Volume 15 • Issue 3 • 2023

ENGINEERING MANAGEMENT IN PRODUCTION AND SERVICES

sciendo

ISMSME
International Society for Manufacturing, Service and Management Engineering

received: 15 November 2022
accepted: 15 May 2023

pages: 27-41

# MULTI-SKILLED WORKFORCE SCHEDULING WITH TRAINING AND WELFARE CONSIDERATIONS

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ABSTRACT

Flexibility in workforce scheduling in services is necessary to reduce the impact of demand uncertainty, absenteeism, and desertion while maintaining high service levels. This paper studies the workforce scheduling problem, including multiple skill accumulation, training, and welfare, as well as flexibility for employees and the company. All these elements are modelled and included in a mixed-integer linear programming (MILP) model that maximises their accumulated skill level. A real case study based on the scheduling of lab assistants to laboratory practices at a university in Colombia is used to generate numerical experiments. Different experiments were conducted, and the results show that the level of skill achieved is highly sensitive to the number of assistants and the number of allocations. The experiments also showed that, while keeping the same number of lab assistants, it is possible to include flexibility and welfare constraints. Finally, the proposed model can generate schedules that achieve high levels of skills and meet the different constraints of the model, including balance, accumulation, demand and welfare.

KEY WORDS
**flexibility, multiskilling, workforce scheduling, training, optimisation**

**10.2478/emj-2023-0018**

## INTRODUCTION

A key feature of the current economy is the rapid growth of the service sector, which is labour-intensive, e.g., hospitals, airlines, call centres, education centres, restaurants, etc. In the long term, companies aim to find the right balance between using as little labour as possible while maintaining a high level of service. However, in the short term, the levels of hired staff are difficult to adjust; therefore, management efforts are focused on the efficient assignment of shifts and activities to each employee (Cuevas et al., 2016). In addition, qualitative aspects should be considered,

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Peña, D. A., Osorio, A. F., Orejuela, J. P., & Idarraga, J. C. (2023). Multi-skilled workforce scheduling with training and welfare considerations. *Engineering Management in Production and Services, 15*(3), 27-41. doi: 10.2478/emj-2023-0018

such as the welfare, happiness and equity of employees, as well as rules and regulations in each country. These aspects impose strong restrictions on employee allocation, making the problem attractive from an academic point of view (Ağralı et al., 2017). Furthermore, the variability and seasonality of demand are inherent characteristics of many types of services, generating the need to adjust the number of employees accordingly (Henao et al., 2016).

However, the use of labour scheduling to reduce overstaffing and understaffing in the service industry is often undermined by a lack of flexibility due to the exclusive use of specialised employees (Henao et al., 2015). Therefore, training plans must be considered and included in the labour schedule. Multiskilled workers not only add flexibility at the moment of planning but also help to reduce the negative effects of demand uncertainty and absenteeism (Henao et al., 2016). Developing and accumulating employee skills through a training plan can also improve employee satisfaction, as it can be seen as professional growth.

It is common for labour-intensive companies to face situations where employees are dissatisfied with their shift schedules, either due to the allocation of time slots or imbalances in workload compared to other workers. In the case of companies, there are difficulties in building shift schedules to cope with increased demand or cases of absenteeism. These difficulties are caused by the lack of flexibility of employees to perform various tasks within the company, or the company does not have the time or resources to train staff or hire more people. Training and scheduling are not commonly considered simultaneously. This can lead to situations such as:

- An imbalance in the time and number of activities performed by employees leads to difficulties in the work climate and, in some cases, costs associated with overtime.
- Training is not aligned with the assignment of activities. These two objectives are not addressed simultaneously (assignment of activities and training), which hinders the learning processes of new employees and leads to a concentration of competencies on the part of more experienced employees.
- Imbalance of skills due to the lack of polyvalence of all employees and the concentration of dependence on a few employees.
- Inflexible assignment schemes.
- Probability of underestimating or overestimating the number of employees needed.

To improve the aforementioned situations, this study investigated the workforce scheduling problem, including training and welfare considerations. The most common objective in this type of problem is the minimisation of costs, usually represented in labour costs, while meeting demand. However, the approach in this work is different. While demand must still be satisfied, the objective is to schedule shifts considering such aspects as training. It is important to highlight that the model can be easily adapted to other objective functions, such as minimising costs to achieve certain levels of skills while also meeting demand.

