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Dynamic Production Line Re-balancing by Alternative Plans for Compensating Equipment Failures

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Abstract

As social uncertainty increases, there are changes in values such as safety, sustainability, and response to changes. The manufacturing industry is also required to improve its resilience by dynamically recombining production resources to respond to change. In the operation of a production line, if demand fluctuates due to changes in the external environment or customer needs, or if sudden production fluctuation such as equipment failure occurs, the production line will be stopped due to reconfiguration or equipment restoration. Therefore, the challenge is to continue production and improve productivity even when fluctuation occurs. In order to respond to the above challenges, this research aims to dynamically and quickly re-plan the production line using the existing equipment according to current equipment and production status. In this paper, failures of the production equipment, such as robots and tools, are regarded as production fluctuation factors. In order to continue production with the remaining resources in the event of equipment failure, it is necessary to change the process plan. However, since these are engineering tasks in the production preparation stage, there was the problem of not being able to flexibly change them at the manufacturing site during the production execution stage. In this development, an alternative plan pre-generation and selection method was developed to maintain production by re-allocating tasks during equipment failure. In this approach, first, multiple alternative plans for task allocation for failures in each piece of equipment are planned in advance using a process plan optimization technique. Next, production fluctuations due to equipment failures are detected. Finally, dynamic changes are possible by selecting alternative plans that maximize the throughput of the entire production system. Initial verification results are shown by comparison with the conventional method for equipment failure using simulation on a small-scale robot assembly line for automotive inverter.

Keywords: production line; system configuration; task allocation; alternative planning; dynamic re-planning

1. Introduction

In the manufacturing industry, capital investment in automation is progressing steadily due to the declining working population and the expansion of the robot utilization market. In addition, as social uncertainty increases, it is required to improve resilience by dynamically recombining production resources in the operation of production lines in order to respond to fluctuations. In the assembly process of automobile parts, fluctuations in demand, sudden equipment failures, and variations in operator ability are examples of fluctuation factors that affect the production volume. Trend analysis and consideration of countermeasures for these fluctuations depend on the knowledge of engineers familiar with the production line. In addition, there is a problem that the production line is stopped due to configuration change of the production line and equipment recovery work, resulting in low productivity. The dynamic adaptability required for future manufacturing systems is discussed in [8] in light of the adaptive cognitive production system paradigm.

The goal of this research is to realize a dynamic production planning and execution system that achieves highly effi-

cient production despite fluctuations. Based on the data collected from the production line, the developed system accurately grasps the dynamics of the shop floor and dynamically switches the operation of the production line by linking process planning and production planning. This paper focuses on two functions: (1) generating in advance a portfolio of alternative plans for foreseen production fluctuations, and (2) dynamically updating the product routes by selecting the optimal alternative according to the actual shop-floor status.

Production system configuration addresses determining the optimal combination of resources, as well as their assignment to production tasks, to produce given products using given process plans in the desired volume. System configuration greatly affects the productivity, reliability, product quality, or scalability of the system [10]. The archetype of the production system configuration problem in case of flow systems is the *assembly line balancing problem* (ALBP). Its basic form, the *simple assembly line balancing problem* (SALBP) assumes a single product and uniform stations [13]. Various extensions to that basic model have been investigated, including the detailed characterization of resource requirements (e.g., human operators, robots and tools), multiple potential execution modes, or different task time increments [5]. Mixed-integer linear programming (MILP) is regarded as a powerful exact solution approach, but effective (meta-)heuristics have also been studied widely [2, 3].

