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Digital twin and Value Stream Mapping of Warehousing in Era of Industry 4.0

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Abstract

The rapid pace of technological development and high competition make businesses employ proper approaches to assess the effectiveness of their value creation process or supply chains. The dynamic business environment enhances the uncertainty and the risk of not meeting the business goals. Warehouses might be able to address some levels of uncertainty such as demand fluctuations. Yet, inventory accumulation may lead to becoming a source of inefficiency from the lean methodology perspective. Therefore, the application of the lean methodology and its well-known method, Value Stream Mapping (VSM), has not received much attention in the warehouse efficiency assessment context. On the other hand, Industry 4.0 refers to the ongoing fourth industrial revolution promoting connectivity and information sharing with some key enabling technologies, including the internet of things (IoT), simulation, and digital twin. The digital twin technology is considered a strategic technology and offers a practical way for a system performance assessment. This paper aimed to introduce an approach that integrates the VSM method with the digital twin concept. The proposed structured approach can be used for the performance evaluation of a warehouse while adapting to the dynamic nature of warehousing. The developed digital model can be used for real time warehouse performance monitoring and control when connected with the physical warehouse through communication devices. The proposed approach in this paper is applied to a real case to demonstrate its applicability.

Keywords

Industry 4.0; Warehouse; Digital twin; Value Stream Mapping; Simulation

1. Introduction

1.1 Supply chain and warehousing

Businesses experience high competition these days while facing cost increases and higher expectations from customers. Hence, many organizations are seeking solutions for increased value creation, by improving efficiency, reducing waste, and faster time to market. The dynamic business environment introduces uncertainty to supply chains, enhancing the risk of not meeting the goals. Various strategies can be applied to deal with uncertainty, including having warehouses to address fluctuations in supply or demand. Keeping inventories in warehouses may become a source of inefficiency or waste from lean methodology perspective. Warehouses are complex systems because their design knowledge is largescale and multidisciplinary, and they are dynamic systems. Therefore, data and data modelling play key roles in evaluating and consequently improving the efficiency of warehouses, which directly impact the supply chain efficiency from the inventory management perspective. Optimization is one of the most used methods for inventory management in warehousing. However, the complexity of warehouse knowledge and high level of uncertainty and facing various unexpected events may violate some assumptions in optimization models. Hence, an approach is

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required, which can capture the embodied dynamic within supply chains and particularly warehouses. Value Stream Mapping (VSM) is a key method in lean methodology trying to provide a snapshot of value creation in a system (such as manufacturing or warehousing) and gives insights into sources of inefficiency.

1.2 Industry 4.0 and application of digital twin for dynamic performance evaluation

Industry 4.0 refers to the fourth industrial revolution promoting the application of data in value creation. The key enabling technologies of Industry 4.0 are listed as cyber-physical systems, the internet of things (IoT), Artificial Intelligence, simulation, and digital twin [1]. The digital twin application has been studied for production management, robot optimization, quality assurance, and so on [2]. The digital twin concept revolves around developing high-fidelity virtual models reflecting reality [3]. The digital twin offers a practical way to study a system's performance. The connection of the digital twin with the real system (through connection devices such as IoT) allows data exchange between them and controlling the system.

1.3 Objective

This paper aims to integrate VSM as a method for efficiency assessment with the digital twin concept for the dynamic performance evaluation of a warehouse by considering its dynamic and complex structure. The proposed approach can be used as a decision support system to monitor or modify the warehouse planning parameters to increase its efficiency. To this end, this paper aims to introduce a structured approach to define Key Performance Indicators (KPIs) for a VSM model in the warehousing context to be embodied in its digital twin. This paper proposes a modelling approach to develop the warehouse digital twin which is executable and can receive data from the warehouse through communication devices such as IoT and accordingly optimize the warehouse planning/control parameters. The introduced VSM based KPIs are embodied in the digital twin to assure optimization supports meeting the efficiency objectives.

2. Technical concepts

2.1 Warehousing and VSM

Warehouses perform a series of dynamically interacting processes using various resources, so the approach used for their performance assessment must be able to capture such a complex structure holistically. Lean methodology seeks to improve the performance of operations by eliminating waste. VSM is one of the most used lean tools, aiming to visualize the interactions across different processes as resources, products, or information are used and passed through each stage. Such a high-level illustration allows analysing of the Key Performance Indicators (KPIs) of a value chain. Traditional VSM requires modification to capture the uncertainty tied to warehousing and its dynamic nature. This paper aims to integrate VSM with digital twin concept to allow warehouse performance assessment considering its dynamic and uncertain nature.

