Management system for building production with multi-layer simultaneous auctions

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Abstract
Building production can be regarded as a one-piece production because not only specifications of individual buildings but also working environment for them are different. Additionally, different types of companies/enterprises participate in production. So, there are many uncertainties before production starts and disturbances occur frequently after production starts compared to production of general industrial products in a factory. Since it takes too much time to resolve problems with respect to such uncertainties/disturbances, a conventional production schedule has to include excessive slack/float. To resolve this issue, we propose a management system that consists of multiple agents and a bulletin board module to connect these agents. In the proposed system, both a job and a worker are regarded as agents. An autonomous job is referred to as a demand agent. A worker agent decomposes a job into some sub-jobs, that is, the worker agent generates new demand agents. A demand agent organizes an auction to find a worker agent which can perform a job corresponding to the demand agent itself and a worker agent bids for the demand agent to get the job. The bulletin board module, which controls the conveyance of information, realizes necessary and sufficient communications between agents. Furthermore, by introducing multi-layer simultaneous auctions, each worker agent can shorten its proposed timeline for a job, improving the accuracy of the estimation. As the result, a master schedule without excessive slack/float can be generated.

Key words : Management system, Building production, Autonomous and distributed production system, Auction

1. Introduction

Because a complicated system is needed to satisfy the diverse requirements for production, it is becoming more difficult to manage these requirements using a centralized production management system. Thus, numerous researchers have proposed the concept of an autonomous and distributed production system. In most of those proposals, production facilities and an intelligent system using a network structure are focused on, and it is assumed that production facilities and products exist in a limited space such as an automated factory (Fujii, et al., 1999; Ranky, 1992; Shirase, et al., 2005; Sugimura, et al., 1999; Ueda, 1992; Wiendahl and Garlicks, 1994).

In building production, many different types of companies/enterprises cooperate and are interdependent. So, a building production system can be regarded as an autonomous and distributed production system. But, as construction is executed in an open space, weather affects progress. Additionally, sudden changes in the specifications, an unexpected delay in procuring materials, placement of materials in the wrong location, or double booking a shared facility (e.g., crane) also influence progress because different types of companies/enterprises participate in production. Thus, in building production, there are many uncertainties before production starts and disturbances occur frequently after production starts compared to production of general industrial products in a factory. However, for schedule management of such production, there is no mean to integrate different management systems used in companies/enterprises, and then the conventional production schedule has to include excessive slack/float since it takes too much time to resolve problems with respect to such uncertainties/disturbances.
In this paper, we propose a management system for building production using a bulletin board module and multi-layer simultaneous auctions. The former realizes necessary and sufficient communications among agents, while the latter enables the system to generate a schedule efficiently without excessive slack/float.

2. Problems in building production

In building production, various methods with Monte Carlo Simulation have been proposed to estimate the progress of a project, the operating ratio of facilities, and productivity (Halpin, 1973). Recently, process/operation planning and simulation methods were proposed with 3D-CAD models and work models (Watanabe, et al., 2012). A monitoring method of materials, workers, and facilities with RFID was also proposed for management of the progress of a project (Chae, 2006). Such methods are useful if a centralized management system can know all information about all the elements for production and can control all the elements directly. However, in building production, there are two main problems caused by the structure of the production system and uncertainties/disturbances in production.

- Snarl of information
  In building production, one job such as “arranging bars of posts” can be completed without delay when adequate materials, workers, and facilities are arranged in the right location at the right time. Nowadays, materials, workers, and facilities are managed by different systems. Thus, different management systems must negotiate with each other. Moreover, such negotiations may be performed indirectly. For example, the sub-management system for workers cannot communicate directly with the sub-management system for facilities. The process involves the sub-management system for workers reporting to its top system. Then the top system communicates with its counterpart for facilities, which then relays the message to the sub-management system for facilities.

  Such a structure impedes efficient communications. When a disturbance, such as a delay in a certain job occurs, each manager (materials, workers, and/or facilities) tries to compensate for such a delay by rescheduling his own schedule first. If it is impossible, then he asks the other managers whether they can change their current schedule, waits for confirmation, and then re-arranges his schedule based on the answer. Asked managers often request others to reschedule. Then, the propagation of change may come back to the original manager via others. So, compensation for a delay consumes a lot of time.