Although the most common ALBP models are deterministic, stochastic variants have been investigated as well, mostly focusing on uncertain task durations, assuming known theoretical, often independent probability distributions [9]. These approaches typically assume a minimal local response to the fluctuations of durations: stopping the conveyor, discarding the affected workpiece, or calling an additional operator [4], while they leave the global system configuration and task assignment unchanged. More complex types of response, such as the adaptation of task assignments is considered, e.g., in *dynamic line balancing* (DLB) problems [12]. On the tactical (configuration) level, a subset of the tasks is made shareable between multiple stations, usually at the price of purchasing additional equipment and cross-training human operators; whereas on the operational (scheduling) level, the assignment is decided based on the current workload of the stations. More generic techniques for managing changes and uncertainty in manufacturing are investigated, e.g., in [1, 6, 7, 11]. Despite the above, to the best of the authors' knowledge, the idea of generating a portfolio of alternative plans that can be applied upon encountering given types of fluctuations has not been studied in the context of production systems yet.

This paper sets out to discover flexibilities in complex flow-type manufacturing systems in response to different types of fluctuations by modifying the task assignments. Special attention is given to fluctuations due to equipment failure and the variation of demand. The proposed approach is partly based on the earlier work [14], which focused on the integration of production system configuration and task sequencing, but ignored potential fluctuations.

2. Problem statement

The paper addresses the dynamic re-balancing of production lines upon fluctuations, with special attention to equipment failures and variation of demand. Since re-balancing assumes the availability of equipment, control programs, as well as human work instruction and training, the problem must be tackled in two different stages: in the planning stage (1), alternative configurations must be pre-generated according to relevant fluctuation scenarios, while in the execution stage (2), potential fluctuation scenarios must be identified and as a response, the configuration that suits the actual scenario the best must be selected and applied.

The production system produces multiple products and consists of multiple production lines, each containing a number of either robotic or human-operated stations that must satisfy the forecast demand over the planning horizon. Although one production line can produce several products, preliminary experiments confirmed that shorter dedicated lines are more efficient in the current application than longer multi-product lines. The main reason of this phenomenon is the combination of low cycle times and high, constant material handling times at the stations. Therefore, at the time of planning the system configuration, it is assumed that there is a single dedicated line for each product. Yet, in alternatives applied at the time of fluctuations, sharing a line between multiple products is allowed.

The process plan of the products is given in the input, and consists of a fully ordered sequence of tasks. Alternative execution modes are available for each task, which require different combinations of resources and have different durations. The different tasks of the same product can be executed in different modes. One human operator or a single robot can be assigned to each station. Planning starts from a given initial system configuration, which contains the collection of resources installed at the plant. The initial configuration can also be an empty plant, which corresponds to planning from scratch. New stations, robots and tools can be installed with given costs.

A station executes a number of subsequent tasks in the process plan of the given product, and each task must be assigned to exactly one station. A task of a product can be executed by a station in a given mode if it is equipped with all the resources that are required by the task. Besides the processing times of tasks, sequence independent tool changeover times are applied when necessary. The cycle time of the overall production line is determined by the slowest station, and it must be sufficiently low to serve the total demand of the given product.

At the time of planning the system configuration, the objective is minimizing the total production cost, composed of the investment depreciation for all stations, robots and tools, computed using a linear depreciation formula, and the total labor cost.

The generation of alternative assignments addresses fluctuations caused by the failure of any single station. In this case, the equipment is fixed according to the planned configuration (except for stations unavailable due to failures); but the product-to-line, as well as task-to-station assignments can be modified

to ensure the continuity of production. The objective is to minimize the cycle time. The alternative applied at any time is selected in real time based on the identified fluctuation.

It is noted that some mathematically straightforward features of the implemented system are not included in the paper for the sake of brevity, e.g., enabling or disabling different types of investments or execution modes, additional sub-process times at the stations, removal of resources from the initial configuration, etc.