2.2 Digital twin

The digital twin is an emerging technology and is defined as the digital replica of an object or system, mapping its characteristics and behaviour. Gartner, a global advisory IT firm, suggested the digital twin as a strategic technology trend in 2016. China Association for Science and Intelligent Manufacturing academic consortium proposed the digital twin as a top 10 scientific and technological progress in intelligent manufacturing in 2017 [4]. The digital twin concept was introduced in 2003 at the University of Michigan in a Product Lifecycle Management course [5]. NASA defined it as an integrated multi-physics, multi-scale, probabilistic simulation of a system using physical models, sensor updates, historical, etc., to mirror the life of its flying twin. The first introduced digital twin model included three dimensions: physical, virtual, and data exchange [6]. Later a model was introduced with five dimensions: physical, virtual, twin data, services, and connections [7].

In industry 4.0 context, two types of integration are considered in value creation: horizontal and vertical. The latter addresses integration of systems and elements in an individual node (e.g., warehouse system), they exchange information including real-time data (e.g., collected by sensors) and share their status with each other (e.g., machine-to-machine communication), so the entire system can prepare for future jobs. Horizontal integration means all nodes are networked and cooperate, including warehouses, factories, and customers.

3. Literature review

In this section, only those works are reviewed that have similar scope to this paper. Hence, the works that investigated general application of VSM or digital twin, without their integration are excluded from review. The complexity of warehousing systems made researchers narrow down the scope of warehouse performance assessment, such as layout or operational policy assessment. This paper has a system-level scope, so the studies with a narrower scope are not reviewed here and interested readers are referred to the literature [8].

3.1 VSM for warehouse efficiency assessment

The existing studies that applied VSM at the supply chain level mostly demonstrated a warehouse as an inventory 'black box'. This does not offer deep insights into the warehouse performance, yet to have a lean supply chain, the performance of the warehouses as key nodes must be assessed and improved too.

Myerson suggested considering the warehouse function as an assembly line constituting several activities. Thus, warehouse efficiency could be improved by improving the tools and equipment availability [9]. Garcia applied VSM in warehousing assuming that the unit load does not change through the warehousing process [10]. However, a significant proportion of industrial warehouses change the unit of receiving consignment to another unit during the processes, which such a change in the unit load requires more careful consideration for a consistent performance assessment through various processes. Dotoli applied VSM to identify non-value-adding tasks in warehousing processes [11]. A mathematical model was developed to rank the identified wastes, called anomaly. The focus of the paper was on ranking anomalies and no structured approach was suggested to define KPI as a basis for comparison. The scope of the paper was only on the production warehouses, and other types of warehousing were only shown as work-in-progress (WIP) in the VSM model with no information about their operational performance. In another work, Bozer defined any increase in inventory level above the determined minimum level, as warehouse inefficiency [12]. However, if customer order reduces considerably, the inventory level will exceed the determined minimum level, or, if the demand increases, the inventory level decreases. Such an increase or reduction in inventory is not an indication of efficiency reduction or improvement in the warehouse.

3.2 Warehousing, VSM, and Digital Twin

Not many studies analysed the integration of VSM with a digital twin in the warehousing context. However, there are some works that studied the application of other industry 4.0 technologies in the warehousing context. Although their scope is different from this paper some of them are explained here.