  Note that the material manager has to know “how many” workers are arranged to assemble a certain material but does not need to know “who”. This indicates that all the information in one management system does not have to be sent another system every time. Therefore, we have proposed a total management system architecture to realize necessary and sufficient communications among multiple management systems (Arai, et al., 2008; Ariyoshi, et al., 2009).

- Excessive slack/float included in the schedule
  Building production can be regarded as a one-piece production because not only specifications, but also the working environment (e.g., geographical conditions, material yard, or traffic restrictions) for individual buildings are different. So, the estimated schedule of a project by a contractor when bidding is inaccurate due to uncertainties arisen from such differences. Furthermore, a contractor has to make a bid before it contracts out some jobs in the project to its sub-contractors. The schedule may be improved by asking all contractors in its contractual hierarchy to estimate a timeline and gathering those timelines because a lower level contractor may provide more accurate schedule considering a given specification/environment. However, such asking and gathering process requires a lot of time. Therefore, each contractor has to incorporate slack/float against uncertainties/disturbances into its estimated schedule. This schedule adjustment is repeated whenever a job is contracted out. As the result, the total schedule has excessive slack/float.

  With respect to production of general industrial products, auction-based scheduling has been proposed as an effective scheduling method for an autonomous and distributed production system (Fujii, et al., 2006; Kaihara, et al., 2009). A hierarchized scheduling/rescheduling method was proposed for a large-scale production system (Hino, et al., 2000; Tanimizu, et al., 2001; Nakamura and Takata, 2005). We apply these concepts to building production. In this study, it is assumed that a contractor presenting the shortest completion time wins a bid. This means that a contractor
cannot win if it puts excessive slack/float into a schedule. To minimize slack/float, a contractor must ask its sub-contractors to estimate their schedules and select the sub-contractor presenting the shortest timeline. However as mentioned above, generating a total schedule without excessive slack/float is time consuming because such an auction must be held at each layer of a hierarchical structure starting at the lowest layer. It would be more efficient if contractors could modify their timeline according to the replies from sub-contractors in the lower layers during an auction, suggesting that auctions can occur simultaneously on multiple layers. However, a multi-layer simultaneous auction leads to snarl of information. Therefore, we propose a management system with simultaneous multi-layer auctions based on the developed system by Ariyoshi et al. (Ariyoshi, et al., 2009).

3. Proposed system architecture
3.1 Behavior before production starts

In building production, a contractor decomposes a job which the contractor won a bid for into some sub-jobs and distributes them to sub-contractors. How this job is decomposed depends on the individual contractor. Considering this fact, we propose a management system using the structure shown in Fig.1. It consists of two kinds of agents: demand agents and worker agents.

A demand agent is one which realizes smooth and efficient communications between worker agents. It can be regarded as an autonomous job which can make decisions, so, it has information about the type and amount of a job. A demand agent is generated by a worker agent and has the following functions:

- To search for worker agents which can perform the demand agent itself
- To organize an auction (first-price auction) for selected worker agents
- To determine the interim winner according to the earliest job completion time and inform the worker agents of the auction results
- To recommend the worker agent which generated the demand agent to regenerate other demand agents if any.
A worker agent is characterized by one which desires a job and has the following functions:

- To decompose a job corresponding to a demand agent in an auction into sub-jobs, that is, to generate new demand agents from the bidden demand agent based on its rule
- To regenerate other demand agents if a demand agent previously generated by the worker agent itself was not bidden

Here a job is assumed to be a combination of some units that cannot be further decomposed. Worker agents which can perform the unit job are referred to as the lowest worker agents in this study. The other worker agents undertake combination of some unit jobs. They decompose such a combination into some groups of unit jobs or some unit jobs based on their own knowledge and experience. So, how to decompose a job depends on each worker agent and situation.

The lowest worker agents can shorten their proposed completion timeline for unit jobs by improving their ability. If they do not become interim winners, they try to improve their timeline for the relevant jobs. Figure 2 shows an example of an ability improvement curve. Note that it is assumed that the lowest worker agents can estimate their completion time for unit jobs accurately with reference to their current ability in this study. Because all the schedule of the upper layers are worked out based on their completion time, slack/float can’t be eliminated from the schedule if it is inaccurate.

The other worker agents can change how a bidden job is decomposed in order to become an interim winner. For example, dividing one sub-job where a bottleneck occurs into two sub-jobs and distributing both to two lower worker agents may shorten the total timeline.