3. Solution approach

Fig.1. shows the architecture of the developed system, which includes the proposed *Factory Configurator* (FC) and *Dynamic Planner* (DP) functions added to conventional production management and control systems such as ERP, MES, and SCADA. It is noted that in more complex production environments (e.g., make-to-order systems with strict order due dates), further functionalities, such as Advanced Scheduling and Material Requirements Planning (MRP) are required that are omitted from this figure. Here, FC generates an initial plan for system configuration, as well as alternative task assignments to manage fluctuations. Control programs for the initial configuration and all alternatives are generated using appropriate planning functions. During the execution phase, DP detects production fluctuations from production logs, selects the optimal alternative assignment according to the current 4M (Man, Machine, Method, Material) status, and dynamically switches configurations. As an example, consider an equipment failure at a given station. Failure information is detected and fluctuation is identified via PLC, SCADA, and MES. For the detected fluctuation, DP selects the plan with the highest throughput from among the alternative plans prepared in advance by FC. The selected alternative plan is then communicated via the MES to the shop floor to resume production. The following sections detail the functions of FC and DP.
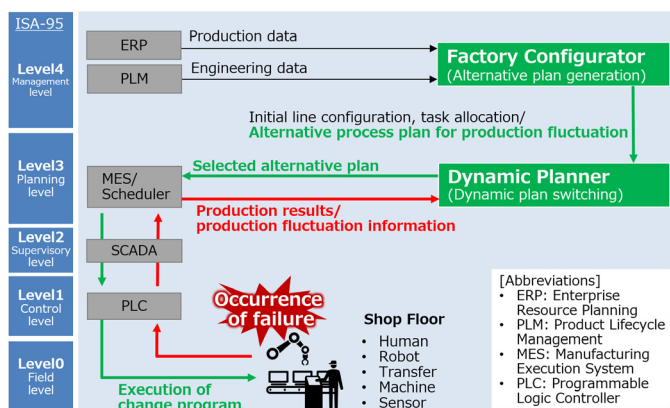

Fig. 1. Functional configuration of the developed system.

Indices	
τ	Task (index)
s	Station (index)
m	Execution mode (index)
r	Robot type (index)
j	Tool type (index)
Input parameters	
D	Product demand [pcs]
$R(\tau, m)$	Robot type req'd by task τ in exec. mode m (index)
$J(\tau, m)$	Tool type req'd by task τ in exec. mode m (index)
$H(\tau, m)$	Human operator is req'd by task τ in exec. m (boolean)
$T_{\tau m}$	Processing time of task τ in mode m [sec]
U_m	Tool changeover time in mode m [sec]
α_s	Station s is available (binary)
ϱ_{sr}	Station s is equipped with robot type r (binary)
δ_{sj}	Station s is equipped with tool type j (binary)
γ_s	A human operator is available at station s (binary)
Decision variables and objective	
$x_{s\tau m}$	Task τ is assigned to station s in exec. mode m (binary)
$u_{s\tau}$	Changeover time before task τ at station s [sec]
C	Cycle time [s]

Table 1. Notation.

3.1. Factory Configurator

FC is responsible for computing the optimal system configuration under different assumptions using the appropriate variants of a MILP model in the following planning use cases. During *initial line design*, when a new dedicated production line is configured for a new product, as well as in *yearly planning*, when the configuration of the dedicated line is adjusted to the changes in requirements, e.g., the variation of the long-term demand forecast, the objective is minimizing the total production cost. The corresponding MILP variant was presented in [14]. In *monthly planning*, a part of the demand can be reassigned between unchanged lines to respond to major deviations from the long-term demand forecast. In this multi-product, multi-line MILP variant, line configurations are fixed, whereas products and their tasks are re-assigned to minimize makespan, i.e., the time required to satisfy the monthly demand. Finally, the MILP variant presented in Fig. 2 is used for computing the alternative assignments applicable upon equipment failures. The problem is solved separately for each feasible combination of a product and a line, and for all possible selections of at most one failed station in the line. Notation is listed in Table 1. It is noted that notation is slightly more complicated than necessary for this specific model in order to maintain consistency with [14].