Leng et al. proposed a digital twin system that used real-time warehousing data to optimize the packing and storage assignments operations. However, the application of this approach was limited to automated high-rise warehouses [13]. In the production system context (not in warehousing), a digital twin-enabled VSM approach was introduced by this reference [14]. That approach was based on developing a simulation model that used the VSM model results to simulate the performance to help finding the bottlenecks and other system problems, and finally, to improve the system parameters. Ali and Phan conducted a literature review on the application of industry 4.0 technologies to achieve sustainable warehousing [15]. Similar to manufacturing systems, they concluded that the application of industry 4.0 technologies in warehousing can support improving operational efficiencies, particularly a fully automated warehouse can achieve high efficiency by reducing energy consumption, waste, resource consumption, and unpredicted machines breakdowns [16]. The economic sustainability of warehousing while applying Industry 4.0 technologies was investigated by this reference [17]. An artificial reality software called "Pickup Simulo" was proposed to provide insights into the efficiency of warehousing activities. The effectiveness of using IoT in terms of data sharing and visibility in warehousing processes such as order picking, loading, and shipping was demonstrated in terms of errors and damages reduction, and consequently reducing resource waste. Likewise, the application of blockchain-enabled digital legend was analysed by this reference [18], concluding improvement in reducing the likelihood of product tempering, consignment rejection, and economic losses. It is agreed that there is a lack of a general approach for digital twin development that can be used in different fields [19].

In conclusion, although VSM has been applied in supply chain and manufacturing system assessment context, but its application has not been studied in warehousing context. On the other hand, given the fact that the digital twin is a new concept, integration of the VSM and the digital twin has not been studied in the literature. This is a research gap that this paper aims to address and the proposed framework as the integration of the VSM and digital twin is a novel contrition by this paper to this field.

4. Digital twin, Simulation, and VSM integration

4.1 Application of VSM in warehousing and KPI modelling

VSM method intends to evaluate a value stream against the overall system objective(s). In warehousing, the ultimate objective is to fulfil customer orders, which their specifications are not known in advance. This uncertainty complicates defining an identical evaluation unit for all processes. An automated warehouse with a seamless connection between a data-driven digital twin, IoT, and cloud technology has potentials to achieve high efficiency in its operation if processes are configured properly, if right data are collected, and analysed such that providing insights for improvement of warehouse performance. Hence, having a proper data model with the proper KPI is crucial for performance. In this section, an approach is proposed for proper modelling of KPIs for efficiency assessment in the warehousing context from the lean methodology perspective.

Dividing the process to the value adding and non-value adding is a principle in lean methodology to identify sources of waste, so by eliminating or reducing the number of non-value adding activities the system can perform more efficient. The former is considered as those that change physical shape/assembly of a product. In warehousing context, there are generally no substantial changes to shape/assembly. Hence, warehousing activities are often not considered to be value-adding. However, warehouses change the item unit type. Warehousing processes can be divided into five abstract classes; receiving, storing, picking, sorting, and shipping [20, 21]. In receiving process, the inbound consignments are accepted and converted into items that can be stored in the warehouse. The value created is transforming inbound items into 'warehouse-able' items (Stock Keeping Units: SKUs). In storing process, warehouse-able items are allocated into storage modules. In order picking process, the customer-requested items are retrieved from the storage modules. In the sorting process, the picked items are qualified to satisfy order requirements and prepared to be shipped. In shipping process, the orders are despatched from the warehouse. Each process has an objective in transferring the item status, receiving transfers the supply consignment to SKUs, storing process transfers SKUs to stored SKUs, picking transfers the stored SKUs to picked SKUs, sorting transfers the picked SKUs to customer order, and shipping transfers the customer order to shipped orders. To identify value-adding activities, this paper suggests modelling the warehouse function based on those five abstract processes. Considering a pool of possible processes and sub-processes, the warehousing function, W_f, can be represented as shown in (1).

$$W_f = \{(\alpha_i, P_i)\}\ ;\ \ i\epsilon\,\{1, \dots ,5\}, \alpha_i = \begin{cases} 1 \text{ if } P_i \text{ is an enabling process for warehousing function} \\ 0\ otherwise \end{cases} \quad (1)$$

$$P_i = \{(\beta_k, SP_k)\}\ ;\ \ k\epsilon\,\{1, \dots , k\}, \beta_i = \begin{cases} 1 \text{ if sub} - \text{process k is needed in } P_i \\ 0\ otherwise \end{cases}$$

This paper defines those activities which operate after the item transits to the required status from the abstract process as non-value adding. Each sub-process of a process should be analysed with respect to its abstract process and thus a value-adding activity in one process can be non-value-adding in another. Receiving and shipping processes interact with suppliers and customers respectively, so, they deal with different units for the same item type, respectively supplier consignment and customer order units. The receiving process may encompass various sub-processes to convert the supplier consignment to SKU (e.g., palletizing). As soon as the item unit is converted to SKU, the remaining sub-processes in the receiving process and in storing process operate on an SKU base. Depending on the picking process design, it can operate on SKU or order basis. The sorting process qualifies the picked SKUs to meet the order specification. Hence it also operates on a dual basis, SKU and order. Finally, the shipping process dispatches orders, and this generally operates on an order basis but may include some sub-processes that operate on an SKU basis as well.

