

Digital Twins for Logistics in Steel Manufacturing Process

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Abstract

Steel works produce several thousands to several tens of thousands of steel products in a multi-stage process. Products are transferred between plants which have different processing lines. Therefore, the logistics in steel manufacturing processes are usually complex and this causes problems such as shortage or oversupply of stocks. Nippon Steel Corporation and NS Solutions Corporation have developed digital twins for visualizing, analyzing and simulating logistics. In this article, we introduce the concept of the digital twins and their application examples.

1. Introduction

The steel manufacturing process is a breakdown-type multi-stage process consisting of processes such as blast furnace, converter, continuous casting, rolling, annealing, and surface treatment. In its respective processes, a lot production system is employed wherein the products with an identical manufacturing condition are produced continuously. Since the processing order and/or the manufacturing lot differ in the respective processes, the combinations of these manufacturing conditions can range from several thousands to several tens of thousands, significantly complicating the production structure. Although continuous manufacturing with large lots under consistent conditions is ideal for maintaining quality and reducing costs, the variability in manufacturing conditions and delivery terms for each product makes it challenging to formulate a production plan and schedule that balances quality, cost, and delivery time. To achieve this, Nippon Steel Corporation has been developing a system to support the formulation of a production plan and scheduling, paying attention to balancing quality, cost, and delivery term for the respective processes and respective facilities.¹⁾

However, in the steel manufacturing process, since various types of transportation equipment such as carriers and automated guided vehicles (AGVs) are used for inter-process transportation, not only the production plan and scheduling in the respective processes, but also the smooth transportation of products and/or semi-products to the downstream process without causing the accumulation and/or shortage of materials, namely logistics rectification, is important. For instance, if materials are accumulated between plants due to the delay in arranging carriers to transport materials to subsequent facilities, not only is the transportation time prolonged, but over-stocking

also takes place in the former facility as its materials are not received, while the subsequent receiving side facility runs out of materials due to the delay in material supply. In the case that inventory exceeds the capacity of the rear yard of the delivering side facility, the former facility is unable to deliver processed products, and the operation of the facility has to be suspended. Additionally, facilities also have to be stopped in the case of shortage of materials. The suspension of a facility stops the supply of materials to other facilities, and this leads to reduction in production of the steel works as a whole. Furthermore, the disruption of logistics rectification is not only caused by the shortage of transportation equipment, but also by the quality of the products produced, the variations of processing time due to the difficulties in operation, and the decrease in the amount of maritime transactions of products due to deterioration in weather.

Therefore, in order to rectify logistics, it is necessary to make decisions regarding the production plan, scheduling, and instructions to on-site work etc., that do not just target a specific process alone, but that also consider the logistics of the entire steel works, or at least the processes before and after the subject process. In order to properly execute such decision making, it is important to study the optimized action from the viewpoints of quality, cost, and delivery term via the process of precisely recognizing the current logistics and simulating future logistics. However, in the steel manufacturing process, thousands of types of products are manufactured differently through facilities ranging from several tens to several hundreds, therefore, it is not easy to grasp the inter-process influences, and to execute the abovementioned decision-making process. Furthermore, the steel manufacturing process takes a long term since the process

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has many production stages stretching from the raw material stage to the final products stage. Accordingly, the state of a certain process (working rate, quantity of inventory, and so forth) often exerts influence on the states of other processes several days later; therefore, retrospective time series analysis of data is necessary, and this further complicates the decision making process.

Thus, in this research, we have developed a logistics digital twin platform, which enables reproduction of the logistics from past to present, and future logistics simulations based on the logistics data extracted from steel works. Chapter 2 introduces the concept of the logistics digital twins and the developed platform “Geminant”. Subsequently, as examples of the applications, Chapter 3 introduces the visualization of logistics and the analysis of the bottlenecks in the sheet finishing process, and Chapter 4 discusses the development process of the logistics simulator intended for the support of the inter-process carrier control and its application example. Chapter 5 describes the logistics simulation model to support the inventory control and its mechanism to sustainably improve the model so that it continues to exert its effect. Chapter 6 summarizes this article and refers to future work.

2. Logistics Digital Twin Concept

The logistics digital twin concept aims at reproducing the past and present logistics from the actual data and also at simulating the future logistics. **Figure 1** shows the overall concept of our digital twin.

