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Procedia Computer Science 180 (2021) 706–713

Procedia Computer Science

www.elsevier.com/locate/procedia

International Conference on Industry 4.0 and Smart Manufacturing

Capacity planning of a mixed-model assembly line for prefabricated housebuilding elements

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Abstract

This paper deals with new opportunities of Industry 4.0 applications for capacity planning on mixed-model assembly lines for industrialized housebuilding. We formulate a linear programming model for capacity planning on several parallel production lines and show how this model is fed with accurate data. The solution of the linear program in turn generates a detailed allocation of personnel and workload assignment for a given planning period. We discuss the planning approach and describe the implementation on a real world environment.

Keywords: Prefabricated housebuilding; mixed model assembly line; capacity planning; flow line

1. Introduction

Industrialized housebuilding is characterized by the prefabrication of building elements or modules in a factory and the assembly of these components on construction site [1]. The purpose of splitting production into prefabrication and on-site assembly is to reduce inefficiencies in the construction process, which is achieved by a higher process orientation especially in prefabrication [2]. In addition, production is performed at a fixed location, which means that the elements are manufactured under controlled conditions [3]. The processes can thus be designed and managed much more efficiently compared to traditional construction methods [4].

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1877-0509
10.1016/j.procs.2021.01.293

Even though the industrial housebuilding offers many advantages, especially in the area of prefabrication higher investment costs for the production facilities are incurred. These plants require sufficient capacity utilization to operate profitably [5]. When there is a high demand for production capacity, it is often preferable to improve the utilization of existing plants rather than to make new investments, which in turn must be used to full capacity. A better utilization of production capacity through appropriate capacity planning methods is therefore an essential aspect in improving economic efficiency [6,7].

At the same time, it is not surprising that more accurate data can significantly improve production planning [8,9].

For the prefabrication of elements in industrialized housebuilding, mixed-model assembly lines represent an important form for organizing the production [10]. In order to improve productivity and efficiency of mixed-model assembly lines, well considered capacity planning and product sequencing is important [11]. The application of capacity planning models can support the work of production planning and result in more target-oriented solutions.

One of the first works on this topic is by [12]. Therein, new algorithms are developed to balance the schedule of mixed-model assembly lines with the goal of a constant usage rate of each part of the assembly line. In a recent work in this field by [13], an artificial bee colony algorithm is used to solve the problem of lexicographic bottlenecks in mixed-model assembly lines. The goal is to distribute variations in workload evenly across the existing work stations to balance the assembly line. The new introduced algorithm is thoroughly tested on well-known test problems in this domain.

The aspect of personnel planning in combination with capacity planning on mixed-model assembly lines is examined by [14], among others. The authors use four different models (linear and non-linear) to optimize the efficiency of the use of labor and machinery for small batch production of aircrafts. They evaluate alternatives for cycle time and labor allocation to minimize labor and inventory costs. Requirements for tasks, work stations and labor are considered in these models.

A similar problem is also encountered in the assembly of trucks. [15] use a rolling planning horizon to solve the daily problem of assigning workers and floaters to the production line to minimize the labor costs of a labor-intensive transfer line for assembling trucks.

The purpose of this paper is to investigate new opportunities of Industry 4.0 application in element prefabrication on mixed-model assembly lines of industrialized housebuilding. To this end, a model is presented to support capacity planning, product sequencing and personnel planning. This analytical approach of simultaneous capacity and personnel planning for the mixed-model assembly line production is new in the field of industrialized housebuilding. Additionally, it is illustrated how the solutions of this model can be continuously improved through real-time data input.

2. Material and methods

The case company prefabricates wall elements for industrialized housebuilding on three mixed-model assembly lines. All three production lines are located on one site. Employees can be moved from one production line to another as required. Furthermore, the capacity utilization of the production lines can be balanced under defined conditions.

The prefabrication level of elements produced will be defined as “prefabrication and preassembly” according to the production classification matrix for industrialized building from [16], which means that windows, doors, electrical and plumbing installations are built-in components and plastering activities are performed in the prefab plant. The degree of product standardization is defined as “customized standardization”. This level of standardization provides the opportunity to use a building system that incorporates standardized production methods and technical solutions. This ensures the efficient prefabrication of elements. The customer order decoupling point is at the same time positioned in a way that customers can design their house very individually. Wall lengths can thus be chosen at will or a wide variety of window types can be installed at desired positions in the wall. This results in a large number of variants that must be considered in the capacity planning model.

