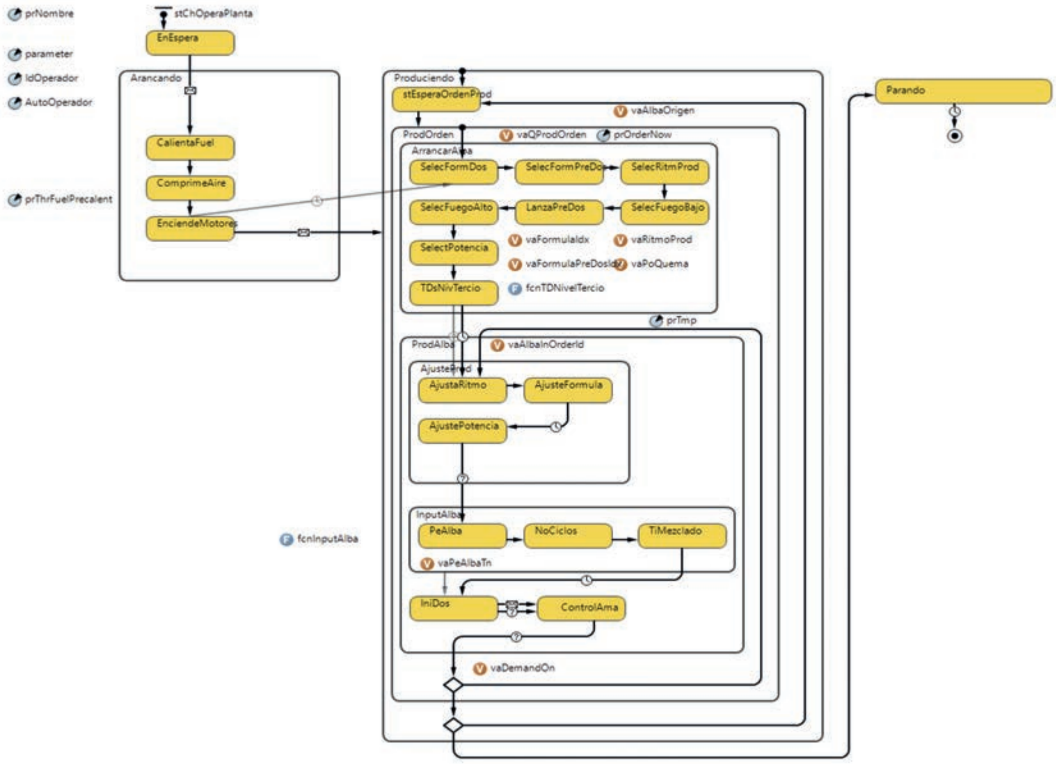


Figure 4. Statechart of the Operator agent

3.5 Construction site logic agent

This agent is used to model the HMA demand from the construction sites, and can be in two scenarios: demanding or not demanding HMA (Figure 4). Therefore, the statechart used to model this logic consists of two states, preparatory works, and HMA demand, which are entered or exited based on the scheduled start of each road section, the quantity of HMA required for each section, and the quantity of HMA received from the production site. To account for this, the Twin model continuously evaluates whether the current quantity of received HMA is equal or higher than the demanded, and if it is true, transits from the "stDemandaAsfalto" to the "stPreparandoTramo" states, where it will remain until the time reaches the next scheduled road section start. At this moment, this agent sends the corresponding work order to the Operator, who sets and operates the plant to meet the requirements of the work order.