The SKU represents the most aggregated level of planning unit in the warehousing context; hence this paper suggests conducting process evaluation using SKU as a base unit. Warehousing processes can be categorized into SKU-based and not SKU-based, which each is subdivided into two sub-categories: '*direct*' and '*variable*'. In the direct sub-category, the process parameters are a direct function of the number of operational units. For example, in the labelling process, the operation time is a direct function of the number of labelled SKUs. In the variable sub-category, the process parameters may vary from one process to another. An example of a variable parameter is the travel distance (and consequently process time) in the picking process, which may vary for different orders depending on requested items in customer orders. There is no need to convert the process operational unit for SKU-based processes. The not-SKU-based processes may operate in one of the following situations:

- Input SKU, output not-SKU: number of inputs (SKUs) can be used to formulate process parameters.
- Input not SKU, output SKU: number of outputs (SKUs) can be used to formulate process parameters.
- Input not SKU, output not-SKU: using 'expected' approach to estimate the average for the number of SKUs in a process (explained below).

Expected: a probability distribution function can be fitted to the variable parameter (e.g., the number of operating SKUs) of a process by using its historical data. Accordingly, the '*expected value*' of the variable process parameter can be used to estimate a process KPI.

For 'direct' type processes, since process parameters are a direct function of the number of operational units, x, the KPIs can be formulated on SKU base. For processes with 'variable' parameters, the KPIs can be calculated with the 'expected' approach as explained din mor detail in the next section.

4.1 Digital twin integration with VSM

Warehouse systems as complex systems demonstrate emerging behaviour as the result of interactions between their individual elements and with their environment [22]. The emerging behaviour or performance of a warehouse system can hardly be formulated with analytical formulation [23]. Simulation is a widely accepted approach for the validation of design or planning parameters. In the industry 4.0 context, simulation can serve many purposes, including scenario analysis and performance assessment. In this section, an approach is introduced to develop a digital twin for a warehouse that embodies the explained KPIs from the VSM perspective while the developed model has simulation capabilities. This helps to observe the possible emerging behaviour of the warehouse because of suggesting changes in the process chain after the VSM application. This makes the digital twin experiment-able that can support the validation of a warehouse plan and as a runtime environment can be used as a test bed to assess the warehouse performance as a function of dynamic interactions prior to applying any changes in the warehouse system.

The Object-Oriented (OO) method is a well-known approach for analysing complex systems [24]. Hence, this research suggests its application in developing the digital twin model of a warehouse. Abdoli introduced OO-based architecting guidelines for the holistic modelling of an engineering system by decomposing the system into processes that deliver its main function as a transformation of an item's state from input to output [23]. Accordingly, a warehouse can be modelled as a class diagram, as a composition of classes representing the warehousing processes. On the other hand, Finite State Machine (FSM) is a formalism that visualizes the structure of a system by its elements and embodies its behaviour by dynamic states defined for its elements. Hence, this research suggests constructing the digital twin in FSM formalism to achieve an experiment-able digital twin, due to the promising features of FSM including system visualization plus its simulation capabilities. Thus, the suggested OO-based approach by Abdoli [23] is mapped to FSM by embodying a nested state structure. The warehouse system is modelled as a parent state decomposed into sub-states embodying its processes, called process-state. In FSM, functions can be defined for a state to model its behaviour, so a function is associated with each process-state to model its dynamic behaviour, called process-functions. A process-function returns the parameters of a process with its outputs (e.g., equipment available capacity, number of operating SKUs), called Dynamic Variables (DVs). Relations between functions (in exchanging DVs) must be defined to embody the interactions between processes. Some variables can be defined in process-functions to return the values of KPIs (e.g., process time) at the end of the simulation.