2.1. Data sources and generation

Various data sources are required for the capacity planning model. This section describes where the data used in the model comes from. The model is based on data from both the ERP system and a REFA working time study conducted by the research team. Data on the order backlog, the bills of materials for the house types and the workforce lists originate from the industry partner's ERP system. Data on the work processes are based on existing process descriptions provided by the industrial partner. After an analysis of the current state of the processes, the process data is collected by means of a REFA time study.

In the case study, the order backlog to be processed is considered for about six months in advance and can be continuously called up from the ERP system. Although the industrial partner produces individual buildings, the data in the order backlog database contains the basic data of the houses to the extent that standard house types can be assigned. Variants that define the house design and the corresponding wall lengths are recorded in the database. This enables an assignment to these standard house types.

Bills of material of previously often sold house types serve as a data basis for the calculation of standard houses. Specifications of the walls that have an impact on the production activities and their duration were thus determined. These specifications either represent variants, such as the number of windows installed, the type of plaster used, or define the length of wall produced.

Another source of data on personnel resources is the workforce list with the associated qualifications profiles. This can be obtained from the ERP for daily planning. Therefore, this data source thus provides a basis for determining the capacity of personnel resources.

The data on the work processes are collected, to a large extent, by the researchers on site. Based on process descriptions provided by the industry partner, the business processes in the element production are modelled using BPMN 2.0 and subjected to an iterative evaluation. The evaluation was undertaken applying the methodology of participant observation according to [17] and periodic analysis workshops with managers responsible for element production. Sequence relationships of the activities are derived from the process models and represented in a priority graph. Simultaneousness and sequence restrictions of the activities as well as the omission or execution of activities for variants can be represented with the help of priority graphs [18]. The determination of such relationships in the manufacturing process is of crucial importance, especially in mixed-model assembly lines, since the process duration can vary significantly from component to component [11,19].

A REFA working time study carried out by the research team serves to collect data on the duration of activities and the use of personnel and work station resources. The required qualification profiles of the employees for the execution of the activities are defined and documented along with the requirements for the employee resources. In addition, the sequence relationships between the activities are again observed and verified.

The reason for carrying out the REFA working time study on site was the lack of sufficiently precise data on the duration of the activities available to the industrial partner. As the duration of the activities is considered to be very stable values, while the production process remains the same, there is no need to use more complex data collection methods.

2.2. Information flow

The production of wall elements for prefabricated houses is carried out in a line production where several variants are manufactured. Fig. 1 is a layout diagram of the investigated production facility. Data from the individual lines (external, internal and special line) and work stations as well as the wall elements produced and the employees assigned are summarized in a single data pool. The mathematical optimization model uses this database to allocate work orders according to machine capacities at the individual work stations and personnel resources.

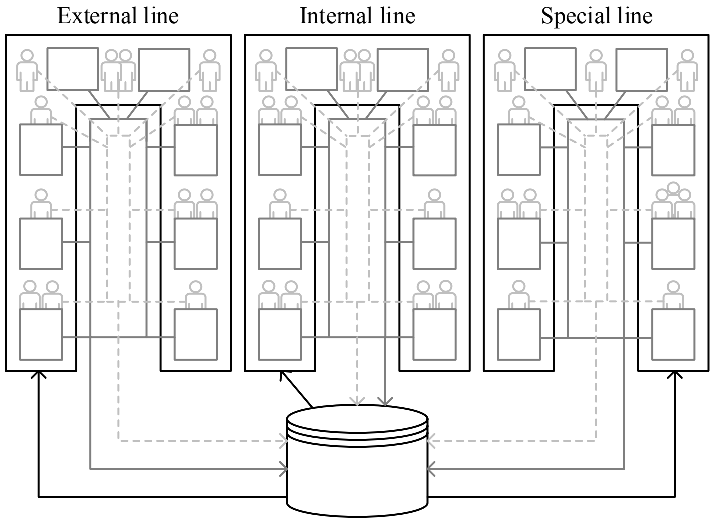

Fig. 1. Different production lines with the individual work stations on which the personnel is assigned according to their qualifications. The differently collected data is used as input for the optimization model.

2.3. Model

This section introduces the linear program used for capacity and personnel planning and maximizing production output. Table 1 lists and briefly describes the used indices, parameters and variables.

Table 1. Indices, parameters and variables needed for the mathematical model.

