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Utilization of DS-CPS Technology in Raw Material Logistics & Yard Operation and Maintenance[†]

KUMANO Akira[*1] YAMAMOTO Shun[*2] ISHIGAKI Yusuke[*3]

Abstract:

In order to optimally and stably carry out raw material distribution and stockyard operation, which are the most upstream process of steel works, an ore carrier scheduling, blending, and stockyard layout planning system and a monitoring system for the early detection and prevention of failures of conveyor belt facilities using Data Science (DS) and Cyber Physical System (CPS) have been developed.

1. Introduction

Raw material distribution and stockyard operation, which are the most upstream process in a steel works, play a key role in stabilizing the operation of the steel works as a whole.

With the development of information infrastructure, the volume of data has increased exponentially in recent years, highlighting the importance of Data Science (DS) as a problem-solving technique utilizing advance data analysis, and the Cyber Physical System (CPS), which creates value by aggregating the huge amount of sensor information (big data) in physical space in cyberspace, and then feeding the results of analysis by various techniques back to physical space.

JFE Steel Corporation is promoting improvement of its data infrastructure to accelerate development utilizing the above-mentioned DS and CPS, and now collects the various kinds of data necessary to achieve both stable operation and operational optimization.

This paper describes efforts to optimize ore carrier scheduling, ore blending scheduling and stockyard layout planning, which optimize and stabilize operation by applying DS-CPS to raw material logistics and stockyard operation, and efforts related to monitoring of raw material conveyor belts, which is a maintenance technology for stockyard operation.

2. Raw Material Logistics and Yard Operation

2.1 Outline of Raw Material Operation

Raw material operation planning work consists of ore carrier scheduling, ore blending scheduling and stockyard layout planning. The daily work of raw material operation is carried out based on these plans.

The mission of ore carrier logistics from raw material mines to each of the company's steel works is to ensure a stable supply of the raw material brands required by each steel works so that stock shortages do not occur. Shipping companies conduct operating management in line with the ore carrier schedule presented by JFE Steel.

The mission of raw material distribution in a steel works is to stably supply the raw materials used by sintering furnaces, blast furnaces and steelmaking shops, and to ensure that those materials possess the required quality. **Figure 1** shows an outline of the distribution of ore raw materials in a steel works. After an ore carrier arrives at the steel works and berths, the raw material loaded on the vessel is unloaded by an unloader. The unloaded raw material is then transported to a temporary holding yard called the crude ore yard ("ore yard" in Fig. 1) by a conveyor system, and is received in the yard based on the stockyard layout plan. In the crude ore yard, all raw materials, including coal, ore and aux-

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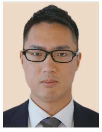
[*2] Cyber-Physical System Research & Development Dept.,
Steel Res. Lab.,
JFE Steel



[*1] Senior Researcher Deputy Manager,
Cyber-Physical System Research & Development Dept.,
Steel Res. Lab.,
JFE Steel

[*3] Senior Researcher Manager,
Cyber-Physical System Research & Development Dept.,
Steel Res. Lab.,
JFE Steel

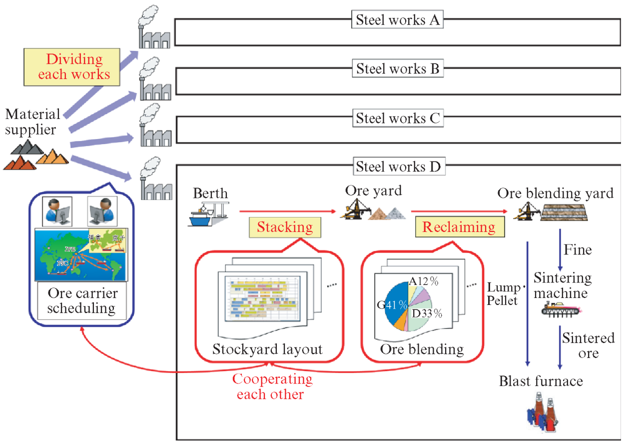


Fig. 1 Outline of raw material operation of iron & steel works

iliary materials, are divided into a coal system and an ore system as stocks of each brand. Ores are transported from the crude ore yard to the fine ore treatment process for sintering and the lump ore treatment process for use in the blast furnace. After blending based on the ore blending schedule so as to achieve the required quality, these materials are stacked in the blending yard. Blended fine ore is conveyed to the sinter plant, and lump ore is conveyed directly to the blast furnace. Pellets and sintered ore are called treated ore, and are conveyed from the crude ore yard to the blast furnace. Coal is conveyed to the coal treatment process, and is conveyed to the coke plant after blending in blending bins.