At Layer-1, the past and present logistics are reproduced. Simultaneously, the actual data to be input for logistics visualization are to be accumulated as the data model which enables tracking individual products. Furthermore, by commonizing the data model regardless of the target process, we can visualize the flow amount between facilities, stock yards, and transportation equipment with graphs. This includes the information not related to the process characteristics such as inventory amount and time series transitions of operating rates for facilities and transportation equipment without creating systems specific to the respective targeted processes. 3D logistics visualization is also used to take the physical interference into account. However, although the detailed conditions of the respective subject processes need to be built in individually, the system development is effectively implemented by arranging common parts on

the digital twin platform.

At Layer-2, based on the data model, the logistics conditions are recognized through the statistical analysis, the time series analysis of inventory, processing term, operating rate, and the extraction of the bottleneck process and critical pass. As an example of factor analysis in the case of a logistics problem, it is important to determine whether there is a significant difference in the mean processing time per product type and whether any transportation equipment is operating at a lower rate than usual. By componentizing the logistics analysis processing, when data are prepared, analysis can be immediately conducted without depending on the subject process.

At Layer-3, future logistics are predicted based on the simulator, and the production plan and schedules are formulated according to the prediction results. For example, the effectiveness of the decision making based on the recognition layer of Layer-2 is confirmed in advance by simulation. In addition, the measures which are mathematically optimized are automatically determined by the optimization model such as mathematical programming. By using the data model of Layer-1 consistently for the simulator and mathematical model, we ensure consistency in visualization, logistics analysis, simulation, and optimization.

By utilizing the intelligent scheduling platform equipped with the abovementioned respective layer, applications for solving logistics problems in every steel works can be promptly provided for implementation. Actions determined at the application layers are provided to the actual process, and further, by gathering the actual data, we can apply the Plan-Do-Check-Action (PDCA) concept to a business and system (data and model).

Based on this concept, this research is conducted as a collaborative research between Nippon Steel and NS Solutions Corporation. Nippon Steel develops the application layers, the Systems Research & Development Center of NS Solutions develops the digital twin platform, and the intelligent scheduling platform in-between are jointly developed by the two companies. Hereunder, “Geminant”, the digital twin platform developed based on above concept, is introduced.

The Systems Research & Development Center of NS Solutions aims at creating common recognition among the system users by utilizing the digital twin technology in an actual production site. We consider that the realization of the “interactive twins”, which enable future trials in the digital world, in addition to the “viewable twins”, which visualize the physical world in the digital world will lead to deeper reciprocal understanding.

As described earlier, the flow of business improvement based on data goes through visualizing data (Layer-1), recognizing current status (Layer-2), and predicting future and appropriate decision making (Layer-3), and then actions are taken in the real world. We consider that, by gradually expanding the scope of the digitalized process, the objectivity and rapidity of business operations can be enhanced. As a step to expand the digitalization, we set four stages including observation, estimation, fusion, and automation (**Fig. 2**). The statement above refers to the completion of digitalization of: the data visualization process (Layer-1) at the “Observation” stage, and the recognition and the prediction processes (Layer-2, 3) at the “Estimation” stage. Furthermore, at the “Fusion” stage, the digital world and the physical world are synchronized on a real-time basis, reconciling the predicted values and actual values. The last stage is “Automation” where human judgement is no longer necessary. To achieve “Automation” at the final stage, we consider that it is important to continue to rotate the cycle of improvement particularly

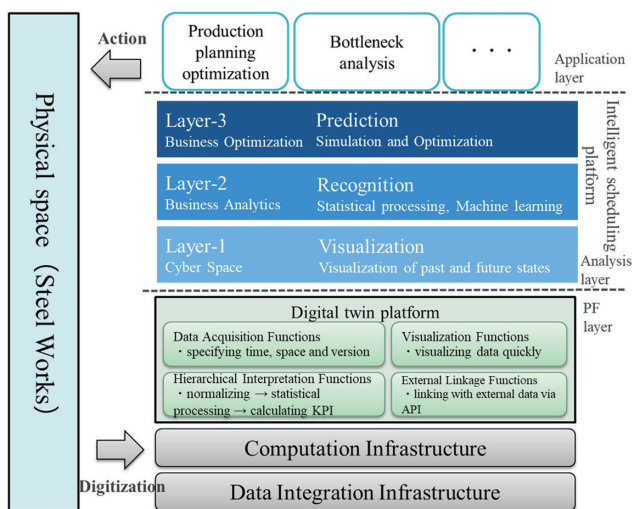


Fig. 1 Logistics digital twin concept

even after entering the fusion stage, and therefore, it is indispensable to realize “viewable twins” and “interactive twins”, and then, to continue to rotate the cycle of improvement even to these twins. The Systems Research & Development Center develops the digital twin platform Geminant as the platform to improve the “viewable” and “interactive twins” constantly. (Fig. 3).