As shown in Fig.3(a), if upper worker agent 05 is an interim winner, one of its lowest worker agents bidding for each sub-job also becomes an interim winner. For example, worker agents 08 and 11, which are interim losers, try to shorten their completion timeline by improving their ability to win bids of demand agents a02a05a and a02a05b, respectively. If the revised estimate requires the shortest time, then agent 08 or 11 may become an interim winner as shown in Fig.3(b).

If upper worker agent 05 is an interim loser, then none of its lowest worker agents become interim winners as shown in Fig.4(a), and all of its lowest worker agents try to shorten their estimated timelines. Through such efforts, upper worker agent 05 and some of its lowest worker agents may become interim winners as shown in Fig.4(b). Note that the lowest worker agents do not know whether their upper worker agent is an interim winner or not. They just improve their ability to become an interim winner.
Interim loser
Interim winner
Worker agent 05
Demand agent a02a
Worker agent 08
Demand agent a02a05a
Worker agent 09
Demand agent a02a05b
Worker agent 10
Demand agent a02a05c
Worker agent 11
Demand agent a02a05d

(a) Worker agents 08 and 11 increase their ability. (b) Worker agents 08 and 11 become interim winners.
Fig.3 Behavior pattern #1 for becoming an interim winner

Interim loser
Interim winner
Worker agent 05
Demand agent a02a
Worker agent 08
Demand agent a02a05a
Worker agent 09
Demand agent a02a05b
Worker agent 10
Demand agent a02a05c
Worker agent 11
Demand agent a02a05d

(a) All the lowest worker agents increase their ability. (b) Worker agents 05, 08, and 11 become interim winners.
Fig.4 Behavior pattern #2 for becoming an interim winner

Interim loser
Interim winner
Worker agent 05
Demand agent a02a
Worker agent 08
Demand agent a02a05a
Worker agent 09
Demand agent a02a05b
Worker agent 10
Demand agent a02a05c
Worker agent 11
Demand agent a02a05d
Worker agent 21
Demand agent a02a05e
Worker agent 22
Demand agent a02a05f

(a) Worker agent 05 is an interim loser. (b) Worker agent 05 deletes and regenerates demand agents. (c) Worker agent 05 becomes an interim winner due to re-auction for new demand agents.
Fig.5 Behavior pattern #3 for becoming an interim winner

If upper worker agent 05 cannot become an interim winner despite the efforts of the lowest worker agents as shown in Fig.5(a), then it must re-decompose the job corresponding to demand agent a02a and regenerate the lower demand agents. In the example shown in Fig.5(b), the agent re-decomposes the job into three sub-jobs, and existing demand agent a02a05b is deleted while new demand agents a02a05c and a02a05d are generated. This implies that the auction with respect to demand agent a02a05b becomes invalid. Consequently, the bids of worker agents 10 and 11 are cancelled, and auctions with respect to demand agents a02a05c and a02a05d are initiated. If jobs corresponding to demand agents a02a05c and a02a05d can be performed in parallel, the total timeline for demand agent a02a may shorten, enabling worker agent 05 to win a bid as shown in Fig.5(c). Additionally, a worker agent re-decomposes a job when lowest worker agents do not bid on the sub-jobs. Thus, all worker agents in each layer try to shorten their completion time unless they become interim winners of an auction.
Initially non-lowest worker agents estimate the completion time and decompose a job into sub-jobs prior to inquiring about the availability of the lower worker agents. After receiving replies from all the lower worker agents, worker agents can modify their proposed timeline as needed during an auction. As worker agents shorten their completion time to become the final winner, a master schedule without excessive slack/float can be generated.

In this paper, we introduce the bulletin board module to realize communications among agents (Arai, et al., 2008; Ariyoshi, et al., 2009). All agents register their offering information including triggers for their reaction on the bulletin board module. Then the bulletin board module monitors all registered information and when it detects a trigger, it informs relevant agents. For example, worker agents register the result of their auctions as a trigger to improve their ability or to re-decompose a job.

When a demand agent is generated, it searches for worker agents that can perform a job corresponding to the demand agent itself by referring to the bulletin board module. After that, the job is auctioned. Information about whether each worker agent is an interim winner is sent to each worker by the demand agent via the bulletin board module. The feature of these processes is that agents do not receive information about changes irrelevant to them, which they do not have to know. Thus, the auction for each job is executed by the relevant demand agent, while the bulletin board module controls the conveyance of information, and each worker agent only has to decide whether to bid. Note that method/technique for improving the ability or decomposing a job of each worker agent is also hidden from the other worker agents. So, know-how of each worker agent can be protected.