The digital twin of a warehouse can use both historical and real-time data. An FSM model can receive data in different formats (e.g., XML) from physical objects [25]. This allows the developed digital twin to receive data from the cloud, containing collected data from physical objects (e.g., forklifts) by communication devices (e.g., IoT) or interact directly with them and get data (e.g., storage module status). An FSM model can be used to generate codes (e.g., Programmable Logic Controller) to control physical objects as well [26, 27]. The proposed approach is shown in Figure 1.

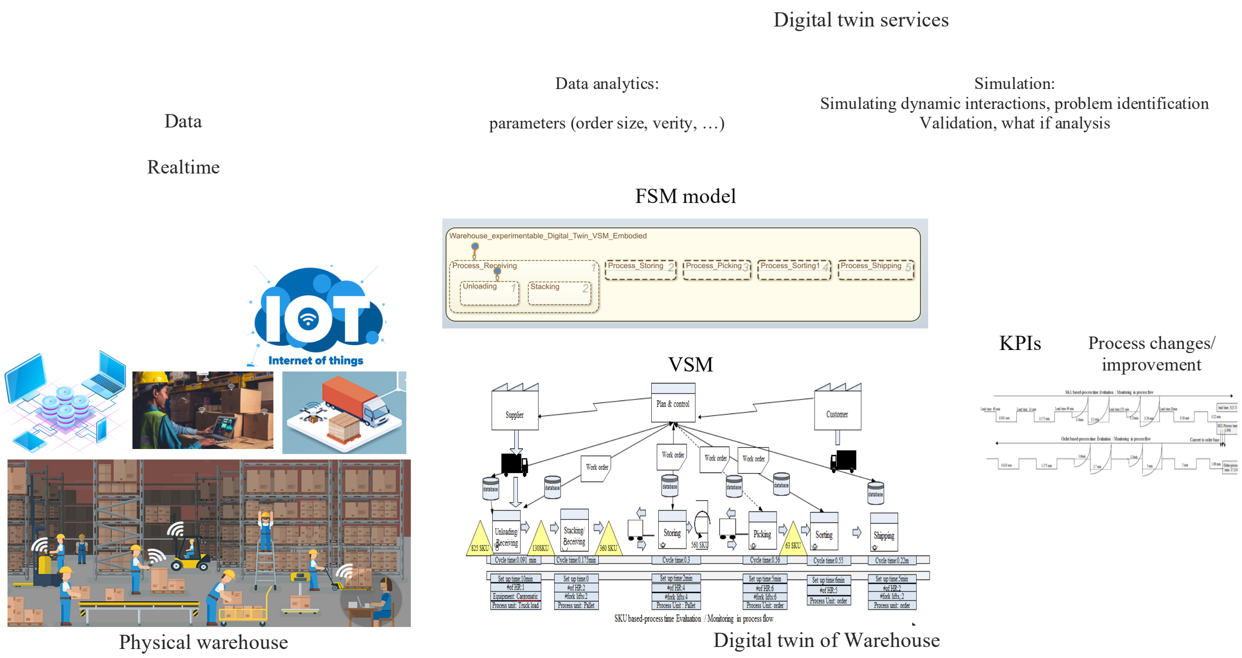

Figure 1: FSM-Digital twin integration with VSM

Embodying the VSM-based KPIs in the digital twin allows capturing the dynamic nature of a process in efficiency assessment. The order picking process is a good example of a process with variable process time and many research formulated that as a function of many parameters as shown in Equation (2), such as a_l: picking aisles length, a_w: picking aisles width, a_h: picking aisles height, T: number of aisles, o_s: order size,

o_{dv}: order diversity [28]. Order diversity can range from one to maximum order size. The former represents a single order line, whilst the latter indicates one single item per SKU in an order. Such formulas can be embodied in the process-function of the order picking process to predict the process time. The process parameters can be deterministic or non-deterministic. The former ones are fixed, such as the number of aisles whereas the latter, such as order diversity or order size, may vary from one order to another. These non-deterministic parameters introduce variability to the process time and leading to have 'variable' the process type as mentioned before. By using historical data, the order profile can be mapped to a probability distribution function. The digital twin has access to historical data or can be connected to physical objects through IoT. The embodied data analytics models in the digital twin can use the available data and fit a probability distribution to the non-deterministic parameter in a warehousing process, such as the order size and variability. The expected value of a random parameter can be used to evaluate a process against the KPIs. For example, after the digital twin fitted a probability distribution to the order size, then the order picking time can be calculated. This logic applies to all variable processes with non-deterministic parameters.