2.2 Problems of Raw Material Operation

In deciding the ore carrier plan, the first objective is to ensure that the company's steel works, which are the unloading side for ore carriers, do not run out of raw material stocks. Next, the person responsible for planning considers reduction of transportation costs, that is, ship freight costs and demurrage fees. However, due to the mutually contradictory relationship between maintaining a stable supply of raw materials and reducing transportation costs, it is extremely difficult to design the optimum plan which satisfies both.

Since there are also cases where raw materials cannot be arranged according to the plan due to constraints on reclaimers depending on the raw material stacking location, it is necessary to develop a coordinated plan for blending and the stockyard layout. However, it had been difficult to create well-coordinated plans due to the huge amount of information concerning the raw material operation and the fact that planning relied on human work. This situation resulted in frequent changes in the initial ore blending schedule and increased auxiliary material consumption for composition adjustment. Moreover, since it is also difficult to predict the long-term trend in raw materials yards, even for even experienced personnel, yard efficiency could not be maximized from the long-term viewpoint. This led to increased offshore waiting time for ore carriers, which caused large demurrage fees.

In addition, because ore carrier schedules are easily affected by the weather and other factors, frequent revisions are unavoidable. Since the raw material distribution plans within the steel works are drawn up based on the scheduled arrival time of the raw materials, these distribution plans must also be revised when the ore carrier schedule changes, and the time required to revise these various plans had also become a problem.

Although simultaneous optimization of the ore carrier schedule, the ore blending schedule and the stockyard layout plan is ultimately required in order to solve these problems, simultaneous optimization in the planning units required for practical purposes was difficult due to the very large number of problems that must be managed. On the other hand, if the granularity of these schedules is reduced to a manageable level, the schedules may not adequately reflect the actual conditions of the raw material operation. Therefore, in addition to individual optimization of the three types of schedules, these problems were solved by reducing the time required to prepare schedules, and by making it possible to revise the schedules, when necessary, by high speed calculation.

On the other hand, distribution of raw materials in a steel works is supported by belt conveyors installed at a large number of locations. Equipment control of these conveyors is extremely important because the effects once trouble occurs at a belt conveyor will not be limited to the raw material operation, but will also directly affect blast furnace operation, causing substantial loss. For this reason, there is a high need for condition monitoring by diverse types of sensors. However, because a large number of belt conveyors are installed over the wide area of the raw material yard, with a total length sometimes reaching several 10 km to several 100 km, the cost of wiring for data collection would be prohibitive. To overcome this problem, wireless monitoring utilizing ICT (Information and Communication Technology) instead of communication cables had been demanded.

Among the efforts to solve the problems outlined above, this paper describes efforts toward optimization of ore carrier scheduling, ore blending scheduling, and raw material pile layout planning, particularly for the ore system, which handles a large volume of materials, and efforts to enable early discovery of anomalies and advance prevention of trouble by condition monitoring of belt conveyors used in raw material transportation.

3. Optimization of Ore Carrier Scheduling

3.1 Ore Carrier Scheduling Problem

In ore carrier scheduling task, it is necessary to prepare the optimum ore carrier schedule which will ensure both a stable supply of raw materials and minimization of transportation costs, while also considering the constraints on berths and other facilities and equipment. However, it is difficult to draw up plans for transportation-related restrictions because a comprehensive judgment of the total schedule as a whole is necessary, and there are limits to the ability of humans to create the optimum schedule that simultaneously satisfies both supply and transportation cost requirements. Although computerized planning is conceivable, if an exhaustive calculation approach is used, the number of candidate plans will increase exponentially with the number of variables to be decided, and the time required would be excessive, even with a supercomputer. Therefore, in this paper, we report an example of the development of a system that efficiently supports schedule preparation task by a scheduler engine utilizing optimization technology.