The objective is to minimize the cycle time of the product on the given line (1). Constraint (2) ensures that every task τ is assigned to exactly one station in exactly one execution mode. Inequalities (3)-(6) state that a task can be assigned to a station in a given mode only if the station is available and it is equipped with the required robot, tool, and human operator. Inequalities (7) and (8) compute the tool changeover time before task τ at station s. If both task $\tau - 1$ and τ are assigned to station s, but they require different tools, then $u_{s\tau}$ is at least the changeover time of mode m by constraint (7). Inequality (8) states that a changeover is also required if the first and last tasks on the sta-

$$\text{Minimize} \quad C \tag{1}$$

subject to

$$\sum_{s,m} x_{s\tau m} = 1 \qquad\qquad \forall\, \tau \tag{2}$$

$$\alpha_s \geq x_{s\tau m} \qquad\qquad \forall\, s, \tau, m \tag{3}$$

$$\varrho_{sR(\tau,m)} \geq x_{s\tau m} \qquad\qquad \forall\, s, \tau, m \tag{4}$$

$$\delta_{sJ(\tau,m)} \geq x_{s\tau m} \qquad\qquad \forall\, s, \tau, m \tag{5}$$

$$\gamma_s \geq x_{s\tau m} \qquad\qquad \forall\, s, \tau, m : H(\tau, m) \tag{6}$$

$$u_{s\tau} \geq U_m(x_{s(\tau-1)m} + x_{s\tau m} - 1) \qquad\qquad \forall\, s, \tau, m : \ J(\tau, m) \neq J((\tau-1), m) \tag{7}$$

$$u_{s\tau} \geq U_m(x_{s\tau m} + x_{s\tau'm} - x_{s(\tau-1)m} - x_{s(\tau'+1)m} - 1) \qquad \forall\, s, \tau, \tau', m : \ J(\tau, m) \neq J(\tau', m) \tag{8}$$

$$\sum_m x_{s\tau m} \leq \sum_{s' \leq s,m} x_{s'(\tau-1)m} \qquad\qquad \forall\, s, \tau > 1 \tag{9}$$

$$\sum_\tau u_{s\tau} + \sum_{\tau,m} T_{\tau m} x_{s\tau m} \leq C \qquad\qquad \forall\, s \tag{10}$$

$$x_{s\tau m} \in \{0, 1\} \qquad\qquad \forall\, s, \tau, m \tag{11}$$

$$u_{s\tau} \geq 0 \qquad\qquad \forall\, s, \tau \tag{12}$$

Fig. 2. MILP model for generating alternative task assignments.

tion require different tools. Line (9) encodes precedence constraints. Constraint (10) ensures that all stations can operate with the desired cycle time, given the durations of the assigned tasks, as well as the changeover times between them. Finally, lines (11) and (12) list the binary and non-negative variables. FC was implemented in FICO Xpress version 8.8.

3.2. Dynamic Planner

The challenge in realizing *Dynamic Planner* is to select the optimal alternative configuration at high speed according to the dynamics of 4M resources in response to production fluctuations. In this development, by utilizing an ontology that is a knowledge model of 4M resources, it is possible to quickly extract the information necessary for alternative plan selection by linking products, processes, production resources, etc. The main functions that make up the *Dynamic Planner* are the following three.

1) Ontology data management: defining classes for information such as production resources, line configurations, and task assignments, associates relationships between data, and manages synchronization. By tracing the relationship between data using ontology, it is possible to specify related data at high speed without performing data table search processing as in conventional data management.
2) Production fluctuation detection: identifying production fluctuation events such as production delays, equipment

failures, and variation of task durations in real time from line status information managed by ontology data.
3) Alternative configuration selection: selecting an alternate plan suitable for fluctuations on each line based on the fluctuation information detected in (2) and the line status by associating ontology data.

Due to space limitations, the detailed flow of each function is omitted. DP was implemented in Python using the ontology editing library owlready2.