$$Eexpected\ (order\ picking\ time) = \tag{2}$$

$$\sum_{order\ size=1}^{Order\ size} \sum_{Order\ diversity=1}^{Order\ diveristy=order\ size} P\left(order_{order\ size}, order_{order\ diversity}\right) \times$$

$$f\left(aisle_{length}, aisle_{width}, aisle_{heigth}, Equipment\ travelling\ time, order_{order\ size}, order_{order\ diversity}\right)$$

According to the introduced approach, all warehousing processes can be evaluated against an identical unit, the SKU. This approach enables the application of a dynamic VSM for holistic warehousing performance assessment. It is preferable to interpret warehousing efficiency with respect to the ultimate objective of the warehousing function, which is satisfying customer orders. Hence, SKU-based KPIs are needed to be transformed into order-based KPIs. Thus, it is suggested to utilize the explained *expected* approach to characterise the order profile by using its historical data. For example, if the storing process time for a single SKU was calculated 5 minutes and the expected order size was 20, then the expected process time for the order can be approximately 100 minutes. The proposed approach stands as a decision support framework, however, the experts still can define some constraints based on the stakeholder objectives. For example, the experts can set a threshold for the minimum value of SKUs to assure having some levels of safety inventory.

4.2 Scenario analysis with digital twin

The executable digital twin allows testing a wide variety of scenarios which may lead to different behaviours and warehouse performance [19, 29]. Such scenarios can be modelled in the FSM model by defining some events or probability functions to model variations from initial assumptions, such as supply frequency or equipment failures. Simulation for what-if assessment can assist in analysing the effects of variations on the warehouse performance within the supply chain. This approach can be applied in any system containing variable processes with non-deterministic process parameters.

5. Case study

The case study warehouse was a distribution centre of a pharmaceutical company. The receiving process needed to change item-unit from supplier consignment to pallet, then from pallet to SKU, and later in the sorting process from SKU to customer order. The receiving process included unloading and stacking sub-processes. The warehouse had an ERP system containing warehousing information including the inventory status, incoming supplier consignment, and customer orders. The unloading process was performed by an automatic Cargomatic, five loads each weekday, each containing 33 pallets of 10 SKUs. Both unloading and stacking are considered value-adding, since they convert supplier consignments to warehouse-able items.

Some example calculations are provided here, and the VSM results are shown in Figure 2. Since the SKU quantity is constant in each load received, the receiving process is formulated on an SKU basis as follows.

Unloading-time for truck load=30 minutes, Unloading-time per SKU=30/33×10= 0.091 minute.