The target of this development is the ore carrier schedules prepared by JFE Steel for ore transportation to all of the company's production sites. The loading schedule at the loading port is given as input, and operation schedule of ship that will carry the load and the unloading schedule at the unloading port are prepared by the scheduler. The items to be considered when preparing the unloading schedule are the constraints of berth equipment and minimization of the three items of out-of-stock situations, the number of multi-unloading operations and demurrage fees. Unlike general shipping plans, it is also necessary to considered the fact that an asymmetrical supplementation relationship exists between the groups in which ore brands are aggregated as units for stock volume management (e.g., Group 1 ore can be used as Group 2, but Group 2 cannot be used as Group 1). Moreover, berth occupancy time is calculated based on unloading capacity (t/h), but reduced berth efficiency due to berth repairs, etc. must also be considered.

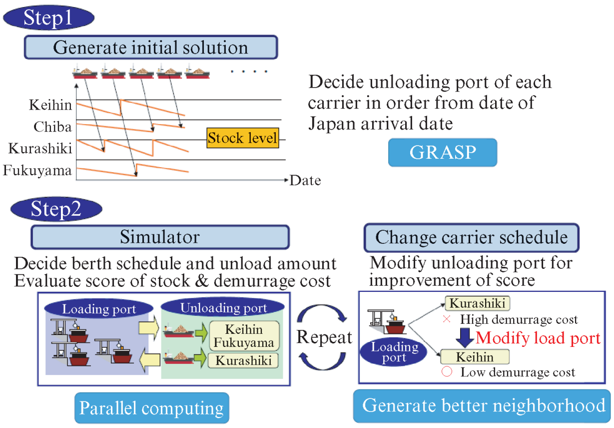


Fig. 2 Algorithm of ore carrier scheduler

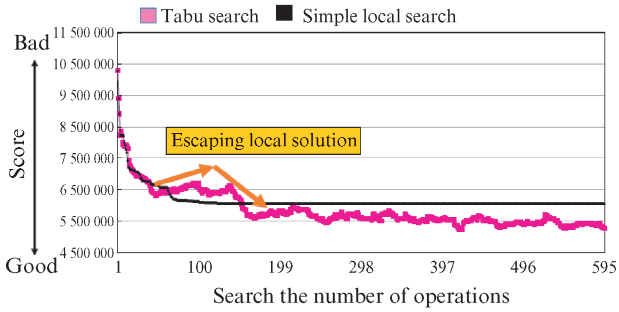


Fig. 3 Performance of tabu search

3.2 Ore Carrier Scheduler

In order to incorporate the above-mentioned compensation relationship and changes in cargo handling efficiency, etc., a detailed simulation function was developed for ship movements (i.e., sailing or berthed/at anchor). The ore carrier scheduler engine improves the schedule by executing iterative simulations (**Fig. 2**). Tabu search$^{1)}$ is used in iterative improvement and is not limited to local solutions. **Figure 3** shows the condition of escaping local solutions. In addition, the following processing was introduced to achieve high calculation speed.

- The initial schedule is generated by the GRASP method$^{1)}$, so that the search is initiated from a good initial schedule.
- In generation of neighborhood solutions in the tabu search, the neighborhood solutions are not generated randomly, but are focused on neighborhood solutions that appear to improve.
- Parallel processing is used in the simulations.

High speed was achieved by applying these techniques, which shortened the calculation time for a long-term schedule of 6 months to 5 minutes, and practical application was judged to be possible. In addition, an off-line verification confirmed that the number of multi-unloading operations could be reduced by 6 %.

Since weather and other change factors are difficult to handle quantitatively in the simulation engine, in the introduction of the actual system, a function that makes it possible to change schedules interactively was implemented in order to reflect this type of changes in the schedule (**Fig. 4**). For example, in case of a voyage that may have an extended unloading time, the planner can create a schedule conforming to reality by inputting the predicted unloading time and running the engine again. At present, a practical version of this system is

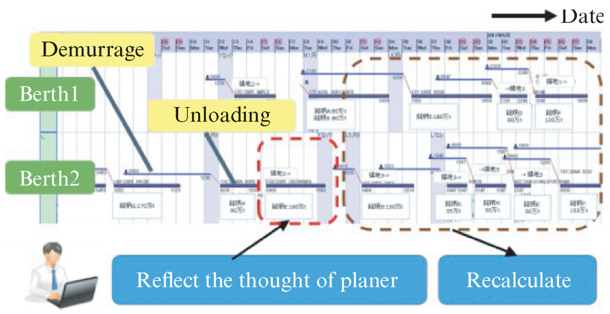


Fig. 4 Interactive scheduling system

being developed, and introduction in the ore carrier scheduling task is being promoted.