Geminant provides a 3D visualization function. In the Geminant, as the common data model for 3D visualization is defined in advance, 3D visualization is realized without creating visualization individual results. By storing the actual status in the common data model form, this function visualizes the data from the past and the present as “viewable twins”. In addition, as “interactive twins”, it enables viewing of the result of the future predictions by storing the predictions and optimizations results as the same data model. Currently, Geminant is only available in Japan. Application examples of Geminant are introduced hereafter.

3. Application Example 1: Visualization of Logistics and Analysis of Bottleneck Factors

Since the logistics in steel works are complicated, even when facility operation is suspended due to the limitation of stock yard availability and/or the shortage of materials of the subject products (lack of materials) occur, it is difficult to find the root causes of logistics problems. For instance, with shortage of stock yard space in daily operation, pluralities of factors are conceivable such as excess flow of steel materials from the foregoing process and/or decrease in delivery to subsequent processes. However, as the foregoing process

and/or the subsequent process are also influenced by their own foregoing process and/or subsequent process, and as the cause may reside in such processes, it is difficult to identify the cause. Furthermore, in order to identify the problematic factor among the multiple possible causes of problems, and take actions to identify solutions accordingly, it is important not only to understand the status of each facility, stockyard, and transportation equipment but also to grasp their spatial linkage. As one method, we develop a system that visualizes as a network such linkage among production facilities, stock yards, and transportation equipment. This system is referred to as the “logistics network visualization system” in this article²⁾ (Fig. 4).

In the steel manufacturing process, logistics analysis is required for analyses ranging from macroscopic analysis of the plant-wide balance to microscopic analysis of changing the transportation order in a plant. If the visualization system is built taking into account the analysis subject, implementing the visualization system will take a long time. Therefore, in the proposed logistics network visualization system, the sheet-processing process-flow data prepared in the standardized format per steel material are used for input. By arranging data in accordance with the data format, it is possible to visualize and analyze logistics. The sheet-processing process-flow data include allocated ID, processing route, and starting and finishing time of processing. In this system, logistics are visualized by using the actual logistics data arranged in the regular format.

The logistics network visualization system visualizes the flow of steel materials throughout the process of facilities, storage yards, and transportation equipment, each assumed as a node in the graph, in the form of an oriented graph by using the input of the process-flow data of the respective steel materials. The node expresses a process (storage yard, facility, transportation equipment), and the configuration of the node denotes the type of process (storage yard: square; facility: circle; transportation equipment: diamond; and so forth). The edge shows the inter-process steel material flow, the thickness of which corresponds to the amount of flow (number of steel material, weight) per period, moving time, and the term inclusive of the processing time in the subsequent process. Furthermore, the respective process is indicated in red as issuing an alarm depending on the extent of tightness with respect to the processing capability. This is aggregated during the time series interval corresponding to the interval of image drawing so that the process with a high degree of tightness can be easily extracted.