After multi-layer simultaneous auctions, the parent demand agents and child demand agents, which correspond to the adopted jobs and sub-jobs, respectively, are connected via the bulletin board module. Furthermore, worker agents as the final winners are connected to individual demand agents as shown in Fig.1(b). Demand agents that are not adopted are deleted and worker agents that lost cannot participate in the construction project.

### 3.2 Behavior after production starts

After a construction is underway, each demand agent monitors the progress of the corresponding job. If the job becomes delayed, the demand agent informs the worker agent via the bulletin board module. Then the worker agent selects a behavior pattern shown in Fig.3, Fig.4, or Fig.5 to shorten the timeline and recover the delay. Consequently, multi-layer simultaneous auctions and the bulletin board module realize efficient management of building production.

### 4. Case study

In this section, we explain a simulation system to demonstrate the effectiveness of our proposed system. We developed a pilot system with 17 worker agents and 13 demand agents using Glue Logic, which was originally proposed by Takata (Takata, 1994). The project corresponding to the top-level job in this pilot system can be decomposed into sub-jobs and each sub-job can be decomposed into sub-sub-jobs, which correspond to unit jobs. Thus, the system has three layers of demand agents. In other words, auctions are executed in three layers. Table 1 shows individual jobs in detail.

| Job (project)         | Sub-jobs                         | Sub-sub-jobs (unit jobs)         |
|-----------------------|----------------------------------|----------------------------------|
| Framing one floor     | (The job decomposition depends on the individual worker agents.) | Arranging bars of posts          |
|                       |                                  | Assembling post form panels      |
|                       |                                  | Arranging bars of walls          |
|                       |                                  | Assembling wall form panels      |
|                       |                                  | Concreting                       |

Table 1 Jobs for a case study

Figure 6 shows the Gantt chart just after the multi-layer simultaneous auctions begin. In Fig.6, the interim winners are worker agents 02, 03, 04, 06, 08, 10, 11, and 12. As each worker agent estimates its completion time without waiting for replies from its lower worker agents, the estimated completion time shown in Fig.6 is not accurate and includes slack/float. In the case of each-layer auction, such slack/float cannot be eliminated because it is difficult to request the lower worker agents to estimate their completion time within each auction.
Figure 7 shows the result after modifying the first schedule shown in Fig.6. This modification, that is, elimination of excessive slack/float in each timeline is executed by the demand agent. If another worker agent, for example worker agent 01, incorporated excessive slack/float due to inaccurate estimation before the modification and if its timeline becomes shorter than that of worker agent 02 after the modification, worker agent 01 becomes the interim winner.

Figure 8 shows the Gantt chart of worker agent 05 which is not adopted as a part of the total schedule because worker agent 05 bid for demand agent a02b but was not the interim winner. Then, all the lowest worker agents of worker agent 05 try to improve their estimated timeline by applying behavior pattern #2 shown in Fig.4.

Figure 9 shows the result of the above behavior. Although both sub-sub-jobs shortened their estimated timeline, the total completion time for demand agent a02b, that is, the completion time of worker agent 05 is still longer than that of worker agent 04. Thus, worker agent 05 re-decomposes the sub-job into three sub-sub-jobs; that is demand agent a02b05b is deleted and demand agents a02b05c and a02b05d, which can be performed in parallel, are generated.

Figure 10 shows the result of the above re-decomposition. Because the proposed timeline of worker agent 05 becomes shorter than that of worker agent 04, worker agent 05 becomes the interim winner of demand agent a02b. Figure 11 shows the Gantt chart after worker agent 05 becomes an interim winner. Thus, by introducing multi-layer simultaneous auctions, each worker agent can continuously shorten its proposed timeline during an auction, generating a schedule without excessive slack/float.

Note that the proposed method does not guarantee that an optimum schedule is generated within the allotted auction time. If an auction time is very short, then worker agents may not have sufficient time to improve their proposed timeline because the pace of schedule improvement depends on the time required for worker agents to make a decision. Thus, a longer auction time provides a better, but not necessarily the best schedule.