4. Optimization of Ore Blending Scheduling

4.1 Ore Blending Scheduling Problem

Figure 5 shows an outline of the ore blending scheduling problem which was the target of this development. In ore blending scheduling, ore use plans are drawn up in units of several days and one month so as to minimize the ore cost, which is the objective function. These schedules are based on the constraints of upper and lower stock levels and the property constraints of the ironmaking and sintering process, under conditions in which the ore composition information, arrival schedules of ore carriers, stock information level, production plans, etc. are given as the input information.

In actual operation, more than 20 brands of ore are used, and the schedules are large and complex, as schedules covering a 1-month period must be prepared in 5-day units while satisfying inventory constraints, sinter strength constraints, slag fluidity constraints and the like. Therefore, the accuracy of schedules prepared manually by personnel was rough, and there was room for improvement. If ore blending scheduling is modeled as a mathematical programming problem[1)], it does not become a simple linear programming problem[1)], since nonlinearity exists in basicity calculations for the molten iron slag, and ingenuity is necessary in the solution method. This problem can be formulated as a linear programming problem by fixing key variables as constants, and a faster solution is possible by performing this operation, but in this case, the output solution largely depends on the method of fixing the variables.

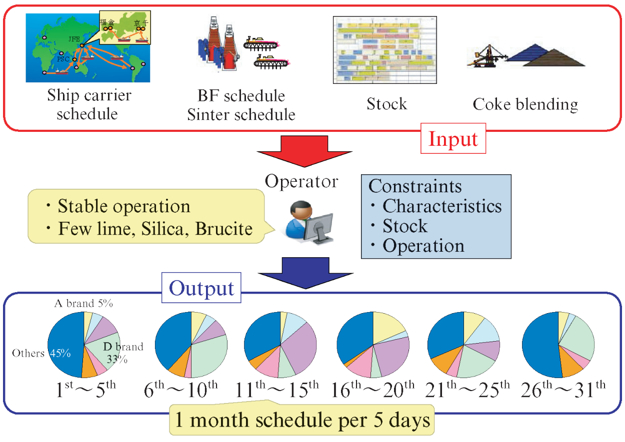


Fig. 5 Outline of ore blending problem

Therefore, we developed a model utilizing two-stage approach (hereinafter, Hybrid model)[2)], in which variables having nonlinearity are fixed as constants once and solved as linear programming problems, and a metaheuristics[1)] search is conducted to find fixed variables that improve the evaluation functions of the obtained solutions. Particle Swarm Optimization (PSO)[3)] was applied as the metaheuristic technique because PSO has the advantages of fast convergence and excellent maintainability and flexibility. The basic concept of PSO is to search the solution space while the candidate solutions (particles) that constitute the population (swarm) exchange information in order to search for solutions by using the optimal information of the individual particles and the optimal information of the swarm.

4.2 Algorithm of Hybrid Model

Figure 6 shows an image of the algorithm of the Hybrid model. In the fixing-method search area (PSO part in the figure), nonlinear variables are expressed as K particles with multidimensional vectors, and PSO searches for the optimal position vector. In the Linear Programming portion (LP part in the figure), the same number of linear programming problems as the K number of linearized particles is solved, and K blending schedules are obtained as solutions. The solutions

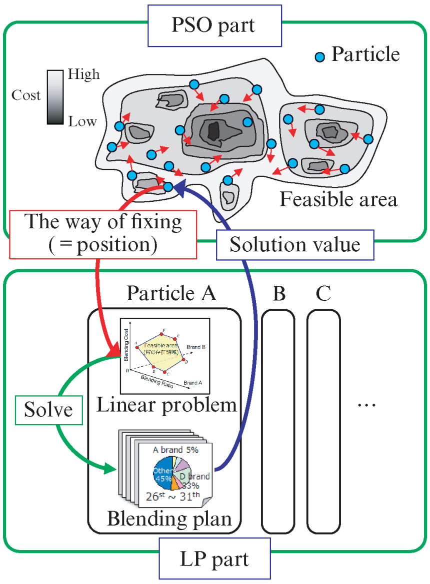


Fig. 6 Algorithm of Hybrid model

obtained in this manner become comparative indices of the particles and are used in the PSO algorithm of the fixing-method search area. Ore blending scheduling problems which include nonlinear variables can be solved quickly by iteration of this operation.