Indices	
H	Set of standard houses h (hipped roof, saddle roof)
W	Set of wall types w (internal and external wall, flap tile upper floor, sanitation wall etc.)
L	Set of production lines l (external line, internal line, special line)
T	Set of periods t
U	Set of designs u (anchors, angles etc. per wall)
A_l	Set of activities a_l per production line l
E	Set of floater groups e (skilled and unskilled employees like electrician and carpenter)
S_l	Set of work stations s_l per production line l
F_e	Set of work stations f_e per floater group e
Q	Set of requirement profiles q
$I_{h,w}$	Set of wall number $i_{h,w}$ per house h and wall type w
Parameters	
$B_{h,w,l}$	Assignment, 1 if standard house h of wall type w is produced at line l, 0 otherwise
B_{s_l,a_l}	Assignment, 1 if activity a_l is performed on work station s_l, 0 otherwise
B_{f_e,a_l}	Assignment, 1 if activity a_l is performed on work station f_e, 0 otherwise
$G_{i_{h,w}}$	Length of wall number $i_{h,w}$
$O_{a_l,u}$	Occupancy time when carrying out activity a_l for respective design u
$P_{i_{h,w},u}$	Percentage of designs u of wall number $i_{h,w}$
D	Duration of period
$K_{a_l,q}$	Required number of employees for activity a_l with required job profile q

J_{a_l}	1 if activity a_l can be carried out simultaneously with other activities, 0 otherwise
$C_{f_e,q,t}$	Personnel capacity for work stations f_e with required qualification q in period t
$M_{i_{h,w},u}$	Number of designs u per wall number $i_{h,w}$
R_l	Storage capacity for production line l
$V_{i_{h,w}}$	Proportion per wall number $i_{h,w}$
Y_τ	Percentage in storage from (previous) periods τ (1, 1, 0.25)
Variables	
$n_{h,w,l,t}$	Number of completed work orders of standard house h and wall type w on production line l in period t
$d_{l,t}$	Inventory of production line l in period t

The objective function of the model maximizes the output of finished work orders per standard house h, wall type w on the respective production line l in period t. The following additional constraints must be complied with.

$$\sum_{h\in H}\sum_{w\in W}\sum_{l\in L}\sum_{t\in T} n_{h,w,l,t} \quad \rightarrow \quad maximize$$

$$\sum_{h\in H}\sum_{w\in W}\sum_{i_{h,w}\in I_{h,w}}\sum_{u\in U} n_{h,w,l,t} * B_{h,w,l} * P_{i_{h,w},u} * M_{i_{h,w},u} * O_{a_l,u} * K_{a_l,q} * B_{f_e,a_l} \leq C_{f_e,q,t}$$

$$\forall f_e \in F_e, q \in Q, t \in T \quad (1)$$

$$\sum_{h\in H}\sum_{w\in W}\sum_{a_l\in A_l}\sum_{i_{h,w}\in I_{h,w}}\sum_{u\in U} n_{h,w,l,t} * B_{h,w,l} * B_{s_l,a_l} * P_{i_{h,w},u} * M_{i_{h,w},u} * O_{a_l,u} * J_{a_l} \leq D$$

$$\forall\, s_l \in S_l, t \in T \quad (2)$$

$$\sum_{l\in L} n_{h,w,l,t} = V_{i_{h,w}} * \sum_{w\in W}\sum_{l\in L} n_{h,w,l,t}$$

$$\forall\, h \in H, w \in W, t \in T \quad (3)$$

$$0.25 * \sum_{h\in H}\sum_{w\in W}\sum_{l\in l} n_{h,w,l,t} = \sum_{w\in W}\sum_{l\in L} n_{2,w,l,t}$$

$$\forall\, t \in T \quad (4)$$

$$\sum_{\tau=0..2\,|t-\tau>0} Y_\tau * \left(\sum_{h\in H} \sum_{w\in W} \left(n_{h,w,l,t-\tau} * B_{h,w,l} * \sum_{i_{h,w}\in I_{h,w}} G_{i_{h,w}} \right) \right) \leq R_l$$

$$\forall\, l \in L|external\ \&\ special\ line, t \in T \quad (5)$$

$$\sum_{h\in H} \sum_{w\in W} \left(n_{h,w,l,t} * B_{h,w,l} * \sum_{i_{h,w}\in I_{h,w}} G_{i_{h,w}} \right) \leq R_l$$

$$\forall\, l \in L|internal\ line, t \in T \quad (6)$$

Constraints (1) guarantee that the personnel capacity for each work station f_e per floater group e with required qualification q in period t is not exceeded while producing the work orders. The left hand side of these constraints computes the working time in work station f_e with requirement profile q in period t. This depends on the number of finished work orders, on which line they are produced, the percentage of designs and wall numbers, the occupancy time for the activities of each design, the required number of employees for the activity conducted and whether or not the activity is performed on this work station.

The next constraints (2) refer to the available working time per period. The left hand side of these constraints calculates the working time performed on line l with activity a_l in period t. This is calculated by multiplying the number of completed work orders per standard house and wall type produced on line l in period t with the allocation of wall to line, percentage of designs per wall number and occupancy time for activities that cannot be performed simultaneously with others.