Figure 5. Statechart of the Construction site agent

4. APPROACHES FOR SOLVING MODELING ISSUES

4.1 Case 1: Twin model architecture structuring and agents interaction

4.1.1 Agent based simulation approach

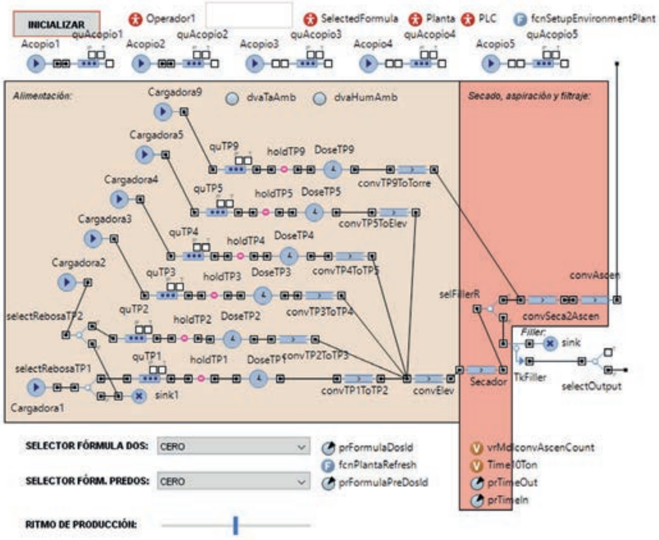
As described in section 3.1, this modeling approach has been used to address the complexity of the system's scope, as well as for modeling the communications system by which the agents interac each other.

4.2 Case 2: Drying and heating subsystem modeling

4.2.1 Discrete event simulation approach for the modeling of physical processes (Figure 5):

In this subsystem, the following physical elements and processes have been modeled:

- The dryer itself is represented as a conveyor object designed as "Secador", which receives the Ari entities from "convElev" and heats them. To model the mechanism of heat transference, a data-based model (DBM) was built based on the data provided by the SENSASFALT system (Layer 1 of the DT). This DBM is embedded in a function object which is dynamically evaluated in the "Plant agent" described below, where more details will be given.
- The dedusting unit and the humidity and filler extraction mechanism are modeled as follows: the model decides whether Ari entities are transformed into Filler entities and then destroyed or just destroyed, based on these rules:
    - o X% of aggregates of "0/6" gradation are transformed into filler (TkFiller) and then removed, where "X" stands for a coefficient empirically determined by Padecasa. This way, both the loss of weight due to filler filtering, and the generation of filler is modeled. The generated filler goes to a silo modelled as the "AcopioFillerR" queue object).
    - o Y% of aggregates are removed, where "Y" is the humidity of the aggregates in the feeding hopper. This way, the loss of weight due to humidity extraction is modeled.
- The mechanism for incorporating cold RA after the dryer has been modeled as the conveyor object designated as "ConvSeca2Ascen", which receives the Ari entities from the quTP9 hopper through the "convTP9ToTorre" conveyor.
- The elevator transporting heated aggregates has been modeled as a conveyor object designated as "ConvAscen".



SELECTOR FÓRMULA DOS: CERO
SELECTOR FÓRM. PREDOS: CERO

Figure 6. Flowchart of the Dryer feeding and the Drying and heating subsystems.

4.2.2 System dynamics and data-based model approaches for continuous evaluation

4.2.2.1 Fuel temperature

The Plant agent interacts with the Operator agent by providing updated information regarding the physical plant that is required by the plant's operator to take decisions, and by receiving the orders which are in turn communicated to the Physical processes agent to articulate these decisions. For example, one of the first decisions the operator have to take is when to startup the air compressor. This will happen immediately after the fuel has reached a given temperature, and it is modeled as a condition included in Transition "trPrecalFuel". However, to take this decision, the operator has to know which is the temperature of the fuel along time, and this is not a discrete variable but a continuous variable, which the DES approach cannot address. To overcome this limitation, the Twin model is coupled with the dynamic system approach, which affords continuous evaluation of the dynamic variables. In the case of the temperature of the fuel, it has been modeled as the dvaTFuel dynamic variable in the Plant agent, which continuously evaluates this temperature based on the time passed since the fuel heater (trResitFuelOn) was turned on.

4.2.2.2 Aggregates' temperature and fuel tank level

Another example of the need for continuous information is the aggregates' temperature, which may require burner power adjustments from the Operator. To model this, the dvaSecador has been created, in which the "TaAriSeca" and the "CaTFuel" dimensions, which respectively stand for the temperature of the aggregates at the exit of the burner, and the quantity of fuel remaining in the fuel tank, have been created.