4.3 Verification of Results

Based on the data for 3 consecutive months, which represents the turnover cycle in the ore storage yards, the average cost for a manual plan prepared by three staff members and the cost for a schedule calculated by the Hybrid model three times for each 1-month period were compared, and the results were verified. Although iron ore is the main raw material of the steel making process, because long-term purchasing contracts are concluded in advance for iron ore, the amount of purchases cannot be reduced immediately by optimization of the blending schedule. Therefore, this comparison was based on the blending amounts of auxiliary materials, which can be purchased flexibly.

Figure 7 shows the results. This graph shows the blending amounts of the auxiliary materials for the 3-month schedules, where the average blending amount in the manual plan prepared by the staff members is 100 %. The result of the blending plan calculated by the Hybrid model was 98.7 %, confirming that auxiliary material consumption can be reduced by more than 1 % by using the Hybrid model. A system implementing this technique has been applied in the production process at West Japan Works Fukuyama District and is producing positive results.

5. Optimization of Stockyard Pile Layout Plan

5.1 Stockyard Pile Layout Planning Problem

Figure 8 shows an outline of the stockyard layout planning problem. The aim of the stockyard pile layout plan is to select stacking (receiving) locations and piles to be reclaimed in a way that maximizes yard efficiency (minimum yard occupancy ratio, minimum line switching) based on the constraints of conveying equipment capacity and conveying time when the ore carrier schedule for stacking (receiving), the blending schedule for reclamation and the current yard status and stock levels are given. The stockyard layout plan is extremely complex, as stacking and reclamation must be considered simultaneously, and it is also necessary to consider which spaces ore should be stacked in and reclaimed from, and whether the ore should be divided into multiple piles or not. Because the number of pile layout combinations increases explosively in long-term plans with lengths of 1 month or more, it was extremely difficult to prepare the optimum pile layout plan.

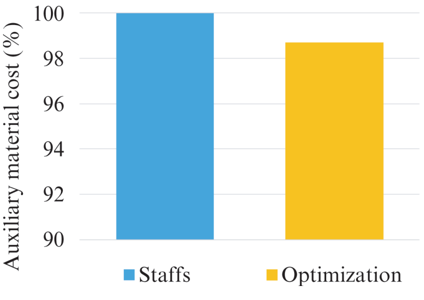


Fig. 7 Comparison of results by staffs and optimizations

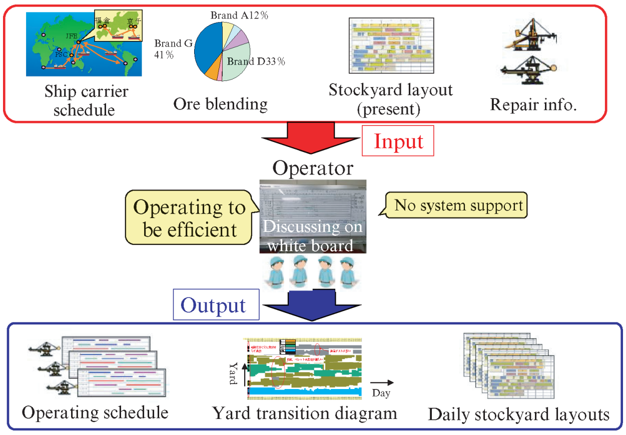


Fig. 8 Outline of stockyard layout problem

Therefore, the authors developed a pile layout planning optimization system with an original technique that adds a multipoint search function to the Greedy method[1)], which enables high speed calculation.

5.2 Stockyard Layout Planning Optimization Algorithm

As mentioned previously, a metaheuristic algorithm based on the Greedy method is used in the stockyard layout planning optimization system. **Figure 9** shows the method of applying the Greedy method. The pile condition of the yard is divided into multiple patterns depending on the selection of stacking locations and piles to be reclaimed. Yard efficiency is generally improved by reducing the number of piles in a yard because a smaller number of piles increases the effective capacity of the yard by reducing dead space, and also reduces the time and work required for line switching during stacking and reclaiming. Therefore, the Greedy method is applied to minimize the number of piles in the yard, and the pattern which minimizes the number