4. Computational experiments

Experiments were performed on a use case involving the assembly of automotive inverters. A product family of 9 different models is produced in a common assembly system, where assembling a product requires the execution of at most 39 tasks, see Figure 3. The tasks can be executed by human operators (all tasks) or by one of the three available robot types, which operate at different speeds and are available with different purchase prices (33 out of 39 tasks, excluding 6 tasks for cable assembly that require the dexterity of the human hand). This corresponds to four possible execution modes for each task. Moreover, each task requires at most one of the six available tools, such as robotic grippers or screwdrivers.
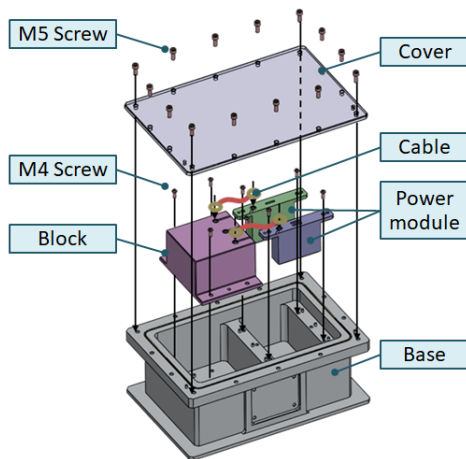
Fig. 3. Sample inverter product.

4.1. Alternative configurations (Factory Configurator)

Experiments simulated rolling horizon planning over a 10-years horizon, which involved all the presented planning use cases: yearly planning for computing the initial line configurations and adjusting them according to a 3-years demand forecast to minimize total operating costs; monthly planning to reassign a part of the demand upon major deviations from the long-term demand forecast; as well as generating alternative assignments after each yearly modification of the lines.

Over the 10-years horizon, FC generated altogether 1226 alternative assignments: 3.8% of this was an assignment to the own, fully functional line of the product; 29.6% to another fully functional line (a few product–line combinations were infeasible due to the lack of required resources); 4.3% to the own line with one station skipped (i.e., typically, only one station could be skipped at the price of deteriorating throughput, whereas other stations had resources that could not be replaced); and 62.3% to another line with one station skipped (often multiple stations could be skipped on the line originally configured for a more complex product). The overall simulation took roughly 1.45 hours: 16 s for solving the 10 yearly planning problems (an average of 1.6 s per instance); 716 s for solving the 120 monthly re-assignment problems (6.0 s per instance); and 4516 s for generating the alternatives (3.6 s per instance).

4.2. Evaluation in simulations (Factory Configurator and Dynamic Planner)

A problem-specific production simulation evaluated the effects of dynamic production line re-balancing with FC and DP. Since the focus is on equipment failure as a production fluctuation, to simplify the problem, tasks that require manual work (cable assembly) were removed, and the resources were limited to robots and tools. Monthly reconfiguration of the system was omitted, and FC generated the optimal line configuration and alternative plan based on the estimated maximum annual production volume of each product. Nine failure modes, such as robot and gripper failures, were defined, and for each failure

mode, the probability of occurrence (0.001% - 0.02%) and recovery time (2-16 hours) were defined. For example, failures of robots with unknown causes are rare, and the frequency of failures per robot is estimated to be about once every 24 months. Based on this, the frequency of occurrence per robot per product was defined as 0.001%. On the other hand, failure to pick up parts by the suction hand is more frequent than failure of the robot. In this verification, 0.02% per cell per product was defined based on our results. Failures of cell equipment other than robots and poor screw tightening were also defined as failure modes.

For multiple inverter lines with a wide variety of products and fluctuating production volumes, production simulation reproduces the occurrence of equipment failures and calculates the overtime costs necessary to make up for production shortages due to delays. In this verification, the assembly line is automated by robots, so only one person is required as a manager. If the standard working hours for one month (8 hours × 20 days) are exceeded, overtime costs for this manager will be incurred. It is assumed that overtime work covers the production shortage caused by demand fluctuations and equipment failures, at the price of an overtime cost of 5 200 JPY/hour.

The subjects of comparison here are (1) the conventional method, in which the line is stopped until it is restored after each failure, and the (2) proposed method, in which upon equipment failures, DP selects the optimal alternative from the configurations generated in advance by the FC and resumes production. In the latter case, a changeover time of 30 minutes is accounted on each affected line.

In the production simulation, monthly demand fluctuations of ±50% are assumed based on the eight-year annual production plan for each model, and the time to reach the demand for each month or the production volume for the specified work hours is calculated. Based on the defined failure modes, a total of 3 792 failures occurred in the production simulation on 9 lines over 8 years.

