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Job and product rotation for maximising the production output on multi mixed-model assembly lines for element prefabrication in industrialised housebuilding

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ABSTRACT

This paper analyses the production planning for the multi mixed-model assembly lines (MMMAL) for building elements prefabrication. Industrialised housebuilding (IHB) prefabrication plants struggle with increasing the productivity of existing prefabrication equipment through the application of traditional planning methods. This research aims to apply a linear programming model to solve this planning problem. To test the model a wall element prefabrication plant with three distinct lines formed the test ground. Three scenarios are defined and evaluated to map job and product rotation, this is to generate more flexibility and enable better response to bottlenecks. The model is implemented to determine the optimal solution for each scenario and the experiments were done with real production data. Firstly, the formation of floater groups to improve worker scheduling and, secondly, the product rotation, is expanded to circumvent production bottlenecks. In a third scenario, the previous two are combined. The linear optimisation model allowed to improve the production planning for MMMAL by increasing the output by more than 50 % compared to the initial situation. Additionally, more than 70 % skilled worker resources can be saved. The contribution of this paper is that it shows the improvement potential in production planning for MMMAL through the application of an optimisation model using a combination of job and product rotation.

1. Introduction

In many industries multi mixed-model assembly lines (MMMAL) are common at the same production site, the need to jointly plan them has been noticed in recent years (Jiang, Li, Li, & Li, 2012; Saif et al., 2019). Especially in the industrialised housebuilding (IHB) sector, there are a large number of such plants, which have initially caused high investment costs and are amortised over a long period of time (Segerstedt & Olofsson, 2010). Newer production technologies can contribute to increase productivity and profitability, but result in additional costs from investments (Hazır, Delorme, & Dolgui, 2015). However, such investments are not always required, as improved planning methods for MMMAL can also have the same improving effects.

Smart planning approaches can also address the problem of understaffing of skilled workers. In a real production environment, they could be used more efficiently by targeting them for activities that require a high level of skills (Gronalt & Hartl, 2003; Şahin & Kellegöz, 2019; Gräßler, Roesmann, Cappello, & Steffen, 2021; Battaïa & Dolgui, 2022). Unskilled workers, which are much easier recruited, fulfil remaining easier tasks. One way to better address this issue is to use floater groups, which take on specific tasks at different workplaces, thereby deploying skilled workers in a more targeted way. However, scheduling workers across multiple lines also creates new challenges that need to be taken into account in capacity planning.

This paper deals with IHB off-site production facilities, where wall elements are produced on multiple production lines. A building consists of several different components, namely exterior walls, interior walls, ceilings and roof elements. In IHB the houses produced, and thus also the

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walls, are based on individual customer orders. Each wall element has specific characteristics that influences the various production activities and their duration along the production line (Johnsson, 2011; Lessing, Stehn, & Ekholm, 2015). Consequently, most of element prefabrication lines in IHB can be characterised as mixed-model assembly line production, where the manufacturing take place on multiple production lines. In order to improve their productivity and efficiency of such production sites a production planning model is introduced. Ahead of introducing the model, the following research questions (RQ) were stated: RQ 1: How can (1) job, (2) product and (3) job & product rotation be implemented in capacity planning for a MMMAL in IHB? RQ 2: What effect has this flexibilisation of the production lines on the production output in IHB?

This model is developed using data from an industry partner that manufactures the various house types on three different production lines within a single factory. A distinction is made between the interior and exterior wall line (IW and EW) and the special element line (SE), each of which is divided into workstations. Most of the activities at the lines are still operated manually and some of the stations need several workers who may have different skills. Currently, there is a fixed assignment between workers and wall types to production lines. The flexibility of the production system to assign skilled workers and wall types to other workstations and lines as needed, both individually and in a combined scenario to increase overall production capacity, is addressed in this paper. This does not require any modification of existing equipment or expensive investments.

Fig. 1 outlines the conceptual model of the exterior wall u-shaped production line of the investigated industrialized housebuilding facility. Each station is named after the main task that requires the most time. Station 1 is where the wooden frame of the wall is erected. Station 2 is a buffer station where some preparatory work, such as setting the lintels, is done. In Station 3, plasterboard is put in place, and Station 4 is a buffer station where some preparatory work for the electrical installation, which takes place in Station 5, is done. Between stations 5 and 6, the wall is turned around. In station 6, the thermal insulation is inserted into the wall and in station 7, the wooden frame is covered with gypsum fibre boards. The main task in station 8 is to cover the gypsum fibre boards with a layer of thermal insulation. In station 9, the holes in the thermal insulation are repaired and then the wall is covered with plaster in station 10. Station 11 is another buffer station where the wall is lifted into an upright position. In Station 12, windows or doors are installed. In Station 13, the window or door sills are fitted, and finally the window frames are plastered in Station 14. The other two lines are similar in design.

The paper is organised as follows: First the state of the art of mixed-model assembly line research, with a focus on capacity planning, workforce allocation and multi assembly lines is analysed. Secondly, the specific production environment and data used as well as the modelling assumptions and model formulation are presented in the material and methods chapter. This is followed by the computational results, providing an overview of the scenarios and showing the effects of job rotation, product rotation and their combination on the results. Finally, the findings are discussed and the paper closes with a conclusion section.

2. Literature review

Mixed-model assembly occurs when more than one variant of the same generic product is produced in a mixed fashion on a production line. The amount of work can vary from variant to variant, resulting in an uneven flow of work along the line. For a description of assembly line balancing see Bock and Boysen (2021). Boysen, Schulze, and Scholl (2022) give a detailed overview of the work done in the last 15 years in the field of assembly line balancing. All important areas of the decision-making process are highlighted, from data acquisition to new problems and methods to the solution algorithms used. Furthermore, Eghtesadifard, Khalifeh, and Khorram (2020) give an overview of assembly line balancing research papers from 1990 to 2017 and try to predict the direction of future studies.

The focus of this work is on workload balancing of multiple production lines. Starting with existing capacities of each individual production line workers and floaters are assigned to workstation in order to maximise the overall production output. One approach to achieve this is the formation of floater groups to bridge staff bottlenecks. The required qualification of the necessary personnel (specific skilled or unskilled workers) are given. Nakade and Ohno (1999), for example, propose an optimisation problem to find an allocation of workers that minimises the total cycle time for a minimum number of workers in a U-shaped production line. In the model studied, the process, operating and walking times are deterministic and all workers have the same qualification. The dynamic scheduling of workers in a Just-In-Time system to bridge changing bottlenecks is investigated by Cochran and Horng (1999). Workforce scheduling in combination with capacity planning in a

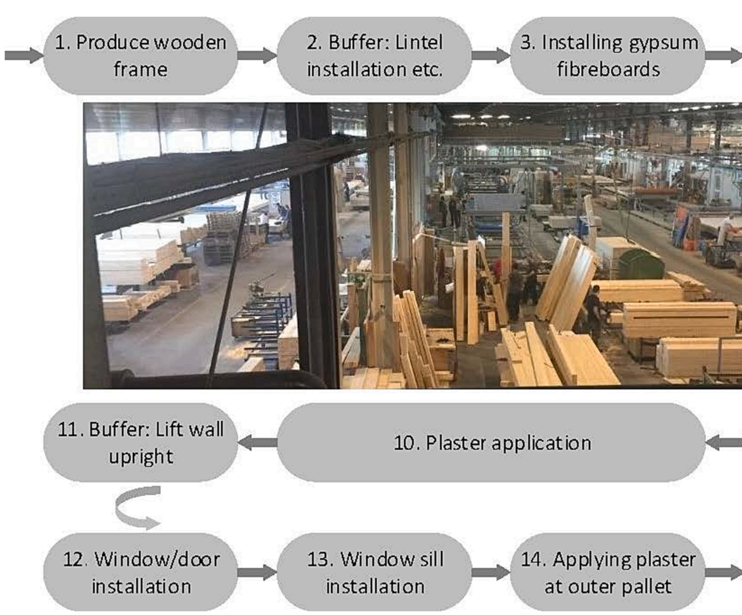

Fig. 1. Schematic of the exterior wall prefabrication line with workstations in their sequential relationship.