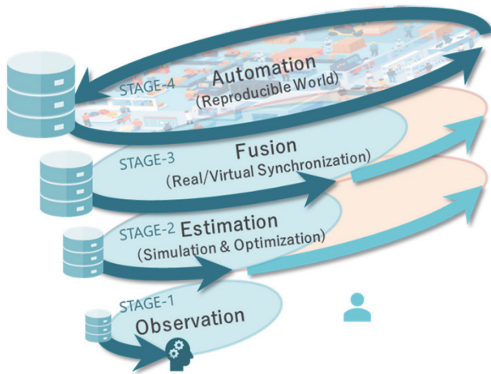


Fig. 2 Four stages to expand the scope of digitization

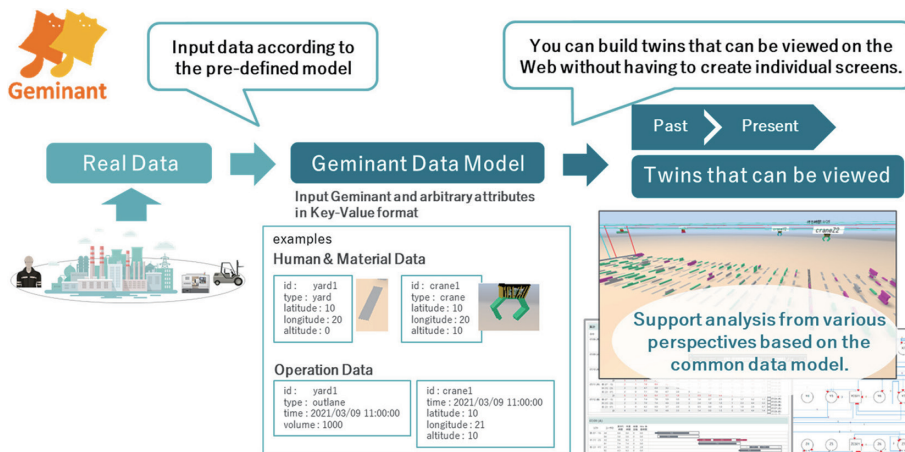


Fig. 3 Geminant technology to accelerate building twins that can be viewed

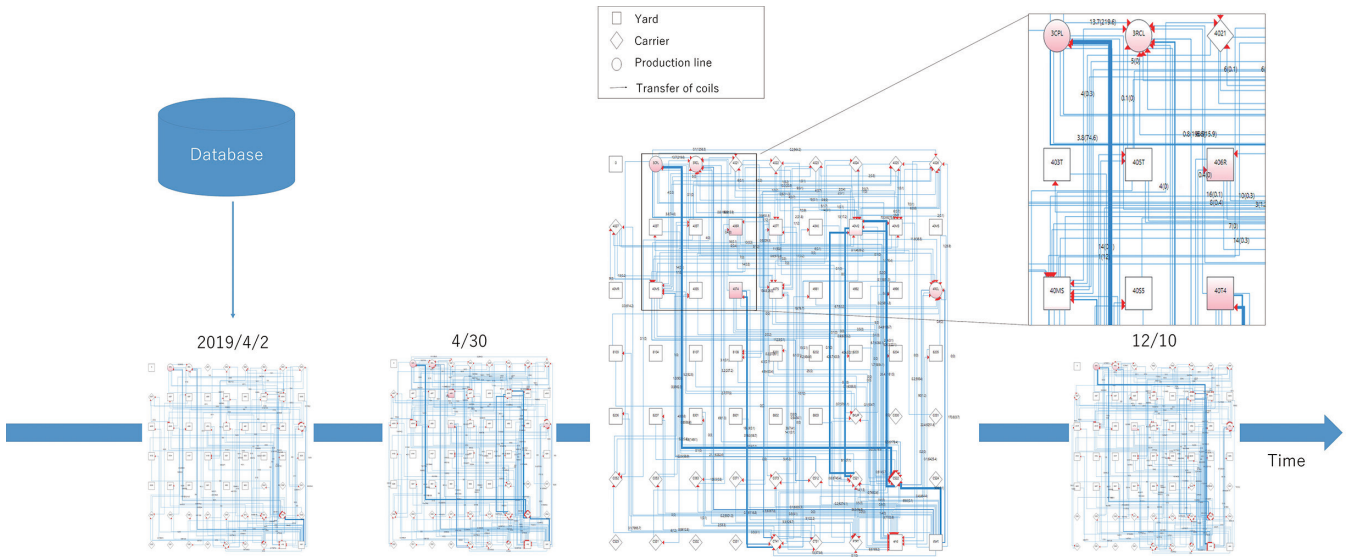


Fig. 4 Logistics network visualization system

As mentioned previously, the logistics in the steel manufacturing process vary hour by hour depending on the products ordered, weather, and the state of logistics. In this system, to track the change in logistics, the logistics network is displayed periodically in time series, enabling the tracking of the change in the logistics. The time series change in the logistics is visualized in an animated form at an arbitrarily chosen time interval (e.g., one hour, twelve hours, one day, one week), thus the change in the respective logistics becomes recognizable.

Furthermore, intuitive grasp of the on-going situation is enabled by freely changing the layout according to the users' request, for example, changing the locations of the node and/or the edge to match the plant layout.