Figure 4 shows the monthly demand volume and the production shortage during the specified normal working hours. From the fourth year onward, the busy production season begins, and the conventional method of stopping the line in case of failures cannot cover the fluctuations, resulting in an increase in production shortages. Of the 96 months covered in simulation, the number of months in which the demand volume could not be met was reduced by 77% from 77 months for the conventional method to 25 months for the proposed method of continuing production with an alternative plan. In addition, according to the calculations in this simulation, overtime costs were decreased by 91% from 34 680 872 JPY to 3 117 708 JPY.

5. Conclusions and future works

This paper introduced a novel approach to dynamically rebalancing production lines as a response to fluctuations. Rebalancing was achieved by the interplay of a production system configurator on the tactical level that generates a set of alternative task assignments, and a dynamic production scheduler
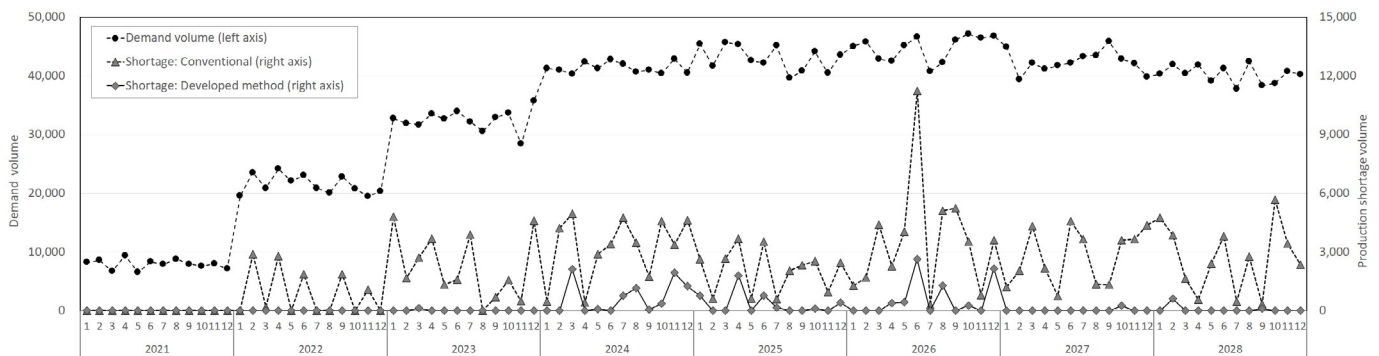
Fig. 4. Changes in production demand volume and production shortages within specified working hours.

on the operational level that at all times selects the alternative that suits the current shop-floor conditions the best. Among the different types of fluctuations in production systems, the paper focused on equipment failures and the variation of demand. The proposed approach was evaluated in a case study based on a real industrial application, where it reduced overtime costs by 91% compared to a baseline approach that assumed stopping the line upon equipment failures.

Future research will address multiple directions. First, while in this paper, fluctuations were limited to equipment failures and demand variation, in real applications it is crucial to cover all types of disturbances, including the availability of materials and human operators, differences in operator skills, variation of task durations, as well as deviations from process parameters assumed at planning time. These fluctuations are particularly difficult to predict in advance. Moreover, this also gives rise to a substantial increase in the number of relevant alternative configurations. In order to avoid the extreme robot and PLC programming effort that comes with the enlarged set of alternatives, selecting a compact portfolio of alternatives that achieves favorable performance on all possible fluctuation scenarios with a limited programming burden is of utmost importance. The implementation of different compensation strategies depending on the reason for the fluctuations and the development of a novel logic for selecting the most appropriate strategy is also required. Finally, the physical demonstration of the proposed approach instead of digital simulation is important. The authors plan to set up a physical verification environment that integrates the development functions of *Factory Configurator* and *Dynamic Planner* with existing systems such as MES. The verification of the data analytics functions of *Dynamic Planner* on real production data, including the identification of production fluctuations, will receive special attention.

Acknowledgements

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