In order to guarantee the desired proportions of the individual wall types w for each standard house h and period t, the constraints (3) are required. Constraints (4) ensure the percentage distribution between hipped and saddle roofs per period t. In order not to overload the wall storage per period t, the drying time of the plaster and therefore its retention time in the storage must be taken into account for the external wall and special line. This is done in constraints (5), which limit the length of the walls in storage to the available length of the line l (external and special line). Constraints (6) ensure that the wall storage capacity is maintained for the remaining internal production line l. However, drying times do not have to be taken into account here.

3. Conclusion and outlook

At this stage of research, only preliminary results are available. Therefore, the intended application of the planning is the main focus here.

Due to the continuous real data integration and the type of processing, the average production times determined are becoming progressively more precise. Therefore, the accuracy of the results of the optimized production model increases with the larger underlying database. The deviations are smaller and the calculated results are consequently continuously improving. This enables better integration into a production control system for releasing orders in production, so that production can be planned more and more realistically. This means that planning can be improved constantly in a continuous process.

The model presented is used for weekly planning per shift. This planning horizon is suitable because of the weekly change of shifts, but also because of the frequent change of personnel in the company under study. In addition, the model can also be applied at two levels and used in a more aggregated form to estimate the production quantity for the individual standard house types. This result can be used as a rough guideline for the sales department.

Production planning in particular benefits from the computerized planning process. Real-time information generated automatically about the degree of completion of the individual walls and the order situation can be used at any time during the planning process. Detailed employee information can also be accessed for efficient planning. By increasing the efficiency of production, the production lines can be better utilized. In addition, the available manpower can be used more efficiently through improved personnel deployment.

In the further course of this research, the influence of variable production, where individual walls are not produced on the usual line (internal walls on the internal line), is investigated. However, the necessary activities and required sequence for the production of the walls must be feasible on the newly selected line. In this way, bottlenecks on certain lines can be avoided and the maximum output of the entire production line can be optimized. In addition, the influence of personnel scheduling is also examined. Here, the employees are deployed throughout the entire production according to their qualifications, in contrast to the current situation where they can change within a line. It is assumed that this will further increase the maximum possible output. These next steps are shown in Fig. 2.

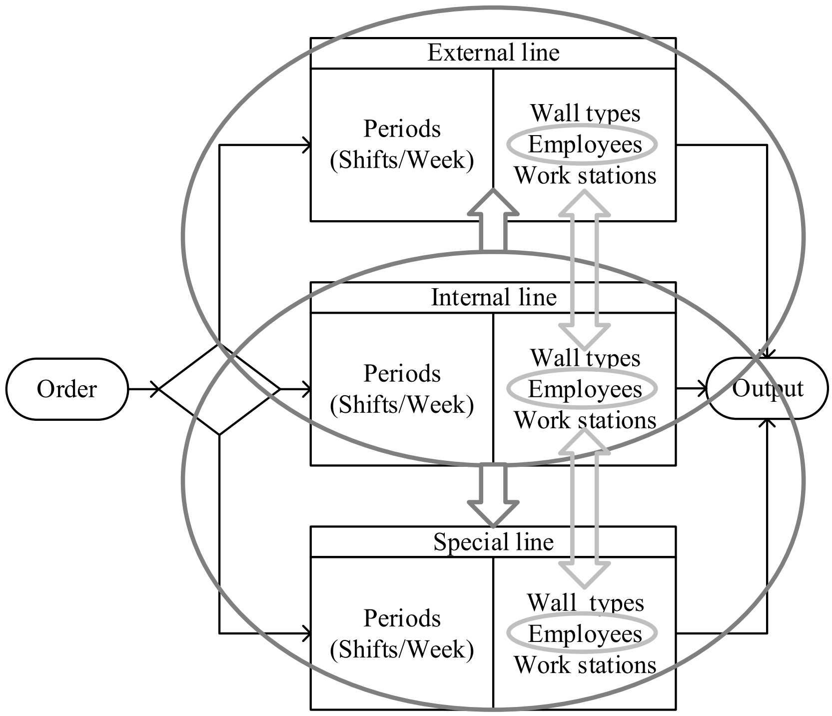

Fig. 2. Capacity planning with flexible production lines and personnel planning. Work order and employees can be scheduled on the individual lines according to demand and requirements.

In addition, smaller and larger line restructurings are being investigated that can be carried out with or without investment in plant and machinery. All these measures are tested and validated with the optimization model, the bottlenecks are evaluated and appropriate measures are taken to optimize the production output as much as possible. The production data is constantly updated automatically and transferred to the ERP system respectively the data pool.

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