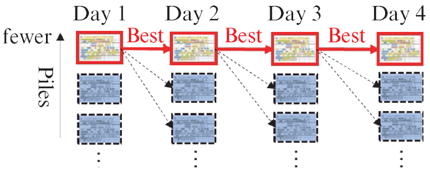


Fig. 9 Greedy algorithm for stockyard layout problem

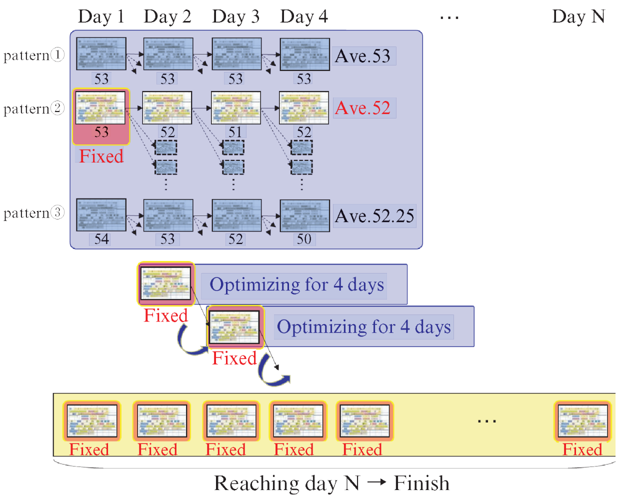


Fig. 10 Algorithm of stockyard layout problem

of piles on each day is adopted. However, if yard efficiency is evaluated by the number of piles in a unit that includes the next several days, a pattern which will further reduce the number of piles may exist. To consider this possibility, a multipoint search function was added to the Greedy method in this algorithm (**Fig. 10**).

Concretely, first, the stacking pattern that results in the minimum pile number group is prepared for Day 1, and plans for each of the following several days are prepared for that minimum pile number group. In this process, stacking and reclaiming are performed in the plans for several days from Day 2 so as to minimize the number of piles in accordance with the Greedy method. Next, the average number of piles for the next several days (piles/day) is calculated, the stacking pattern for Day 1 which minimizes the number of piles in a unit of several days is adopted, and the process advances to the next day. Rolling scheduling[4] is performed by repeating the same operation from Day 2 onward, and is completed on reaching the final day of the plan. This operation makes it possible to minimize the number of piles in a very short calculation time.

5.3 Verification of Results

Figure 11 shows the transition of the number of piles for the case of operation in accordance with a plan prepared by the operators by conventional manual work and the case of operation by following this model, based on the data for 2 consecutive weeks. The blue line in the figure shows the transition of the number of piles based on the optimization results. In comparison with the plan prepared by conventional manual work shown by the black line, the monthly average number of yard piles could be reduced by 4 %. This system was also applied with good results in the production process at West Japan Works Fukuyama District, together with the ore blending scheduling optimization system described in the previous chapter.

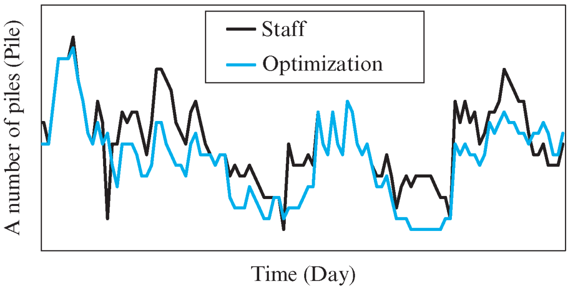


Fig. 11 Comparison of results by a staff and the optimization

6. Equipment Control in Raw Material Stockyards

6.1 Belt Conveyor Anomaly Monitoring

Equipment control of the belt conveyors used in raw material transportation is extremely important because substantial loss is incurred once conveyor trouble occurs. To avoid this kind of trouble, monitoring by many sensors of various types is demanded, but owing to the large number of belt conveyors installed over the large site of raw material stockyard, both the construction and maintenance of wired systems for data collection are prohibitively expensive. Moreover, it is also necessary to develop and install sensors that can properly monitor diverse objects. Therefore, the authors developed a belt conveyor monitoring system which is capable of efficiently detecting anomalies by utilizing ICT.

The sensors installed in this system include visible light cameras to detect belt conveyor shape defects such as breakage of the belt edge, longitudinal rips, holes and other damage, etc., vibrometers, thermometers and microphones to detect anomalies of the drive system and pulley bearings, and visible light cameras, microphones, thermometer and hygrometers, vibrometers, etc. to monitor the condition of raw material clogging in the charging chute section.