mixed-model assembly line is investigated by Heike, Ramulu, Sorenson, Shanahan, and Moinzadeh (2001) in the field of small batch production of aircrafts. Using four different models, cycle times and worker allocation are evaluated with the aim of minimising labour and storage costs. However, requirements for tasks, workplaces and labour are also taken into account. Gronalt and Hartl (2003) analyse a similar problem in truck assembly. Rolling horizon planning is used to solve the daily allocation of workers and floaters on the production line with the aim of minimising labour costs. An algorithm for finding the optimum allocation of workers with different skills to U-shaped production lines while minimising the cycle time is proposed by Nakade and Nishiwaki (2008). A dynamic job rotation tool is presented by Michalos, Makris, Rentzos, and Chryssolouris (2010) that allows efficient allocation of assembly tasks to appropriate operators at any time, leading to a more balanced distribution of the workload. A hierarchical approach for multiple criteria and decision-making algorithms is used for the implementation. The use of floaters in an assembly line for mixed-models with uneven demand and heterogeneous lead times is studied by Cevikcan and Durmusoglu (2011). The floaters help to maintain the fixed cycle time of the production. The authors solve two MIP models sequentially, the first minimising the total usage time and the second minimising the floater handover. They introduce three heuristics for the solution and validate the model on the mixed-model tractor assembly line. In the paper by Azizi and Liang (2013), the aim is to minimise the costs of training, as well as flexibility and productivity losses by scheduling employees, assigning them to different tasks and determining the training plan. For this purpose, a two-phase heuristic is introduced which, applied to different test instances, provides good and fast solutions.

Moreira, Cordeau, Costa, and Laporte (2015) formulate the robust assembly line balancing problem with heterogeneous workers under task time uncertainty and introduce a fast heuristic which can be used to effectively design more stable lines. Simultaneous minimisation of total cycle time and operating costs, taking into account employee allocation, when balancing mixed-model assembly lines is the subject of the work of Ramezanian and Ezzatpanah (2015). For this purpose, a goal programming approach is used and an evolutionary algorithm is developed due to the high complexity of the problem. Hochdörffer, Hedler, and Lanza (2018) examine a short-term staff scheduling system in an automobile manufacturer that takes into account not only the qualifications of the employees, but also the ergonomic load of the workplace and the last occupancy of each employee. Significant improvements were shown in the areas of balanced distribution, qualification preservation, and fair allocation of workers to workstations when incorporating ergonomic aspects. A similar problem to the one studied in this paper exists in car wash machine manufacturing. In the work of März and Mielke (2020) the authors use a simulation-based optimisation approach to reduce excessive overload peaks for workstations by taking into account the availability and qualification of the workforce and using floater groups. An environmentally friendly way, by minimizing energy consumption, to schedule the use of multi-skilled workers while balancing the assembly line is studied by Liu, Liu, Chu, Zheng, and Chu (2021). The problem consists of scheduling products and assigning workers to jobs given a cycle time, and is solved using a bi-objective mixed-integer programming model, genetic algorithm, and simulated annealing. Hashemi-Petroodi, Thevenin, Kovalev, and Dolgui (2022) investigate the effects of model-dependent task assignment, workforce reconfiguration and equipment duplication in mixed assembly lines. By using model-dependent task assignment in a mixed-integer linear program, labour and equipment costs can be minimised compared to fixed task assignment and walking workers.

Since the company under study has three production lines on which the same activities can be carried out up to a certain point, there is also the possibility of product rotation to increase output. It also enables production systems to cope with fluctuating market demand or different product variations by taking advantage of flexible workforce and available capacities. Mak and Wong (2000) studied the design of a manufacturing system in the presence of uncertain demand and production quantities, consisting of several production lines, where each line is dedicated to the production of a number of products. Mathematical models for product grouping and resource allocation were developed and a genetic algorithm approach was also proposed. A model partitioning and clustering algorithm for determining the similarities between models and assigning them to different parallel assembly lines is introduced by Hazbany, Gilad, and Shpitalni (2007). Özcan, Çerçioğlu, Gökçen, and Toklu (2010) develop a simulated annealing approach for the parallel mixed-model assembly line balancing and model sequencing problem. The line efficiency is maximised and the workload is distributed evenly among the available workstations. Jiang et al. (2012) are the first to study multi-mixed-model assembly lines. They introduce order-based cooperative sequencing in MMMALs based on variable neighbourhood search and test it using an industrial case study in an automotive assembly plant. In addition to sequencing, they also consider variations in material consumption, assembly line setup costs, lead times, and also delivery times of individual orders. Öztürk, Tunali, Hnich, and Örnek (2013) simultaneously solve the problems of task assignment and model planning on parallel stations in mixed-model assembly lines. For this purpose, they develop a mixed-integer programming model and a decomposition scheme for large applications. A mathematical model for assigning orders to lines and sequencing is developed by Buergin et al. (2018). It takes into account mixed-model sequencing and level scheduling by monetarising the two criteria. The model is used to plan the production of the Airbus A320 family. Saif et al. (2019) present an order-oriented simultaneous sequencing and balancing problem of multi-mixed-model assembly lines with the objective of simultaneously minimizing the variations in material consumption, the maximum production span between different lines, and the penalty cost for the late models from different orders. For this purpose, a multi-objective artificial bee colony algorithm is presented and applied. Table 1 gives an overview of the application areas and objectives of the papers with real life relevance.

In the field of industrialised house building, only a few works deal with the concept of flexible production planning by using the available capacities of the production lines and the scheduling of employees. Bergström and Stehn (2005) examine the application of enterprise resource planning tools, their use and the operational and managerial benefits in industrialised housing. An enterprise resource planning system for a modular offsite construction production line is presented by Fan (2018). This is used to identify bottlenecks and streamline current processes to continuously improve the production process. The work by Grenzfurtner and Gronalt (2020) in the field of industrialised house building examines how the knowledge of the employees can be used in continuous improvement programmes and what needs to be adapted to facilitate this integration. Huka, Grenzfurtner, Zauner, and Gronalt (2021) present an application for capacity planning on mixed-model assembly lines. It is shown by means of real-time data input how the determined production times become increasingly precise and thus solutions of this model can be continuously improved. This enables better use of the production control system to release orders in production, making planning more realistic.

As shown in the paper by Huka et al. (2021), we use the increasingly precise recorded production times and analyse the potential for improvement in production planning for MMMAL. The identified research gap covers multiple aspects. Firstly, to the best of our knowledge, no published work exists in the domain of prefab production within industrialised housebuilding, which secondly, addresses product and job rotation for MMMAL in this specific domain.

Compared to the previous work in MMMAL, the focus here is not on the simultaneous sequencing of orders on the different production lines, but on the allocation of orders to the different lines and the scheduling of the available personnel at the individual workstations. The main contribution of the paper is to work out a set of iteratively defined scenarios to ensure an increase in production output. Based on the

Table 1
Review of the literature of applied problems, their field of application and focus.