<u>Temperature of the aggregates at the exit of the dryer</u>:

Evaluating these dimensions, however, is not a simple task since it may depend on multiple variables that have to be, in turn, continuously evaluated. In the case of the "TaAriSeca", a data-based model (DBM) was built to enable continuous evaluation. Figure 7 shows an example of this model based on data of one journey, consisting in a quadratic regression (R2=0,59) where the temperature of the aggregates at the exit of the dryer was the response, and the burner power, production rate, humidity of feeding hoppers 1 and 2, and ambient temperature were the predictors. Note that in the case of the production rate, humidity of feeding hoppers 1 and 2, and ambient temperature, the interval confidence is close to the prediction only in a narrow range. This means that the prediction will be accurate only in these ranges, becoming highly uncertain out of them. The cause of this is the lack of data out of these ranges, and to overcome this limitation, the actual model employed in the Twin model was fed with data from journeys covering a wider range of scenarios in terms of ambient temperature, humidity, and production rates. As can be observed in Figure 7, burner power and ambient temperature have a positive effect on the heat transference to the aggregates, while production rate and humidity have a negative effect.

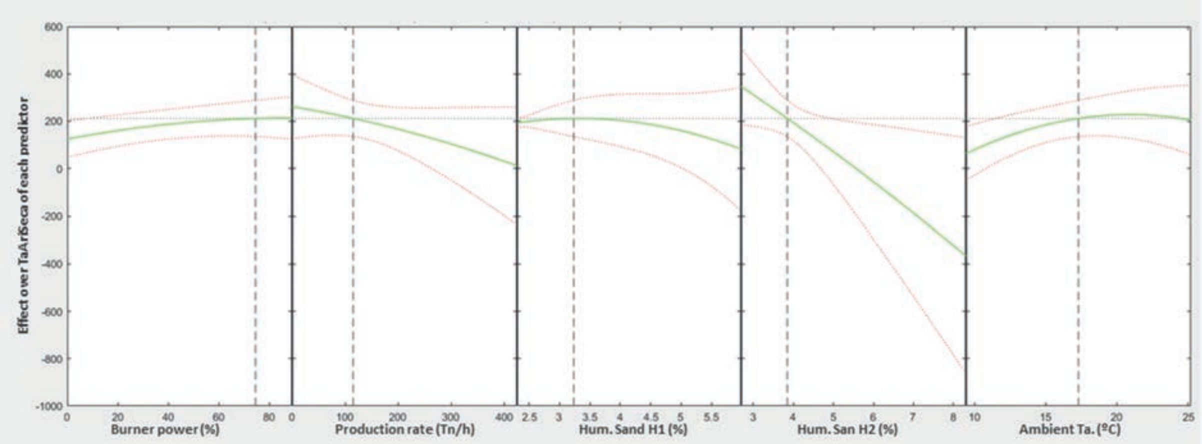


Figure 7 Example of DBM, quadratic regression model fitted with data from 21/6/2023

Fuel consumption and quantity of fuel remaining:

Another crucial aspect for both evaluating the production process performance and for the operation of the plant is the fuel consumption and, consequently, its remanent over time. Since the functional unit in the production process is the mix, the fuel consumption should be measured each time a mix is produced and therefore, it could be considered as a discrete variable from a performance evaluation point of view, and modelled via DES. The fuel remaining (or bitumen remaining), on the other hand, is crucial for the operation of the plant since based on this the operator should decide when to issue a supply order and therefore needs to be continuously evaluated over time. And since the remaining fuel depends on the fuel consumption, this variable also needs to be continuously evaluated, which was addressed via DS.

As in the case of the temperature of aggregates, the continuous evaluation of fuel consumption and remanent has been modeled in the abovementioned dvaSecador dynamic variable, which includes the "CaTFuel" dimension for measuring the remaining fuel over time. This is calculated as the difference between the remaining in the previous moment (current time–dt, where dt=1min) and the consumption since then. To evaluate the consumption, a consumption curve was fitted based on the historical data provided by the SENSASFALT system.

5. TWIN MODEL SETUP AND EVALUATION RESULTS

5.1 Input information

For the running of a whole journey, the Twin model takes the following:

- Environmental/exogenous variables:
    - dvaTaAmb: Dynamic variable representing the ambient temperature over time.
    - dvaHumTP1, dvaHumTP2 and dvaHumTP9: Dynamic variable representing the humidity of aggregates at feeding hoper 1,2 and 9 (RA Aggregate feeded after the dryer) over the time.

To calculate these variables, the simulation model reads an SQL table where the columns are each of these variables, and the rows are time points with their records. These records are read by the simulator, which fits a curve representing their evolve over time, which is in turn used to evaluate the value of each variable at each time step.