This paper considers the flexibility in services through the inclusion of such aspects as skill accumulation to achieve greater availability of employees to perform different types of tasks. This is achieved through experience gained through the execution of tasks by trainees and the training process by expert personnel (trainers), as well as workload balancing to improve the labour environment. This study refers to two types of flexibility: for companies, by having more qualified personnel available to perform different tasks, and for workers, by being increasingly qualified, it is possible to obtain a more balanced workload and even be available for personal matters.

In the case study addressed in this article, laboratory assistants are assigned to different laboratory practices in a university, where they instruct the students on their correct development. Lab assistants must hold a bachelor's degree in a specific area (chemistry, pharmaceutical chemistry, or biology) as well as a certain level of knowledge to operate specialised equipment, depending on the type of practice. The assistants with the appropriate background and higher skill levels can conduct more lab practices. This feature should be considered at the moment of planning since it can generate flexibility in assigning assistants to several practices in different time slots.

Based on the above elements, it is expected that the development of the methodology will contribute to a practical solution to the problem. This research answers the following questions:

- How to optimise the workforce scheduling in a services sector considering training and welfare considerations?
- Is it possible to improve the skill accumulation of employees while meeting demand?

Therefore, based on the literature review, the contributions of this work to the field of knowledge can be summarised as follows:

- Accumulation of skills when a lab practice is carried out. This accumulation applies to trainers and trainees.
- Consideration of two types of skills: those that improve with training or execution and those that remain invariant.
- Flexibility is included for both the organisation and the employees simultaneously.
- A novel MILP that seeks to improve and level the skills of the lab assistants.

The remainder of the article is organised as follows. Section 2 surveys the literature on Labour Scheduling Problem (LSP), skill accumulation and welfare. Section 3 introduces a MILP model for an LSP with skill accumulation, training, and welfare considerations for predefined time slots. Section 4 defines a case study for lab assistants scheduling to develop practices for the Biology, Chemistry, and Pharmaceutical Chemistry programmes in a university. Section 5 describes the experiments performed to evaluate the assignment of lab practices, skills accumulation, and lab assistant training under different conditions. Section 6 presents the results obtained. Finally, Section 7 submits the conclusions and provides suggestions for further research.

## 1. Literature review

### 1.1. LSP

The LSP, also known as the employee scheduling problem and workforce scheduling problem, has been widely studied in operations research since Edie (1954) and Dantzig (1954). Orejuela et al. (2014) defined the LSP as the planning of shifts for employees while satisfying multiple factors, such as the company, employees, legal regulations, and demand requirements. This paper presents the LSP as the problem of assigning employees with different levels of skill to different tasks that require minimum skill levels while satisfying restrictions.

Different aspects of the LSP have been studied. Moreno and Montoya (2016) gave a review on workforce scheduling, classifying papers by the solution tools, the problem objectives, the characteristics of the workforce, the type of shifts, and the demand type. They also classified the workforce as homogeneous or heterogeneous. Homogeneous labour considers that employees have the same level of skill and are the same type of workforce (Al-Yakoob & Sherali, 2008; Jarray, 2009; Ni & Abeledo, 2007; Rocha, Oliveira, & Carravilla, 2014). On the other hand, heterogeneous labour considers different types of employees. In a paper by van der Veen et al. (2015), employees were considered with different skill sets and different contract types, while Goodale and Thompson (2004) considered individual employees with different productivity levels. Karam et al. (2017) developed a model where the skill of the workers is measured by their efficiencies and, thus, affects their execution times of the tasks. More examples of the heterogeneous workforce can be found in other papers (Abdoul Soukour et al., 2013; Cuevas et al., 2016; Yan et al., 2004).

The optimisation objective is another key factor in LSP research. In most industries, costs associated with the workforce represent a considerable proportion of the total costs. This has motivated multiple researchers to develop models minimising these costs. Some of the costs are regular working time cost and overtime cost of internal resources and working time cost of hired external resources (Heimerl & Kolisch, 2010), costs related to different types of activities (Rong & Grunow, 2009), costs of hierarchical workers with different qualifications (Ulusam Seçkiner et al., 2007), fixed and variable costs regarding a minimum of hours worked by the employees (van der Veen et al., 2015).