Authors	Domain	Production system	Volume	Method	Goal
Cochran and Horng (1999)	Bike manufacturing	U-shaped line		Eight new dynamic dispatching rules	Assigning multitasking workers within a JIT production environment
Heike et al. (2001)	Airplane assembly	Mixed-model	Low volume	Linear and two nonlinear programming models	Evaluate cycle time with respect to labour and inventory holding cost; worker allocation problem under different cycle time alternatives
Gronalt and Hartl (2003)	Truck assembly	Serial line	Mid volume	Linear program	Minimise labour cost when solving loading sequence, worker allocation and floater time allocation
Cevikcan and Durmusoglu (2011)	Mixed-model tractor assembly line	Mixed-model	Mid volume	Two mathematical programming models solved sequentially and three heuristics	Minimise utility work time and utility work transfer
Jiang et al. (2012)	Automobile industry	Mixed-model on multiple assembly lines	High volume	Multi-objective optimisation algorithm based on variable neighborhood search methods	Minimizing material waviness and sequence dependent cost and lead times when scheduling orders
Buergin et al. (2018)	Aircraft manufacturing	Mixed-model	Low volume	Optimisation model with piecewise linear cost function	Minimising work overload when covering both assignment to lines and sequencing
Hochdörffer et al. (2018)	Automobile industry	Final assembly line	Mid volume	Allocation model based on integer linear programming	Staff scheduling problem in job rotation environment when preserving qualification and taking ergonomic aspects into account
März and Mielke (2020)	Car wash machine manufacturing	Mixed-model	Low volume	Simulation-based optimisation	Reducing overload peaks at workstations by forming floater groups and considering workforce availability and qualification

current production situation, scenarios with (i) job rotation (ii) product rotation and (iii) a combination of job and product rotation are evaluated.

3. Material and method

In the production of prefabricated houses, the individual walls are manufactured at the production site. A distinction is made between interior and exterior walls as well as special elements such as gable walls, ceiling and roof elements. The individual walls have different specifications, e.g., plastering, windows, doors, sanitary facilities and much more. On the construction site, the walls are put together like a jigsaw puzzle. Three lines are available for production, e.g., exterior, interior and special element line, which have individual workstations. Workers are assigned to these workstations according to their qualifications and requirements. Many different activities are carried out at these workstations with a production cycle time of about 40–45 min. Production takes place in two shifts, with the orders corresponding to the customer's wishes, which have to be fulfilled according to static and constructional aspects. The data relevant for production planning is generated in different ways, from the ERP system and REFA working time studies.

The prefabricated house manufacturer investigated produces individually planned houses according to the customer's request, whereby the customers are offered different selection options at the component, category, and product level. This means that customers can create a wide range of individual plans, such as the selection and positioning of designs such as plugs and switches, windows, doors, roller shutters and many additional designs and component variants based on standard components. Schoenwitz, Potter, Gosling, and Naim (2017) have already described how these options ultimately lead to a customised prefabricated house. Customised planning also means that every house and almost every wall is unique at the level of the wall element.

Although each house and wall is individual, the analysis of the houses produced in the data set provided by the industry partner shows that a general distinction is made between four house types depending on the roof form. In a typical production year, an average of 56 % hipped roof houses, 2 % monopitch roof houses, 17 % barrel roof houses and 25 % gable roof houses are produced. Sales figures from January 2017 to May 2019 are used to calculate the two relevant standard houses. A simplified assumption is made that 75 % hipped roof houses and 25 % gable roof houses are produced. For the calculation of the standard house "hipped roof", the nine best-selling hipped roof house types are evaluated, for the standard house "gable roof", the eight best-selling house types are evaluated. For each house type, the walls are sorted by ground floor or upper floor and by wall type category, since different activities are carried out at the individual workplaces. As mentioned earlier all walls in general are unique but can be classified in the following wall type categories: Exterior wall, interior wall, sanitary wall and jamb wall. For the standard house "gable roof" there are additionally knee wall, gable wall and gable roof wall. In a next step, the number of walls per category, the ratios of the wall types to each other in a standard house and the number and percentages of the designs per wall are calculated from past sales figures.

The general allocation of wall elements essentially results from certain designs and thus required activities (Bhatia, Han, & Moselhi, 2022), such as the installation of window elements or the application of full thermal insulation, which can only be carried out on the exterior wall line and the special element wall line but not on the interior wall line and vice versa. Thus, there are specifics regarding the execution of the activities for each of these lines. The interior wall line produces interior walls, the exterior wall line produces all exterior walls of hipped roof houses and ground floor exterior walls of gable roof houses and the special element line produces upper floor exterior walls of gable and hipped roof houses. In the current state of this production, there is already a small product rotation on the exterior wall line. Personnel is allocated to each workstation according to the requirement profile needed for the executed activities.

3.1. Modelling assumption and model formulation

We formulate a mathematical linear optimisation model to address the planning problems defined above. The model is used for the production planning of one year. Since the objective function is to increase output and there are no seasonal changes, the planning result can be extrapolated from one week's result. This leads to a planning horizon of one week with planning periods of one shift (27600 s). Each shift has different workforce. For the production of the prefabricated house wall types, the three production lines are available at one location. Demand is assumed to be given and is not subject to seasonality. Sequencing of walls or customer orders is not the considered in this paper. Preparation work that is not carried out on the production lines is not taken into account. The personnel employed have a certain requirement profile (prefabricated house builders, joiners, carpenters, electricians, mechanics, plumbers and machine operators, or unskilled workers) and each activity to be carried out requires a certain predefined requirement profile. The notation used for the various requirement profiles for the workforce is as follows:

- Prefabricated house builder (A)
- Joiners (B)
- Carpenters (C)
- Electrician (D)
- Mechanic (E)
- Plumber (F)
- Machine Operators (G)

However, skilled workers can also do unskilled work, but not vice versa. There is also the instruction from the investigated company that unskilled workers are utilised to the maximum and are never a bottleneck in production. All materials and raw materials are available just in time and machine maintenance or material shortages are not taken into account. In addition, complete standard houses must be produced with all the necessary walls.

The model of Huka et al. (2021) facilitates the assessment of the current situation and the scenario calculations. The input parameters were collected using documents and business processes from the industrial partner, data collection and time measurements conducted by the researchers in the plant, data comparisons with the ERP system and workshops with production planning staff. The notation used is listed in Table 2.

The aim of the mathematical optimisation model is to maximise production output, see objective function (1). That is, complete and finished work orders of standard house h, wall type w produced on the respective production line l in period t.

$$\sum_{h\in H}\sum_{w\in W}\sum_{l\in L}\sum_{t\in T} n_{h,w,l,t} \quad \rightarrow \quad maximize \tag{1}$$

$$\sum_{h\in H}\sum_{w\in W}\sum_{a_l\in A_l}\sum_{i_{h,w}\in I_{h,w}}\sum_{u\in U} n_{h,w,l,t}{}^{*}B_{h,w,l}{}^{*}P_{i_{h,w},u}{}^{*}M_{i_{h,w},u}{}^{*}O_{a_l,u}{}^{*}K_{a_l,q}{}^{*}B_{f_e,a_l} \leq C_{f_e,q,t} \quad \forall f_e \in F_e, q \in Q, t \in T \tag{2}$$

$$\sum_{h\in H}\sum_{w\in W}\sum_{a_l\in A_l}\sum_{i_{h,w}\in I_{h,w}}\sum_{u\in U} n_{h,w,l,t}{}^{*}B_{h,w,l}{}^{*}B_{s_l,a_l}{}^{*}P_{i_{h,w},u}{}^{*}M_{i_{h,w},u}{}^{*}O_{a_l,u}{}^{*}J_{a_l} \leq D \quad \forall s_l \in S_l, t \in T \tag{3}$$

$$\sum_{l\in L} n_{h,w,l,t} = V_{i_{h,w}}{}^{*}\sum_{w\in W}\sum_{l\in L} n_{h,w,l,t} \quad \forall h \in H, w \in W, t \in T \tag{4}$$

$$0.25^{*}\sum_{h\in H}\sum_{w\in W}\sum_{l\in l} n_{h,w,l,t} = \sum_{w\in W}\sum_{l\in L} n_{2,w,l,t} \quad \forall t \in T \tag{5}$$

$$\sum_{\tau=0..2|t-\tau>0} Y_{\tau}{}^{*}\left(\sum_{h\in H}\sum_{w\in W}\left(n_{h,w,l,t-\tau}{}^{*}B_{h,w,l}{}^{*}\sum_{i_{h,w}\in I_{h,w}} G_{i_{h,w}}\right)\right) \leq R_l \quad \forall l \in L|exterior\ \ wall\ \ \&\ \ special\ \ element\ \ line,\ \ t \in T \tag{6}$$

$$\sum_{h\in H}\sum_{w\in W}\left(n_{h,w,l,t}{}^{*}B_{h,w,l}{}^{*}\sum_{i_{h,w}\in I_{h,w}} G_{i_{h,w}}\right) \leq R_l \quad \forall l \in L|interior\ \ wall\ \ line,\ \ t \in T \tag{7}$$