- Supply variables: quantity of fuel, quantity of bitumen, quantity of filler, quantity of aggregates of each type.
- Production variables from the work orders: prOrdenTrabajoId, prTaEnObra, prNoAlbasIn, prSelecRitmoProd, prQDemandaTramoIni, prTiIniProdEst, as defined in section 3.4.

To take this information, the simulation model reads an SQL table in which the above variables are the columns, and each work order is a row. The simulation model automatically schedules the production based on that information and starts the process as described in the Operator agent statechart (Figure 4)

5.2 Output information

As results, the simulator provides values for the properties of all agents mentioned, including the mixes ("Ama"), notes of delivery ("Albaranes"), and work orders ("OrdenTrabajo"). Also, all the information regarding consumption, emissions and temperatures over time are recorded and exported to an SQL table to enable further analysis when the Decision-making, visualization, and interaction layer (section 2.4) is operative.

6. CONCLUSIONS

To address the scarcity of digital twin (DT)-based solutions in the asphalt pavement sector, Padecasa is developing a digital solution for improving the efficiency of the hot mix asphalt (HMA) production process of its plants. This DT will be used as an adaptive planning support system capable of optimizing plant operation, as well as site demand and transportation scheduling. As a part of this solution, a preliminary version of the virtual model representing the physical system has been obtained. This model is intended to be used as the simulation engine for the abovementioned planning support system, and therefore it should be able to deal with the heterogeneity associated with the system scope.

In effect, the DT system boundaries had to include plant functioning and operation, site demand and transportation of HMA, and supply logistics, a wide and heterogeneous system that poses several difficulties. On the one hand, structuring the virtual model as a unique overall system would imply an over-dimensioned model in order to address all potential scenarios from the demand side. On the other hand, the system's scope includes different agents or stakeholders, such as construction sites, the plant operator, the production plant, or the suppliers, which dynamically interact with each other. This interaction is articulated via communication procedures and documents, that need also to be modeled. There is also the need to account for both discrete variables, such as the mixes of HMA in batch plants, and dynamic variables such as the humidity or the aggregates or their temperature across the production process, or the level of the fuel or bitumen tanks, that need to be continuously evaluated. Finally, there are some physical mechanisms, such as the transfer of heat to the aggregates that occur in the dryer, or the classification of aggregates by the tower screening process, that are difficult to model as knowledge-based models.

To overcome these issues, a Twin model architecture integrating several modeling techniques is proposed. In this architecture, agent-based simulation (ABS) is used to provide an intuitive and scalable structure to the simulation model, and include the communication system in which the interaction between agents occurs (section 4.1.1). As to the physical production processes, they have been modeled by means of discrete event simulation (DES) (section 4.2.1), while system dynamics (SD) is used to represent the continuous variables (section 4.2.2). Finally, data-based models (DBM) have been used in these cases in which building knowledge-based models entailed great difficulty (section 4.2.2).

In this communication, the overall architecture of the proposed HMA production Twin model is presented, as well as examples of how the integration of the abovementioned modeling approaches allowed the overcoming of the problems identified. As a result, the proposed Twin model is capable of simulating the production process of a whole journey based on the information contained in the working orders, and the environmental variables. During the simulation process, the properties of the "Ama", "Albaran" and "OrdenTrabajo" entities (sections 3.2.1, 3.2.4, and 3.4 respectively), which include information regarding weights (theoretical and real), temperatures across the process, consumption and emission of particles over time, remaining materials and fuel.

As explained above, this work is based on ongoing research, and therefore the presented Twin model is a preliminary version that still has some limitations to be overcome in the next steps. As explained in section 4.2.2.2, the DBM needs of data covering all the range of possible predictor values to provide accurate forecasting in all situations. This needs a wide dataset, including data from different seasons, time span during the day, and types of HMA formula. Since this dataset has not yet been completed, the DBMs are still provisional and have to be refitted. On the other hand, there are some equipment, such as the feeder of cold RA aggregate to the mixer, that have been modeled but are still to be included in the DT's data acquisition system, and therefore, its impact on the process performance (e.g. temperature in the mixer) is yet to be modeled. In addition to this, a HMA storage hopper after the mixer should be also included. Finally, Padecasa's plants are batch plants without a product storage silo after de mixer, and in consequence, continuous production and product storage silos functionalities should be added to the Twin model.

Acknowledgements: The authors acknowledge the financial support by the Spanish Ministry of Science and Innovation, grant number Project: PTQ2021-012235.

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