When using this system for logistics analysis, it is desirable to visualize all steel material process-flow patterns, and identify the problematic issues among them. However, if we visualize all process-flow patterns as the network, the visualization result becomes very complex and it is difficult to manually extract the significant process-flow patterns for bottleneck analysis. Therefore, this research proposes a method to simplify and visualize the logistics network while retaining major logistics information.³⁾

Furthermore, aiming at automatically extracting the graph structure of the major logistics network from actual data, this research proposes the evaluation metrics for selecting an appropriate network structure by simultaneously evaluating the simplicity of the network and the reproducibility of process-flow patterns.⁴⁾ The observed process-flow pattern (example: hot-rolling → galvanizing → shipping, and so on) totaling n in number is expressed as $x = \{x_1, \dots, x_n\}$, and x is assumed to be generated according to the probability model $f(x|\theta;G)$. Herein, $\theta = \{\theta_1, \dots, \theta_M\}$ is an unknown parameter representing the event probability of the process-flow pattern calculated from the candidate graph structure G . For these evaluation metrics as the standard for judgement of superiority or inferiority of the probability model, the evaluation metrics are calculated from the combination of the maximum log-likelihood estimate and the dimensionality number M (Formula (1)).

$$score = -\sum_{i=1}^n \log f(x_i|\theta_{ML};G) + w \cdot M \quad (1)$$

Herein, θ_{ML} expresses the maximum likelihood estimate of the incidence of the process-flow pattern θ . With respect to each candidate

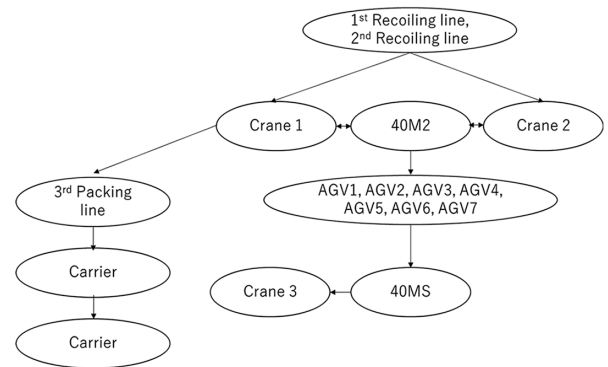


Fig. 5 An example of graph with best evaluation value

graph structure G , this evaluation metrics is calculated, and the graph structure having the minimum value is considered to be the best graph structure. Furthermore, w denotes the weight coefficient, and by changing this weight coefficient, the extraction of the logistics network at the simplicity level required by users is enabled.

The result of network exploration by using this network evaluation metrics is described hereunder. Shown below is the visualization result of the one-year data of logistics in a certain steel work as a network, and as the result revealed, similar processes are unified and the extraction of a simplified network is realized. For example, Fig. 5 shows an example of the network having the best evaluation score values selected from the pluralities of networks built by changing the process unification pattern with respect to the one-year process-flow patterns in a certain steel work and the patterns are summarized as groups consisting of 1st and 2nd Recoiling line, and seven AGVs (AGV1 to 7). These are considered similar to each other in terms of roles in logistics, and even after unification, the patterns visualized as a logistics network do not lose the information of the process-flow patterns.

By using this network visualization tool, one-year logistics data was visualized. As a result, the inventory occupancy rate in a storage yard on a specific day reached an extremely tight level of 98%. To investigate the issue of tightness in the storage yard, major logistics are extracted from the logistics network, and the transportation