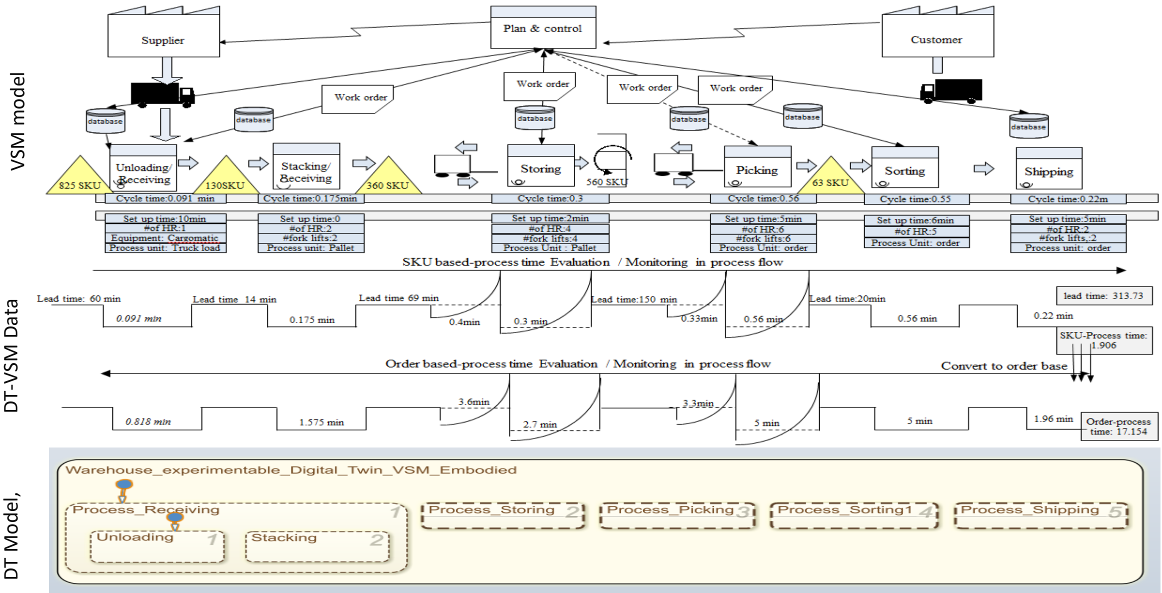

Figure 2: Developed FSM-Digital twin integrated with VSM-KPIs for the case study

In the storing process, an operator needed to drive a forklift to the stacking area and pick SKUs, then drive to the storing area, put them in racks, and come back. The two driving components of this process are considered non-value-added but necessary activities, whilst the positioning of SKUs in racks is considered the main storing process. The transportation and storing process had variable operation time depending on the storage location, (e.g., aisle position and rack height). Using the historical data in the ERP, a Pareto distribution was fitted to the storing process time. In the picking process, an operator needed to pick up ordered items. Likewise, a Pareto distribution was fitted to the picking process by using the ERP historical data. According to the explained approach, the FSM-Digital twin integrated with VSM was developed, as shown in Figure 2. The Pareto diagrams are rotated 90 degrees and the dashed lines show the expected values of each distribution, which can be used for various KPIs estimation. Based on the available data in the ERP, the order size varies from 3 to 11 SKU per order with an average of 9, with larger orders being more common. Hence, the sorting process is converted to an SKU base by considering its expected value of operational units. To demonstrate the order-based KPIs, the process parameters are divided into 9 (average order size).

$\text{Storing} - \text{Process time} = $ 3minutes/pallet $\quad$ $\text{Storing} - \text{Process time}_{-SKU\ based} = $ 3/10=0.3 minutes

$Sorting - Process\ time_{-SKU\ based}$≈0.56 minutes, $Sorting - Process\ time_{-order\ base}$= 5 minutes

The lead time is studied as the main KPI. The lead time before the picking process initiation indicates an SKU's waiting time to progress to successive processes, whereas the cumulative values of lead times after that represent the order lead time. Hence the lead times before the picking process are not converted to order-based values. Based on the developed FSM-digital twin integrated with the VSM model of the warehouse, sorting and picking tend to have the longest processing times, while the transportation elements in the storing and picking imposed the most uncertainty. Hence, combining the storing and picking processes could absorb some variation from both processes. This approach is called the double command storing-picking process and could improve efficiency. The suggested changes in the structure of these two processes could be validated by the digital twin prior to implementation to ensure its applicability. Demonstrating such a future state map is not in the scope of this paper but would follow the same procedures set out in this paper.

6. Results and conclusions

This paper proposed an approach to integrate the VSM as an efficiency assessment with the digital twin concept to allow monitoring and assessing the efficiency of a warehouse.

An approach was introduced for identifying value-adding activities in the application of VSM in the warehousing context, leveraging the traditional VSM to a more dynamic assessment tool that could capture the uncertainty in warehousing processes. An approach was introduced to embody the explained dynamic VSM in the digital twin of a warehouse, developed as an FSM model with simulation capabilities. This can support simulation-based performance evaluation. Such a digital twin can also be used for analysing the impact of possible changes in a warehouse system prior to their implementation. The developed digital twin can use available data including historical data (such as ERP in the case study) or real-time data from communication devices.

A future direction for this research can be an investigation on how the real time data can be used by the developed FSM digital twin model for real-time system improvement. Moreover, automatic model calibration based on VSM results can be investigated as well.

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Biography

Shiva Abdoli is a lecturer in School of Mechanical and Manufacturing Engineering, UNSW. She worked as a researcher in KTH University, Sweden. She received her Ph. D in 2019 from UNSW. After her post-doctoral fellowship, she started as a Lecturer in 2020 at UNSW. She has led industry-based research projects. Her research field includes System design, Industry 4.0, Sustainable Production, and Circular Economy.