In addition, the following constraints must be fulfilled. Constraints (2) ensure that the personnel capacity for each workstation f_e per floater group e with required qualification q in period t is maintained while producing the standard houses. For this purpose, the working time in workstation f_e with requirement profile q in period t is calculated on the left side of the constraints. This varies depending on how many finished work orders there are, on which line they are produced, the percentage of designs and wall numbers, how long the activities of the individual design take, how many employees are needed for the activity and whether the activity is carried out on this workstation or not. The next constraints (3) determine the available working time per period. The working time rendered on line l with activity a_l in period t is computed for this purpose. The number of completed work orders per standard house and wall type produced on line l in period t is multiplied with the allocation of wall to production line, percentage of designs per wall number and occupancy time for activities that cannot be carried out simultaneously with others.

To ensure the desired proportions of the individual wall types w for each standard house h and period t, the constraints (4) are needed. Constraints (5), on the other hand, guarantee the percentage distribution between hipped and gable roofs per period t (75 % hipped roof houses and 25 % gable roof houses, index 2). In addition, the wall storage of the outer wall and special element line must not be overloaded per planning period t. For this, the drying time of the plaster and thus the dwell time in the wall storage must be taken into account. The length of the walls in the wall storage is therefore limited in constraint (6) by the available length of the line l. 25 % of the factory plaster is two-tone and therefore has a longer drying time. Consequently Y_{τ} defines that all walls remain in the wall storage for at least two periods, but 25 % of the walls remain for one more period. Since no drying times have to be taken into account for the internal wall line, constraints (7) ensure that the wall storage capacity of the internal wall production line l is maintained. The left side of constraints (6) and (7) is the inventory level of line l in period t.

4. Computational experiments and results

In a first step, the current situation is evaluated with the model to validate it. Then, different scenarios are defined. Table 3 provides an overview of the configuration parameters of the production system, showing the size of the planning problem at hand.

The investigated IHB prefabrication plant produces two types of houses, which are manufactured on four production lines: EW, IW, SE, and the sanitary production line (SC). Only the first three lines are analysed in this study, as the sanitary completion line does not overlap

Table 2
Employed notation.

Indices	
$\boldsymbol{H}$	Set of standard houses h (hipped roof, gable roof)
$\boldsymbol{W}$	Set of wall types w (internal and external wall, flap tile upper floor, sanitation wall etc.)
$\boldsymbol{L}$	Set of production lines l (interior wall line, exterior wall line, special element line)
$\boldsymbol{T}$	Set of periods t
$\boldsymbol{U}$	Set of designs u (anchors, angles, empty pipework, window, sliding door, single socket, double socket etc. per wall)
$\boldsymbol{A_l}$	Set of activities a_l per production line l
$\boldsymbol{E}$	Set of worker groups e (unskilled and skilled employees like electrician and carpenter)
$\boldsymbol{S_l}$	Set of workstations s_l per production line l
$\boldsymbol{F_e}$	Set of workstations f_e per worker group e
$\boldsymbol{Q}$	Set of requirement profiles q
$\boldsymbol{I_{h,w}}$	Set of wall number $i_{h,w}$ per house h and wall type w
Parameters	
$\boldsymbol{B_{h,w,l}}$	Assignment, 1 if standard house h of wall type w is produced at line l, 0 otherwise
$\boldsymbol{B_{s_l,a_l}}$	Assignment, 1 if activity a_l is performed on workstation s_l, 0 otherwise
$\boldsymbol{B_{f_e,a_l}}$	Assignment, 1 if activity a_l is performed on workstation f_e, 0 otherwise
$\boldsymbol{G_{i_{h,w}}}$	Length of wall number $i_{h,w}$
$\boldsymbol{O_{a_l,u}}$	Occupancy time when carrying out activity a_l for respective design u
$\boldsymbol{P_{i_{h,w},u}}$	Percentage of designs u of wall number $i_{h,w}$
$\boldsymbol{D}$	Duration of shift (27600 s)
$\boldsymbol{K_{a_l,q}}$	Required number of employees for activity a_l with required job profile q
$\boldsymbol{J_{a_l}}$	1 if activity a_l can be carried out simultaneously with other activities, 0 otherwise
$\boldsymbol{C_{f_e,q,t}}$	Personnel capacity for workstations f_e with required qualification q in period t
$\boldsymbol{M_{i_{h,w},u}}$	Number of designs u per wall number $i_{h,w}$
$\boldsymbol{R_l}$	Storage capacity for production line l
$\boldsymbol{V_{i_{h,w}}}$	Proportion per wall number $i_{h,w}$
$\boldsymbol{Y_\tau}$	Percentage in storage from (three previous) periods τ (1, 1, 0.25)
Variables	
$\boldsymbol{n_{h,w,l,t}}$	Number of completed work orders of standard house h and wall type w on production line l in period t

with the other lines since sanitary completion is performed after the prefabrication of elements on the aforementioned lines. Depending on the house type, there are different numbers of wall types manufactured at a total of 29 workstations. The analysed scenarios feature varying worker group compositions, resulting in differing group quantities. For instance, the third scenario comprises a single large pool of workers. Additionally, there are varying numbers of requirement profiles. The last line of the table shows the average number of activities per employee group as well as the number of activities to be carried out, as

Table 3
Size of the input parameters used, broken down into the individual scenarios.

	Optimized actual solution	Scenario 1	Scenario 2	Scenario 3
# standard houses	2 (gable roof and hipped roof)			
# production lines	3 + 1 (EW, IW, SE and SC)			
# wall types	12 (gable roof)/9 (hipped roof)			
# worker groups	27	24	27	1
# workstations per production line	14(EW)/9(IW)/4(SE)/2(SC)			
# requirement profiles	59	52	59	6
Average # activities per worker group	23(EW)/11 (IW)/15(SE)/ (SC)	23(EW)/12 (IW)/24 (SE)/(SC)	24(EW)/14 (IW)/15 (SE)/34(SC)	215(EW)/ 194(IW)/ 122(SE)/34 (SC)

there is only one group in scenario 3. Additionally, Fig. 2 shows graphically the individual scenarios and what changes compared to the status quo. First, the current situation is assessed using the model. In scenario 1, workers can switch between the three production lines, but also between the individual predefined workstations of their current production line. This is shown by the arrows which display shift of floaters, workers and walls to different lines and workstations. The qualifications of the workers and the requirements of the activities at the individual workstations are taken into account. In scenario 2, the interior walls are produced on the other two available production lines to avoid bottlenecks. In addition, exterior walls can also be shifted to the special element line. In the last scenario, scenario 3, the two previous scenarios are combined. All the scenarios considered were built in close cooperation with the operations management team and it got more familiar with the applied procedures.