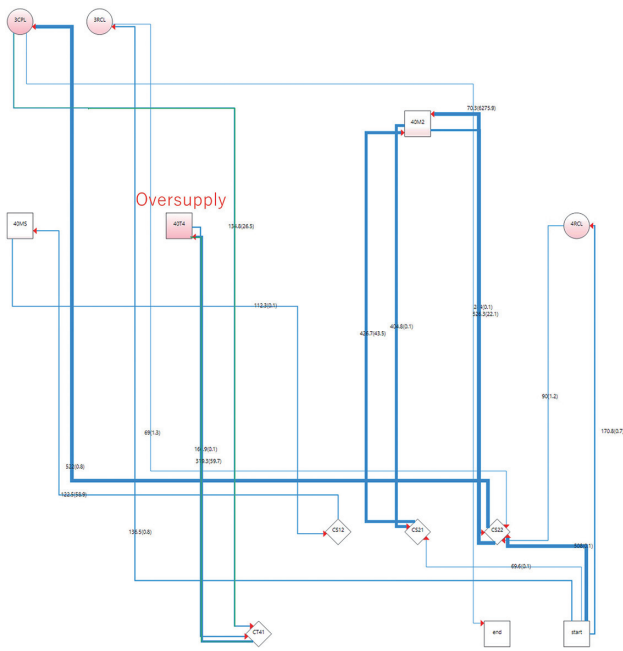


Fig. 6 Extracted logistics problems

equipment carrying coils to the aforementioned storage yard has overloaded (Fig. 6). Furthermore, observing the preceding process, the amount of delivery to the storage yard that is under a tight condition has increased temporarily.

Thus, by visualizing logistics as a network and tracking the time series changes in it, the cause of tightness could be analyzed.

4. Application Example 2: Logistics Control Simulation Technology

In steel works, there are many cases of inter-process transportation such as of molten materials and heavy goods, and they are transported by automatic guided vehicles (AGVs) installed in facilities, freight cars, and/or carriers (heavy material transporting vehicles) which move between pluralities of plants. Thus it is important for reducing logistics costs to optimize the transportation schedules. We developed a carrier logistics simulator intended for the effective implementation of inter-plant carrier transportation. In addition to support business operations by using the simulator, Geminant is also applied to rapidly improve the prediction accuracy of the simulator itself. This chapter describes an example of how the Geminant is used.

In the logistics that interlink plants in steel works, steel materials to be transported from each plant are placed on a stand called a pallet by an overhead crane, and each pallet is transported to the next plant by a transportation vehicle called a carrier. This type of transportation is called “carrier-pallet transportation”.

As mentioned previously, in the steel manufacturing process, the total number of orders can reach as high as several thousands to several tens of thousands, and the manufacturing conditions of respective steel materials differ depending on the process. Therefore, the steel manufacturing process which employs the lot production system for processing steel materials having an identical processing condition all together is characterized by the processing order of each steel material being different depending on the process. Namely, if various steel materials are sent to the next plant according to the processed order in the previous process, the required steel mate-

rials cannot be sent timely to the next plant at the time required. Therefore, the carrier-pallet transportation work which interconnects plants also plays a role of absorbing the difference in processing order in the previous process and in the subsequent process.

As a matter of convenience for such a role, the carrier-pallet transportation work is greatly influenced by the shifts of the actual operation from the planned schedule both in the previous process and the subsequent process. Then, it is necessary to issue promptly the appropriate transportation instructions by grasping the location information of carriers and/or pallets in real time, and by predicting the future logistics status such as forecast carrier arrival time and/or the required time for delivery and reception of the next pallet. To optimize the transportation instruction currently managed by humans, a simulator capable of predicting the logistics status is required.

However, even in the case of predicting the status in the very near future, sometimes the simulation will not be sufficiently accurate due to non-digitized information, numerous restrictions, and the judgement of persons in charge based on their tacit knowledge. In order to solve this problem, it is necessary to revise the simulation model to improve accuracy by visualizing the simulation results and comparing them with the actual operation.

To improve the simulation model accuracy, it is necessary to rapidly rotate the cycle of: 1) executing the simulation, 2) comparing the simulation result with the actual operation result and 3) modifying the simulation.

In rotating this cycle, the visualization technology used for analyzing the difference between the simulation result and the actual operation becomes an important element. In the visualization for the comparison and analysis, it is necessary to narrow the point of attention down to the focal point, and promptly drill down to detailed information during the entire simulation implementation time. Upon drilling down, rather than visualizing a single viewpoint alone, it is important to visualize various viewpoints with various granularities. Each viewpoint should be linked with the others to provide a comprehensive understanding.