An example of belt conveyor monitoring by a visible light camera is shown in **Fig. 12**. The surface of the belt conveyor is photographed by a network camera, and

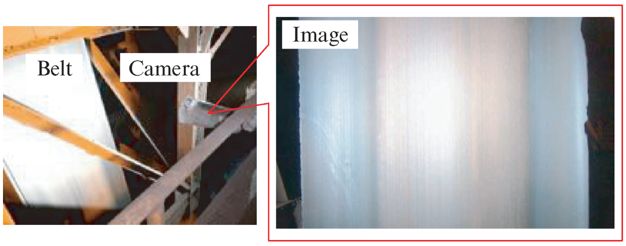


Fig. 12 Image monitoring of conveyor belt

shape defects of the belt are detected by image processing. Although a technology$^{5)}$ consisting of extraction of feature quantities by image processing and tree judgment is generally used to detect shape defects from images, the authors constructed an anomaly judgment model based on a large volume of image data, considering the diversity of shape defects of conveyor belts and disturbances due to photography under the outdoor environment of a raw material stockyard. With the developed model, it is also possible to improve the accuracy of judgments of the existence and features of shape defects by accumulating data.

6.2 Composite Diagnosis of Anomaly Data

The anomalies and trouble which should be prevented in belt conveyor equipment span a diverse range, beginning with fires but also including belt breakage, stoppage of the drive system, leakage of raw material from chutes and others. However, these individual anomalous phenomena generally affect multiple types of sensor information and operational information. This means that anomalies can be detected accurately in the stage of precursory signs, that is, before an anomaly actually occurs, by a composite evaluation of the information from a number of sensors of different types, and the results can be used to carry out efficient maintenance action.

For efficient monitoring of the information from many sensors, the temporal changes in the anomaly degree of each monitoring target are displayed in a heat map corresponding to the magnitude of the anomaly. As anomaly scores, either statistical quantities such as the maximum value or average value are calculated for each sensor, or the degree of deviation from the normal state when an anomaly is detected is calculated for each image. The correlation of anomalies between sensors can also be visualized by a color-coded display corresponding to the degree of deviation. Because the heat map presents a large number of different types of data, including belt shape defects, vibration, noise, temperature, etc., arranged in time series, which can be checked at a first sight, the heat mapping approach is effective for correlation evaluation of multiple sensors.

Figure 13 shows the outline of the system for composite monitoring of belt conveyors. Information from all sensors installed at belt conveyors is collected by edge computers, and statistical calculations for a certain time range are carried out when necessary. In comparison with transmitting the raw time waveform data as-is, the volume of data can be substantially lightened by transmission after preprocessing of the measured data by the edge computers. Anomaly scores are calculated from the data in the database server, which are collected via wireless transmission, and are displayed by heat mapping.

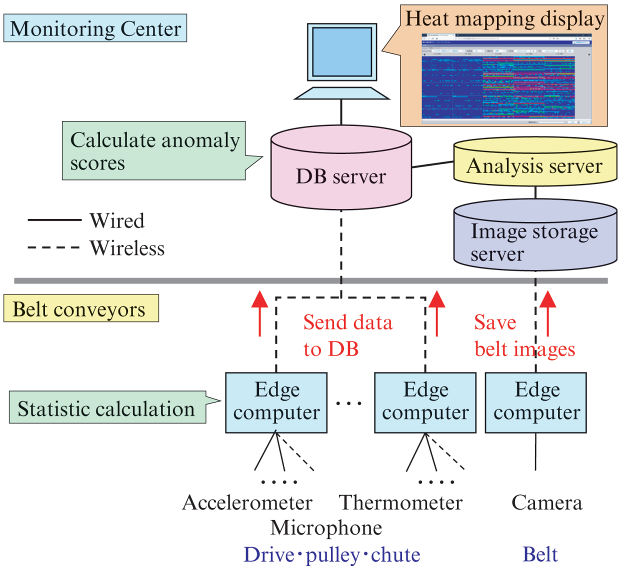


Fig. 13 Belt conveyor monitoring system

As described above, anomalies can now be detected by integrated monitoring of a large number of data of different types.

7. Conclusion

Raw material logistics and stockyard operation are the most upstream process in a steel works. To ensure stable, optimum operation of this processes, an ore carrier scheduling, ore blending and stockyard layout planning system, and a monitoring system for early discovery of anomalies and advance prevention of trouble in belt conveyor equipment were developed using DS-CPS.

These systems are currently contributing to optimization and stable operation of raw material logistics and stockyard operation, and JFE Steel also intends to deploy these technologies at all of its steel works in the future.

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