The ability to solve all the scenarios presented with the exact same model is the sophistication of the model presented. The only thing that changes in each scenario is the data. Specifically, for scenarios 1 and 3, the number and composition of floater groups changes. This, of course, affects the assigned workstations per floater group. These two changed indexes lead to changes in the following parameters: new activity to workstation assignment (depending on floater group) and adjusted capacity per workstation (per floater group), qualification profile and period. If the existing product rotation is extended, scenario 2 and 3, only the parameter that defines the assignment of the standard house and wall type to the production line changes. Of course, within the limits of what is technically possible, the change was made in consultation with the company under study. For the production of the individual wall types, all necessary activities must be feasible on the newly assigned line. This means that the workforce does not have to change either, as the activities are already carried out.

Note that the computations are conducted using FICO Xpress for the optimisation whereby the standard settings of Xpress 8.14 have not been changed and no tuning is investigated. The optimisation terminates by generating the optimal solution after a few seconds. The number of constraints ranges from 500 to 960, depending on the scenario, while the number of decision variables for the analysed problem ranges from 30 to 450, again depending on the scenario.

4.1. *Optimised actual situation*

The mathematical model is validated with the actual situation and the result critically scrutinised and checked for feasibility. Compared to the actual production data of 702 houses per year, 901 houses can be produced annually through the optimal use of resources. However, this assumes ideal production without interruptions, machine breakdowns, full staffing, etc. Compared to the real production data, however, this value corresponds to the peak production output actually achieved. Furthermore, the decision makers of the prefabricated house manufacturer validated and verified the results. Therefore, a valid model can be assumed. During production, bottlenecks can occur at the workstations with regard to working time due to activities that cannot be carried out simultaneously of the walls to be produced and the personnel deployed at the individual stations.

The utilisation rates and bottlenecks regarding the assembly stations of the individual production lines can be seen in Fig. 3.

For the assembly stations, one can see here that the bottleneck of the entire production in the case of the status quo is on the eighth assembly station of the exterior wall line for both production shifts. According to the work instruction, unskilled workers can be utilised to the maximum. Therefore, we focus the evaluation of staff bottlenecks on skilled workers, which is shown for the status quo in Fig. 4.

Here we see that another bottleneck occurs in the first shift for the requirement profile of prefabricated house builders and carpenters on the interior wall station five. In summary, the exterior wall line at workstation 8 has its bottleneck in terms of activities that cannot be

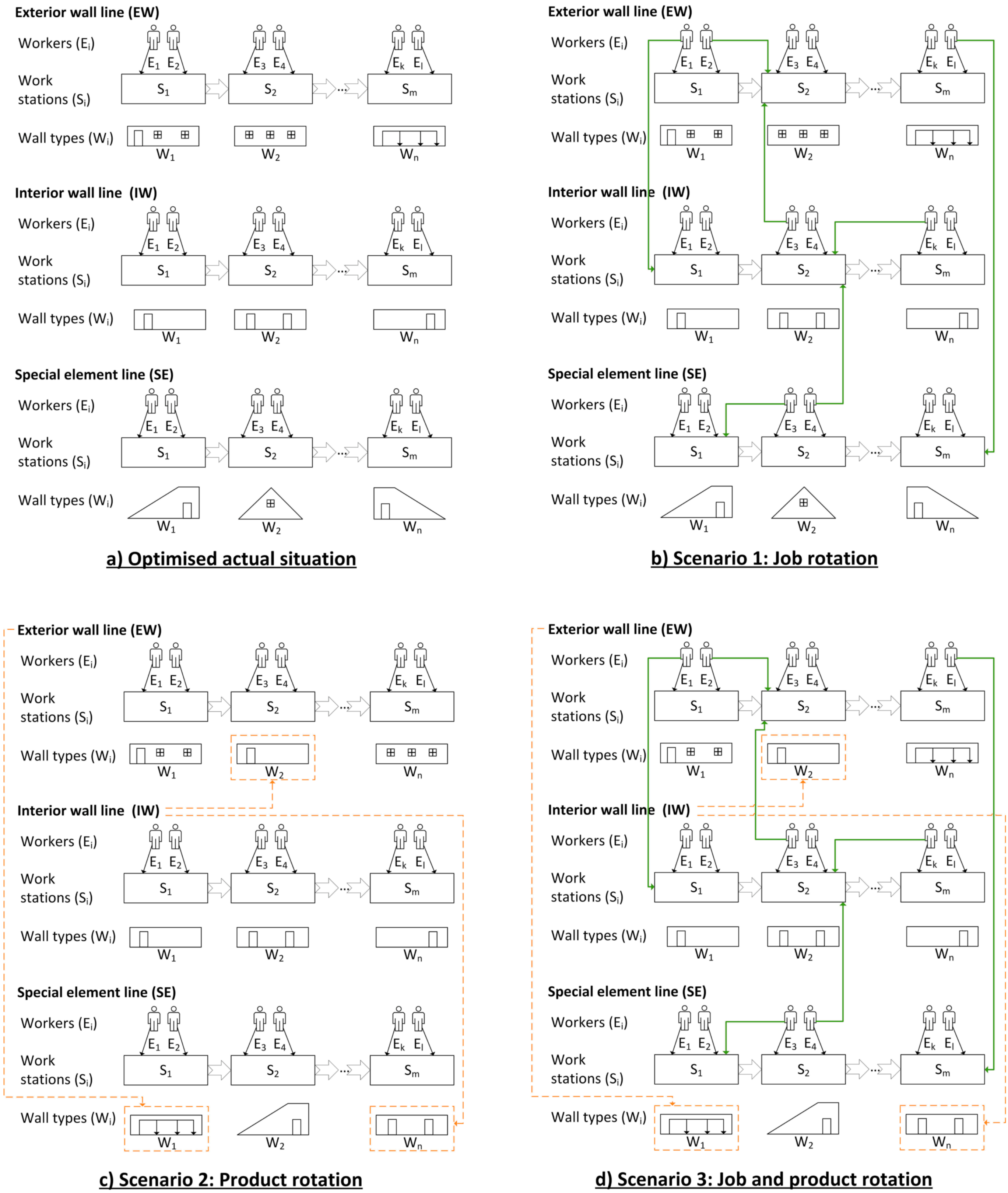

Fig. 2. Graphical representation of the individual scenarios and what is analysed in the process.

carried out simultaneously. However, by making the production system slightly more flexible, the exterior walls can also be produced on the special element line, which is not working on full capacity. This bottleneck is therefore not a bottleneck of the overall system. The bottleneck that limits the overall capacity of the production system is at the interior wall workstation five. In the status quo scenario, the production system can therefore produce 1.46 hipped roof houses and 0.49 gable roof houses per shift, which amounts to about 901 standard houses per year.