An example of how the linked viewpoints having different granularities contribute to improvement is shown in Fig. 7. In this example, three views, namely the graph view which visualizes time series change of the indicator values, the gantt chart view which visualizes the transportation time of each carrier, and the 3D view which visualizes the detailed carrier movement on the map, are linked, and analysis is conducted. By visualizing the simulation data in parallel with the actual data of linked views, and confirming the significant

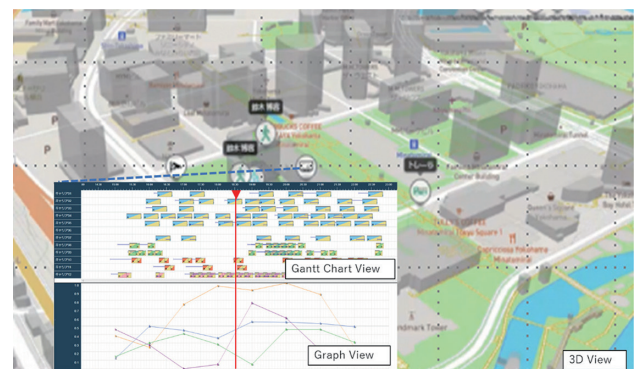


Fig. 7 Example of a screen that is linked by synchronizing the time between the three views

difference in the result, modification of the simulator can be conducted. Therefore, even when an operation variation outside the plan occurs, logistics prediction is enabled by modifying the simulator promptly. With this approach, since the selecting territory of a carrier in a plant and/or adjusting the number of carriers become possible based on the prediction for future logistics, actions of higher accuracy can be taken.

5. Application Example 3: Inventory Prediction Simulation Model and Mechanism of Sustainable Improvement

For cost reduction, it is important to operate the production facility without opportunity loss. Reducing logistics problems such as waiting and/or interference of transportation equipment, shortage of materials in the storage yard, and/or the tightness in the storage yard availability is limitlessly desired. If the inventory at the stock yard and/or the required transportation amount can be correctly predicted when formulating the production plan, it is possible to reschedule the production plan by foreseeing logistics problems. In this chapter, focusing on a case of the steel coil manufacturing process, an example of using a discrete system simulator as the method for predicting the inventory quantity in the respective stock yard based on the production plan is described.

The discrete-event simulator is able to predict logistics with high accuracy for the completely automated process wherein processing time, the process and logistics rule already-known, and the production and transportation are carried out exactly based on such lines. However, in the steel manufacturing process, the processing time varies greatly depending on the products. Furthermore, like the finishing process, the process to be applied is sometimes determined depending on the quality developed during manufacturing. Since there are also some processes in which materials are divided and separately processed to manufacture pluralities of different products based on quality, to simulate logistics accurately, prediction of processing time, selection of process, and processing manner of the respective facilities are required. Furthermore, although a number of ambiguous rules like the judgement of plant workers exist among logistics rules, it is impractical to investigate all logistics rules and input them correctly into the simulator, and further, large cost is incurred for the maintenance of the logistics rules. In this chapter, the mechanism of sustainably improving the prediction accuracy of the logistics simulator by automatic learning of these logistics parameters and the logistics rules from actual data is described (Fig. 8).

Herein, the details of the technology specifically pertaining to the logistics of coils between the cold-rolling process and the continuous galvanizing process, a part of the developed steel coil manufacturing process simulator, are described. Coils processed at the cold rolling plant are transported to the rear storage yard by an overhead travelling crane, then loaded onto pallets and transported to the

continuous annealing facility of the next continuous galvanizing plant. In the continuous galvanizing plant, coils are unloaded from the pallets and transported to the front storage yard by an overhead traveling crane, and transported to the continuous galvanizing facility according to the schedule. To operate the production facility without idle time, it is necessary to allocate the transportation equipment properly for the transportation of coils, while avoiding the tightness in the rear storage yard availability and/or the shortage of the material coils in the front storage yard. Therefore, it is desirable to grasp the problems in logistics and to take necessary actions in advance by simulating the logistics. To simulate logistics, it is necessary to calculate the processing time of the respective facilities before starting manufacturing. However, the processing time differs depending on the standard and/or the size of a coil. Then, a statistical model which predicts the hourly processed weight from the coil attribute based on actual data is constructed, and the discrete-event simulation is executed based on the hourly processed weight predicted by the statistical model. Although the hourly processed weight varies depending on the order mix and/or the operation variations, by equipping the simulator with the function of automatic learning of the statistical model from the actual data, it is possible to sustainably improve the simulator's prediction accuracy.