In the actual building production, the worker agent corresponds to a human worker/manager. By implementing the bulletin board module and the demand agents as computer software, multi-layer simultaneous auctions can be executed automatically. Then each worker/manager will be released from the burden of network communications, allowing people to concentrate decision-making to obtain a job.
5. Conclusions

We propose a management system for building production, which consists of multiple agents and bulletin board modules connecting them to prevent information from being snarled. Furthermore, we introduce multi-layer simultaneous auctions, where the auction for each part of a project is executed by a demand agent and information is controlled by the bulletin board module. Thus, to win a bid, worker agents can easily modify their proposed timeline as many times as they wish based on the responses from the lower worker agents during an auction. As demonstrated in the case study, our pilot system successfully generates a master schedule without excessive slack/float.

References

Arai, E., Wakamatsu, H., Tsumaya, A., Matoba, Y. and Morinaga, E., Management system architecture for realizing dynamic scheduling in project based production, Proceedings of Advances in Production Management Systems Conference 2008 of the IFIP Working Group 5.7 (2008), pp. 35-43.

Ariyoshi, C., Wakamatsu, H., Morinaga, E. and Arai, E., Proposal of system architecture for project based production, Proceedings of the 5th International Conference on Leading Edge Manufacturing in 21st Century (2009), pp. 699-703.

Chae, S., Application of RFID technology to construction progress monitoring, Proceedings of JSME Manufacturing Systems Division Conference (2006), pp.79-80 (in Japanese).

Fujii, S., Kaihara, T. and Tanaka, M., A distributed virtual factory in agile manufacturing environment, Proceedings of 15th Conference of the International Foundation for Production Research, Vol.2 (1999), pp.1551-1554.

Fujii, S., Kaihara, T., Sashio, K., Yokose, H. and Kurahashi, M., A proposal of auction scheduling for cell manufacturing system, Proceedings of the 50th ISCIE conference (2006), pp.213-214 (in Japanese).

Halpin, D. W., An investigation of the use of simulation network for modeling construction operations, PhD Dissertation (1973), Univ. of Illinois.
Hino, R., Izuhara, K. and Moriwaki, T., Decentralized job shop scheduling by recursive propagation method: 2nd report, scheduling for hierarchical systems, Transactions of the Japan Society of Mechanical Engineers, Series C, Vol.66, No.651 (2000), pp. 3791-3798 (in Japanese).

Kaihara, T., Fujii, S. and Miura, K., A proposal of optimization method based on combinatorial auction for production scheduling problem, Transactions of the Japan Society of Mechanical Engineers, Series C, Vol.75, No.752 (2009), pp. 1143-1150 (in Japanese).

Nakamura, T. and Takata, M., A study on structured process scheduler, Proceedings of JSME Mechanical Engineering Congress (2005), pp.1-2 (in Japanese).

Ranky, P. G., Intelligent planning and dynamic scheduling of flexible manufacturing cell and systems, Proceedings of 1992 Japan-U.S.A. Symposium on Flexible Automation (1992), pp. 415-422.

Shirase, K., Wakamatsu, H., Tsumaya, A. and Arai, E., Dynamic cooperative scheduling based on HLA, Knowledge and Skill Chains in Engineering and Manufacturing - Information Infrastructure in the Era of Global Communications (2005), pp. 285-292, Springer.

Sugimura, N., Tanimizu, Y. and Yoshioka, T., A study on object oriented modeling of holonic manufacturing system, Manufacturing System, Vol.27, No.3 (1999), pp. 253-258.

Takata, M., The Glue Logic Project, available from <http://www.ttl.cc.uec.ac.jp/Glue/index.en.html> (1994), (accessed on 1 September, 2009).

Tanimizu, Y., Iwamura, K., Sugimura, N. and Iwata, K., Multi-objective modelling of manufacturing systems: 3rd report, concurrent approach of rescheduling on hierarchical and decentralized manufacturing systems, Transactions of the Japan Society of Mechanical Engineers, Series C, Vol.67, No.654 (2001), pp. 573-578 (in Japanese).

Ueda, K., An approach to bionic manufacturing systems based on DNA-type information, Proceedings of International Conference on Object-Oriented Manufacturing Systems (1992), pp. 305-308.

Watanabe, B., Kano, N. and Ishida, K., Construction process simulation using 3D-CAD models, AIJ Summaries of Technical Papers of Annual Meeting (2012), pp.5-6 (in Japanese).

Wiendahl, H. P. and Garlichs, R., Decentral production scheduling of assembly systems with genetic algorithm, Annals of the CIRP, Vol.43, No.1 (1994), pp. 389-396.