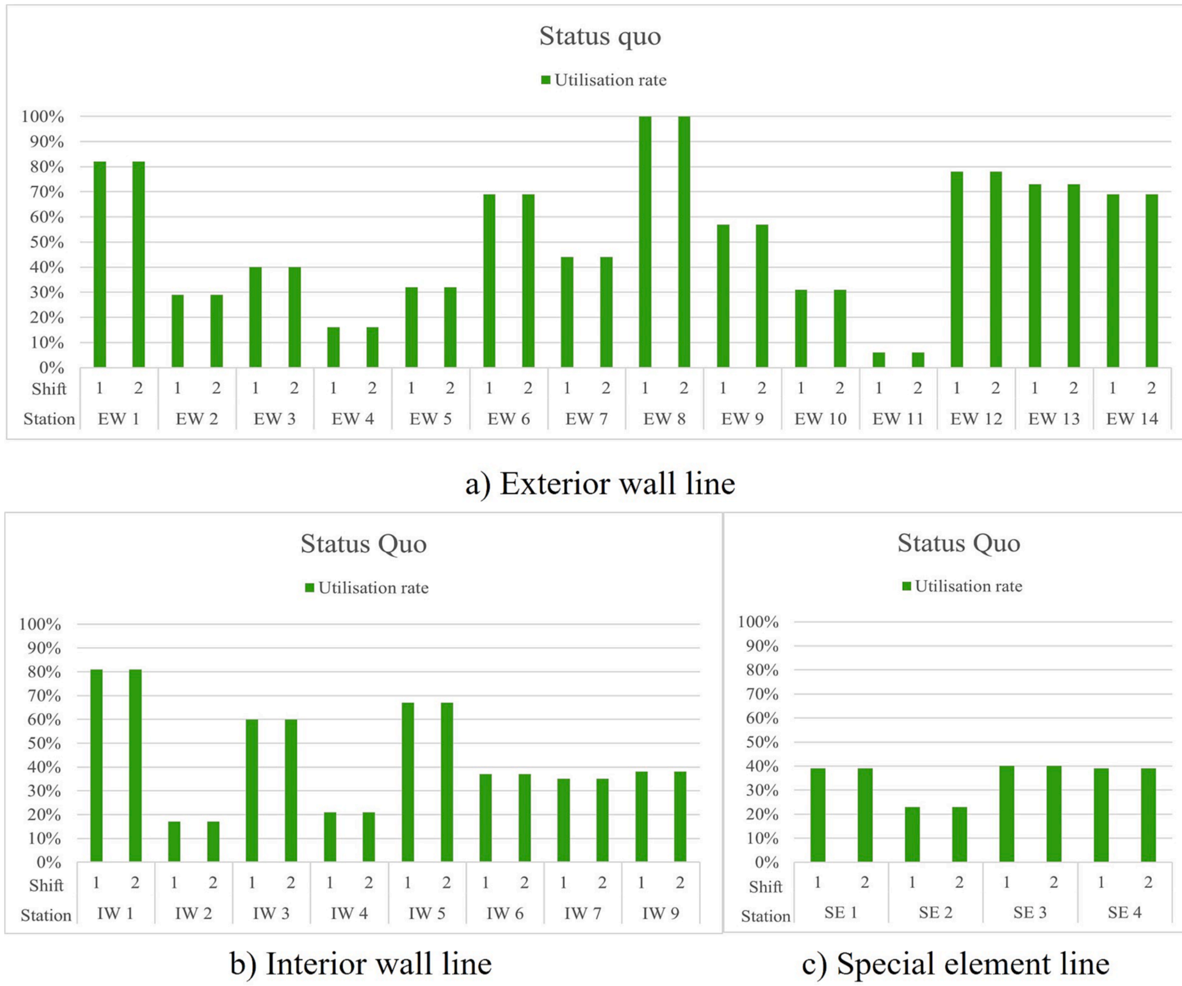

Fig. 3. Utilisation levels of the individual assembly stations in the two shifts of the three production lines.

4.2. Scenario 1: Floater groups

For the first scenario calculation, floater groups are formed in which each worker of a group can take over the activities of another group member if necessary. In the actual state, workers are assigned to workstations according to their qualifications. For this purpose, there are 22 groups corresponding to the number of individually distinguished workstations. The floater groups are assigned to grouped workstations, where the total number and the required qualifications of the workers do not change, but the responsibilities of the floaters and accordingly their activities expand. There is a total of 17 of these floater groups in scenario 1, which are made up of, for example, prefabricated house builders, carpenters, machine operators and unskilled workers or electricians and unskilled workers. For example, on the interior wall line, workstations 3, 5 and 6 are combined and assigned to one floater group, as can be seen in Figs. 4 and 6. All of these stations require prefabricated house builders and joiners for the activities to be performed. Compared to the status quo, where eight worker groupings are needed for production on the interior wall line, scenario 1 only allocates five floater groups. However, the tasks of the individual stations remain the same, only the scope of tasks of the floater groups has expanded according to their area of responsibility.

In this way, longer working hours can be saved, idle personnel resources can be used and the utilisation of resources can be shared. The groups are assigned to the different available workstations of the three production lines. For the differently defined floater groups a new notation is introduced for the calculation, which can be found in Table 4.

Compared to the model presented above, only the groupings of worker and the associated parameters change. In the introduced model, a distinction is made between skilled and unskilled workers, with further subdivisions into electricians, prefabricated house builders, plumbers, carpenters, bricklayers and woodworkers, while in the job rotation scenario several differently composed groups are formed. The changes are therefore all implemented on the data side and the model does not need changing. With this adjustment, the production output of standard houses (divided into the previously defined percentages) can be increased to 1058 per year. The utilisation of the individual workstations of the three production lines can be seen in Fig. 5.

The bottleneck that was already present in the status quo on workstation eight of the exterior wall line could not be eliminated by this scenario. It is still one of the limiting workstations in both shifts. However, another one has occurred on the fourth workstation of the special element line in the first production shift. The next Fig. 6 shows the utilisation rates of the deployed personnel in the two shifts for each workstation.

The new grouping of the workstations into floater groups allows the personnel bottleneck on the interior wall line to be overcome. The improvement in throughput in this scenario is clearly evident in the special elements line. Staff utilisation increases at each workstation. A bottleneck occurs at station three in the second shift. However, this is due to the fact that there are no unskilled workers in the second shift and the skilled workers here also have to take over all the unskilled work.

As in the basic scenario, there is a bottleneck at the exterior wall line at workstation eight in both shifts. In addition, there is a new bottleneck

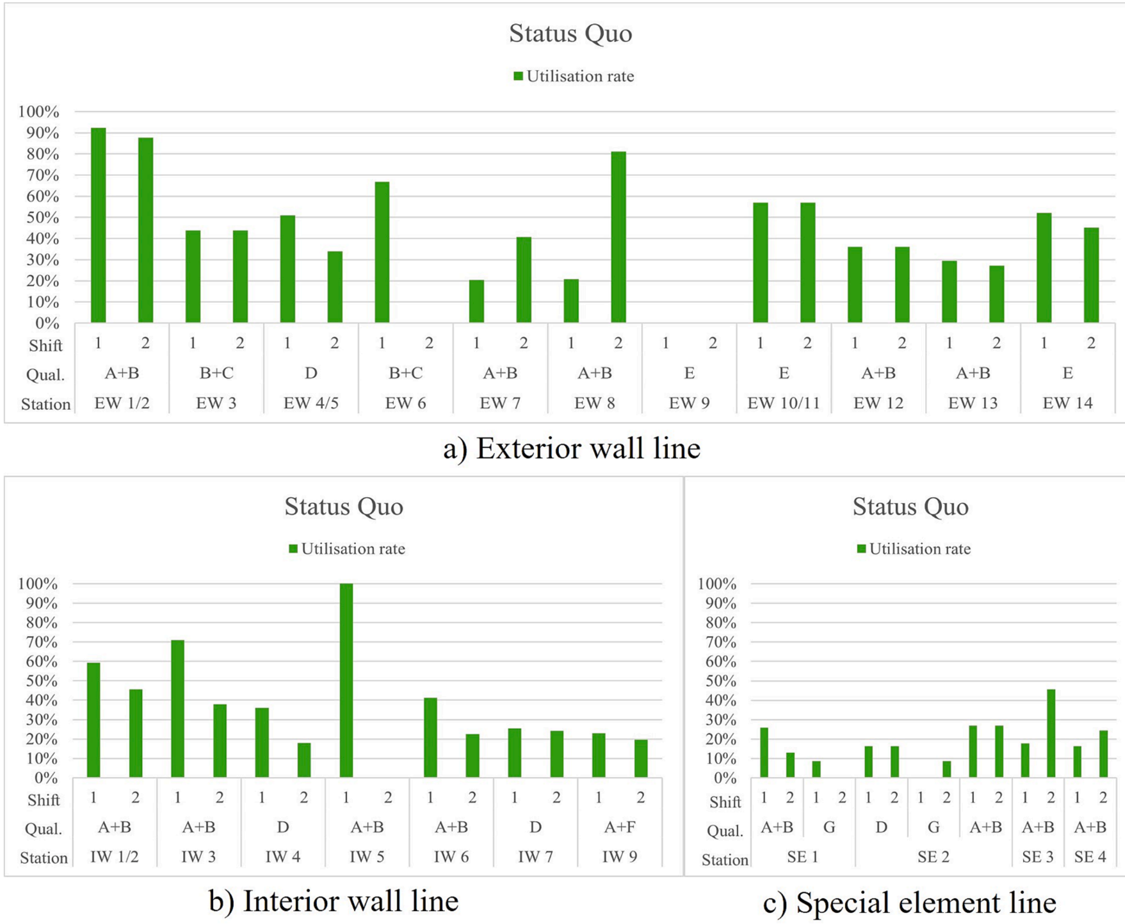

Fig. 4. Utilisation of the deployed skilled workers with different qualifications on the individual workstations in the two shifts of the three production lines.