Furthermore, in front of, and at the rear of the respective production facility, a storage yard directly connected to the production facility is provided, and for instance, the rear cold mill storage yard crane is allocated to two jobs: transportation from the rear cold mill buffer (RearBufferCM) to the rear cold mill storage yard (Rear YardCM), and loading of coils onto pallets from RearYardCM (Fig. 9). The simulator also has to have rules to determine which jobs should be executed. In order to avoid production facility's shutdown due to tightness in RearBufferCM availability, it is necessary to prioritize the delivery of coils from RearBufferCM to RearYardCM. On the other hand, in order to operate the continuous galvanizing facility of the next process, the coil delivery work to pallets from RearYardCM is necessary. Similar rules also exist with respect to the continuous galvanizing front yard crane, front yard of the con-

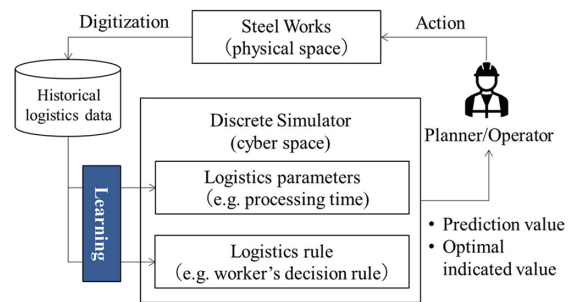


Fig. 8 Mechanisms to sustainably improve prediction accuracy of logistics simulator

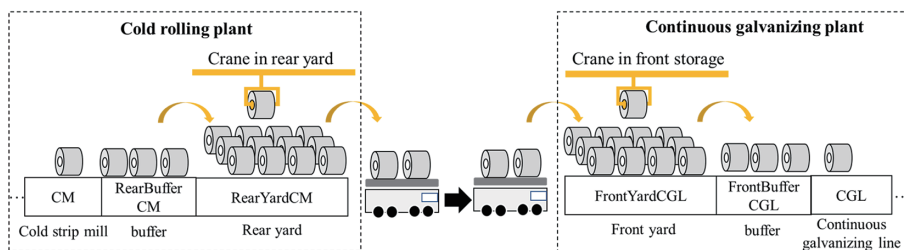


Fig. 9 Coil transfer from cold rolling plant to continuous galvanizing plant

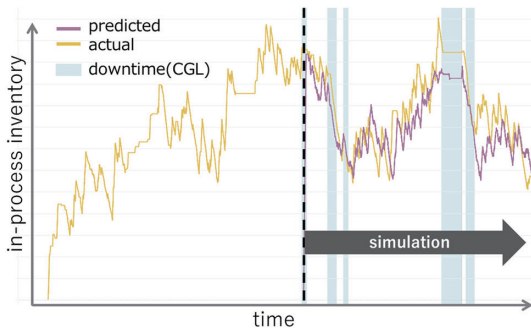


Fig. 10 Comparison of predicted and actual in-process inventory

tinuous galvanizing facility (FrontYardCGL), and the front buffer of the continuous galvanizing facility (FrontBufferCGL). Then, the rule of the operator’s judgement such as which crane should be used depending on the situation was presumed with Bayesian optimization. Bayesian optimization is a method which searches effectively for the optimum solution as to the function with unknown form, and in many cases, the function is assumed to follow the Gaussian process. The method is applied to the search for new candidate experiments in the experimental design method and/or the determination of the hyperparameters of machine learning models. Herein, using Bayesian optimization, a search was attempted for the operator’s judgement rule which minimizes the difference between the predicted values and the actual values of the transition of inventory. **Figure 10** shows the time series transitions of the inventory predicted by the simulation and the actual in-process inventory. It is observed that it is possible to enhance the simulator prediction accuracy by Bayesian optimization employing actual data.

In this chapter, the method of learning simulator parameters and rules from actual data has been introduced. This method not only

enhances the prediction accuracy when a simulator is constructed, but also facilitates the improvement of the simulator accuracy pursuant to the secular change in the logistics process such as changes in the order mix and/or operation.

6. Conclusion

In this article, the digital twin platform “Geminant” which aims at the realization of the logistics digital twin concept for the rectification of logistics, and the application examples in steel works have been described. Geminant is equipped with a function necessary to support of human intellectual work such as recognizing the present logistics correctly, simulating the future logistics, and taking appropriate actions. Furthermore, Geminant promotes shortening of the development term by unified data model and/or analysis module, and it contributes to the efficient logistics. Hereafter, we aim to construct a cyber-space which is completely synchronized to the actual world by expanding the digitalization scope to the “Fusion” stage wherein Geminant is synchronized to the actual world, and further, to the “automation” stage wherein human involvement is minimized.

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