Table 4
Changed notation for scenario 1.

Indices	
E'	Set of floater groups e' that can move within and between the three production lines (one group can contain unskilled and skilled workers)
$F_{e'}$	Set of workstations $f_{e'}$ per floater group e'
Parameters	
$B_{f_{e'},a_l}$	Assignment, 1 if activity a_l is performed on workstation $f_{e'}$, 0 otherwise
$C_{f_{e'},q,t}$	Personnel capacity for workstations $f_{e'}$ with required qualification q in period t

at workstation four of the special element line in the first shift. This is where the windows are installed and the bottleneck arises with regard to the activities that can be carried out simultaneously at this assembly station. The restrictive bottleneck of the initial scenario at the interior wall line can be solved by introducing floater groups and the work instruction that employees can switch between workstations within the respective team if necessary. As a result, throughput can be increased and the personnel bottleneck shifts to workstation three of the special element line in the second shift.

In scenario one, 1.73 hipped roof houses and 0.58 gable roof houses can be produced in the first shift and 1.70 hipped roof houses and 0.57 gable roof houses in the second shift. In summary, this means an increase in production of 18 % on average compared to the status quo and approx. 1058 standard houses can be produced annually.

4.3. Scenario 2: Product rotation

In the second scenario, the product rotation is expanded compared to the current production standard, influencing the assignment parameter $B_{h,w,l}$, indicating if standard house h of wall type w is produced at line l.

To overcome the bottleneck on the interior wall line, these are partly produced on the exterior wall line or special element line. It is also possible to produce ground floor exterior walls of gable and hipped roof houses on the special element line. This means that, compared to the initial situation, entire hipped and gable roof houses can now be produced on the special element line. Since the two production lines, exterior wall line and interior wall line, do not differ significantly up to a certain workstation and the production of exterior walls on the special element line is also possible, the effort and costs for set-up of the lines can be neglected (see Rajasekharan and Peters (2000)). Even the premature ejection of the interior walls from the production lines after completion is possible without any problems and does not pose an obstacle.

With this scenario the bottleneck in shift one on the workstation eight of the exterior wall line can be overcome, see Fig. 7. The limiting assembly stations are station eight of the exterior wall line for the second shift, station one of the special element line in both shifts and station four of the special element line in shift one.

In this scenario, a new bottleneck occurs at workstation 1/2 for the exterior wall line in shift one, see Fig. 8. The staff utilisation on the interior wall line hardly changes and the bottleneck on station five in shift one remains. As in scenario one, a personnel bottleneck occurs on workstation three in the second shift of the special element line.

In summary, several bottlenecks occur at different points in this

Fig. 5. Utilisation levels and the change compared to the status quo at the individual assembly stations in the two shifts of the three production lines when using groups of floaters.

scenario. At the exterior wall line, the assembly station eight is only fully utilised in the second shift, whereby the special element line tries to counteract here until it is also fully utilised in both shifts at station one and in the second shift at station four. There are also various bottlenecks in terms of personnel. The first bottleneck, as already observed in the baseline scenario, concerns the interior wall line at workstation five. By introducing a product rotation, the production of the interior walls is divided between the exterior wall line and the special element line until the maximum staff utilisation is also reached on these production lines, namely in the first shift at workstation 1/2 of the exterior wall line and in the second shift at workstation three of the special element line.

In scenario two, 1.70 hipped roof houses and 0.57 gable roof houses can be produced in the first shift and 1.68 hipped roof houses and 0.56 gable roof houses in the second shift. In summary, this means an increase in output of 16 % on average compared to the baseline scenario and a total annual output of approximately 1042 standard houses.

4.4. Scenario 3: Job and product rotation

For the third and final scenario, the two previously described scenarios are combined and evaluated together. The employees are divided into different groups as described above in scenario one, with modification of the mathematical model on the data side described in Table 3. As explained in scenario two, interior walls can now be produced on all lines and additionally exterior walls on the special element line, influencing the assignment parameter $B_{h,w,l}$ as described in Section 3.3. This leads to an increase in production to 1086 standard houses per year. The bottlenecks on the workstations with these two scenarios combined can be seen in Fig. 9.

As shown in Fig. 9, these changes result in workstation eight of the exterior wall line and station one of the special element production forming a production bottleneck in both shifts. On workstation 7 at the exterior wall line the utilisation can be reduced by 4 %.

In Fig. 10, the bottleneck for skilled workers for the three production lines and two shifts can be seen. In order to increase production and

Fig. 6. Percentage usage and change compared to the status quo of skilled workers with different qualifications employed at the individual workstations in the two shifts of the three production lines when using floater groups.

overcome the staff shortage, additional skilled workers are hired. In particular, at workstations six, a skilled worker qualified as a prefabricated house builder and carpenter is needed in the second shift, and at stations seven and nine, an electrician is hired in the exterior wall line in both shifts. At the interior wall line at station five, an electrician is needed in both shifts and at the special element line at station one, a machine operator is needed in the second shift and at station two, an electrician is required in the first shift. Since none of the respective employees in the status quo scenario existed in these cases, there is also no change to the status quo in Fig. 10. On the other hand, one less qualified worker is needed on the interior wall line station five in the first shift.

In summary, it can be seen that in this scenario, as in the initial state, the exterior wall line at workstation eight has a bottleneck with regard to the activities that cannot be carried out simultaneously. Due to the flexibilisation, exterior walls as well as interior walls are also produced on the special element line. This means there the workstation one is also fully utilised.

Across the entire production system, the company requires an average of 65 % of skilled prefabricated house builders and carpenters, 67 % of electricians, 47 % of bricklayers, 90 % of prefabricated house builders and plumbers and 80 % of machine operators for minimum staffing at maximum utilisation rate, which is less than the number assigned in the initial state. However, the production company shall increase the unskilled workers by an average of 7 % at a realised maximum utilisation rate.

By combining job and product rotation, 1.76 hipped roof houses and 0.59 gable roof houses can be produced in both shifts. Overall, this means an increase in production of 54 % on average compared to the actual situation and approximately 1086 standard houses can be produced annually.

5. Discussion

In recent years, research has begun to identify the importance of MMMAL for industry including the need to develop planning models for these specific use cases (Jiang et al., 2012; Saif et al., 2019;). For example, multiple production lines with the same or similar capabilities are often located at the same IHB production site (Segerstedt & Olofsson, 2010), with insufficient joint resource allocation across lines. In order to better utilise the available resources and increase productivity for multiple lines, new planning problems arise, which we have been considered in our capacity planning model. One contribution of our model is that it enables capacity planning on a tactical level using job

Fig. 7. Utilisation and the change compared to the status quo at the individual assembly stations in the two shifts of the three production lines for working time in the expanded product rotation scenario.

and product rotation within and between production lines. By using the model, practitioners receive a basis for decision-making to better control the allocation of employees to the workstations on the different lines as well as the allocation of the different wall elements. This will enable an increase in productivity and efficiency for MMMAL. The approach is thus a simple and cost-effective solution that allows to increase MMMAL's productivity and efficiency without the need to invest in new technologies. This expands previous research on MMMAL by adding the aspect of capacity planning using job and product rotation, which has not yet been addressed.

This paper further demonstrates the opportunity to apply a job and product rotation approach in capacity planning of MMMAL, to increase productivity of the lines. Table 5 summarises the individual scenarios and the production increase compared to the status quo. By introducing floater groups in scenario 1, the original bottleneck of the interior wall line can be shifted. As a result, 157 more standard houses can be produced than in the optimised actual situation. The new bottlenecks are on the exterior wall and special elements lines. As a result, the production of interior walls is no longer limited, but the production of exterior walls is.

In scenario two, an attempt is made to increase output by introducing product rotation. Compared to scenario 1, 16 standard houses less can be produced per year, as the personnel bottleneck on the interior wall line remains. But 141 houses more than in the optimised actual situation and 340 more than with the actual situation can be manufactured. The last scenario combines the previous two and introduces both newly formed floater groups and product rotation. The highest utilisation rate for staff is assumed. This allows the minimum staffing per workplace to be determined. On average, about 70 % of the skilled staff can be saved, but 7 % more unskilled staff must be employed. With these adjustments, the theoretical annual production of standard houses can be increased by more than half compared to the current situation. In this scenario, there is no staffing bottleneck on any of the three production lines; the bottleneck is now the assembly stations on the exterior wall and special element line in both production shifts.

Table 6 gives an overview of the changing bottlenecks for the

Fig. 8. Utilisation rate and change compared to the status quo of skilled workers with different qualifications employed at the individual workstations in the two shifts of the three production lines when applying an extended product rotation.

examined scenarios in the two production shifts. Since in scenario three the number of skilled staff is variable, there is of course no personnel bottleneck here. Consequently, this paper demonstrates how the coverage of job and product rotation in the planning of MMMAL contributions to a more balanced flow within the lines as well as to an increase of productivity.

The presented planning approach discloses the sleeping production capacities in prefabricated house assembly lines. Our approach allows us to consider system bottlenecks rather than analysing production lines separately. It shows how the production output can be increased considerably by applying effective worker and floater scheduling and by using production line flexibilities in advance. Instead of investing in more advanced and expensive production facilities this approach shows how production output can be increased without or with only a few adaptations in the production line. This is a further contribution of this paper, as it demonstrates the ability to better use available production. Consequently, lots of companies will be capable to shift investments but at the same time increase the output of existing MMMAL.

In addition, the required skills and the number of workers and floaters is addressed by this approach which leads to a well-considered number of workers needed. Previously, the planning of the skilled workforce among different workstations has been addressed for single and parallel mixed-model assembly line settings but not for MMMAL settings. However, this approach is also very promising for MMMAL, as a reduction of skilled workforce can be achieved. Many companies have to deal with understaffing of skilled workers due to difficult labour market conditions, this will enable practitioners to easier fulfil demands on the labour market, without having negative effects on the production output. The actual implementation of workforce planning naturally places considerable demands on operations and should therefore be carefully prepared in further detail. Still to be solved is how these results are used on a regular basis.

The results show the importance of (1) level work force planning, (2) workforce scheduling and (3) skills management for factory operation. The developed approach can be applied also to other low volume and manually operated MMMAL (e.g. trucks, aircraft equipment, tractor).

6. Conclusion

This paper investigates job and product rotation to maximise production output of MMMAL within IHB prefabrication plants by using a linear optimisation model. The model developed was tested based on

Fig. 9. Utilisation and the change compared to the status quo at the individual assembly stations for the two shifts of the three production lines in the combined job and product rotation scenario.

real life production data, provided by an IHB prefabrication plant with three production lines: an interior, an exterior and a special element line. During production, depending on the wall type to be produced (basement, upper floor, sanitary wall, exterior wall, interior wall, etc.), the elements pass through the workstations along a production line, to which skilled and unskilled workers are assigned. To test the new production planning approach, two standard houses were calculated from several house types using past production data, thus validating the mathematical model presented. In the optimised status quo situation, the production capacity is fully utilised, which corresponds to peak times of real production. These results were examined and verified with the management of the prefabricated house manufacturer. In three further scenarios, it is shown that production capacity can be increased without large investments by forming and allocating floater groups and expanding the already existing small product rotation. Furthermore, the two scenarios are also combined into a third. Here, more than 50 % output increase can be achieved per year compared to the initial situation, and the existing bottleneck of the interior wall line in shift one could be eliminated, as the production of interior walls is shifted to the exterior wall and special element line. It should also be noted that in this case 70 % of skilled workers can be saved and 7 % more unskilled workers are needed. For optimal implementation, lines should be operated in a way that facilitates the flexible use of workers at various stations.

The contribution of this paper is that it shows the improvement potential in production planning for MMMAL through the application of job and product rotation. IHB companies will be enabled to increase their productivity, and consequently their competitiveness without cost intensive investments.

Despite its advantages, this approach has certain limitations. It assumes a static underlying product structure and process plans, allowing job rotation to the maximum extent possible. It also assumes that there will be no line or station changes for workers within a planning period and imposes no restrictions on material or tooling provision. It does not take into account differences between shifts and does not consider the greater existing variety of products.

The linear optimisation model was adapted based on data from one distinct manufacturer, however in its general form it is applicable to other IHB MMMAL using both similar production technologies and prefabrication levels. In the next step, the model presented is tested with a sensitivity analysis. Not only is a changed distribution of employee qualifications analysed, but also the effects of a varied distribution of house types. Future research will focus on concrete order or wall sequence planning for the three production lines. This requires a

Fig. 10. Degree of utilisation and change compared to the status quo of the workstations in the two shifts of the three production lines for the deployed skilled personnel with different qualifications when applying job and product rotation.

Table 5
Result of the individual scenarios in terms of standard houses produced per year and comparison of the output increase in relation to the actual state.

Scenario	Description	# of standard houses per year	Increase
Actual situation	Historical production data	702	–
Actual situation	optimised	901	28.35 %
Scenario 1	Job rotation	1058	50.71 %
Scenario 2	Product rotation	1042	48.43 %
Scenario 3	Product and job rotation	1086	54.70 %

Table 6
Personnel and space bottleneck on the individual workstation of the three production lines for the different scenarios in the two shifts.

	Personnel bottleneck		Workstation bottleneck	
Scenario	Shift 1	Shift 2	Shift 1	Shift 2
Optimised Status Quo	IW 5		EW 8	EW 8
Scenario 1		SE 3	EW 8, SE 4	EW 8
Scenario 2	EW 1/2, IW 5	SE 3	SE 1, SE 4	EW 8, SE 1
Scenario 3			EW 8, SE 1	EW 8, SE 1

detailed real-time data model. Not only the sequence of the wall types of an order, but also the mix of production orders will be investigated. In addition, the entire production will be mapped using a digital twin to enable reactive and data-driven production planning. An important future extension of the existing model is the addition of the required preliminary work and its reconciliation with the actual planned production. Furthermore, a next step is to investigate how seasonal demand affects production and workforce planning, as the construction sector in particular is driven by seasonal demand.

Alternative line configurations and the use of bypass stations will also be considered. Another way to continue our research efforts is to better incorporate sequence dependencies of activities in our analysis and to carry out a more detailed workload analysis of drying stations. The results of this paper can be expanded and made more general by considering other and alternative production line configurations and production planning principles in industrialized housing construction.

CRediT authorship contribution statement

Maria A. Gartner: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Data curation, Formal analysis, Investigation, Validation, Visualization. **Wolfgang Grenzfurtner:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Barbara Zauner:**

Conceptualization, Investigation, Methodology, Validation. **Manfred Gronalt:** Formal analysis, Funding acquisition, Methodology, Resources, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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