Regarding the solution strategies, multiple approaches have been taken to solve the LSP. Van der Veen et al. (2015) proposed a MILP model to solve their cost-efficient staffing problem. Huq et al. (2004) and Karam et al. (2017) also proposed a MILP as a solution strategy. However, with large instances, some MILP formulations become impractical solution strategies because of the large computational time needed to find the optimal solution. Because of that, heuristics have become an important and practical option for solving large problems. Petrovic and Vanden Berghe (2012) solved a nurse rostering problem using a metaheuristic and compared it with a case-based reasoning approach.

Goodale and Thompson (2004) compared four individual worker assignment heuristic methods, three of which did not require a computer, and one used a simulated annealing heuristic method. Other heuristic approaches were described by Houghton and Portougal (2005) and Rocha et al. (2014). The first one proposed the use of the stones heuristic, which makes allocation decisions sequentially, while the second developed a constructive heuristic for solving the staff scheduling problem of a glass manufacturing unit.

The LSP with learning effects has received attention in recent years. The complexity of the problem and its nonlinear nature due to the learning curve has made this problem an interesting and relevant subject of research. Bentefouet and Nembhard (2013) described the problem of scheduling heterogeneous workers in a flow line by modelling their performance and learning behaviour. Their objective was to maximise the throughput of the flow line, and they showed how the optimality of this objective depends on the learning and productivity characteristics of the workers. Kim and Nembhard (2013) presented a parallel production system with a heterogeneous workforce in which productivity varies dynamically. They used an exponential learning and forgetting model to represent individual learning and forgetting behaviours of the workforce. De Bruecker et al. (2018) also presented a model considering skill development. They described aircraft maintenance workers with different skills; the workers could be trained for a specific skill if necessary. The solution strategy used is a three-stage mixed integer programming approach to optimise the skill mix and find an optimal training schedule for the workforce to reduce costs. Zabihi et al. (2019) proposed a project scheduling problem in which the efficiency of the workforce depends on the time they spend executing the skill. They presented a mixed integer nonlinear programming model with the exponential learning effect and developed two teaching–learning based optimisation algorithms.

### 1.2. Welfare LSP

Workforce welfare has been a widely studied LSP characteristic because of its importance in employee productivity and satisfaction. Many authors have tackled this problem by balancing the worker's workload. Rocha et al. (2013) tried to level the working days of multiple worker teams by using an objective function that minimises the maximum number of days each team works. Research by Rojas et al. (2008) minimised the difference between the assigned hours to each employee, thus balancing the working hours of the entire workforce, while Kaplansky and Meisels (2007) considered a lower and upper limit of the number of tasks that each worker can be assigned to in each schedule.

Other authors have proposed employee satisfaction as an optimisation objective to ensure the welfare of the workforce. Al-Yakoob and Sherali (2006) developed a model to assign faculty members to classes considering their preferences regarding specific classes and time slots and proposed a dissatisfaction cost function. Akbari et al. (2013) proposed a mixed integer programming model to maximise employee satisfaction based on their preferences in their shift assignment. Al-Yakoob and Sherali (2007) developed a mixed-integer program that considered the employee preferences for stations, off-days, and shifts (see also Al-Yakoob & Sherali, 2007a, 2008). More examples related to employee satisfaction can be found in other papers (Mac-Vicar et al., 2017; Örmeci et al., 2014).

This investigation addresses a problem of an LSP with heterogeneous employees and activities that require different minimum levels of skill. This paper also considers such aspects as the welfare of the lab assistants and training. This paper differs from the described literature in several aspects. First, the balance of the skills attained is considered an objective; these skills are accumulated as the assistants perform their activities. Secondly, the proposed model identifies the lab assistants that do not meet the minimum level of skill required. These assistants are trained by developing practices together with another assistant with a higher level of skill. This allows skill accumulation through the execution of tasks and training at the same time. Furthermore, the proposed model also considers two skill types, one that improves with the execution of activities or training and other skills that remain unchanged (equal to the starting level). In addition, other elements are also included that contribute to the welfare of the assistants, such as availability, the balance of working hours, and flexible scheduling for assistants who are assigned to night shifts the day before. The problem is formulated as a MILP, which is solved optimally with the help of hierarchy constraints and redundant constraints that allow reducing the search space.

## 2. RESEARCH METHODS

### 2.1. MILP model

This section formulates the MILP model for solving an LSP with the accumulation of skill, training, and welfare considerations. The model's sets, parameters, and variables and their corresponding notation are defined:

**Sets**

$A =$ Lab assistants, indexed by $a$
$M =$ Months, indexed by $m$
$S =$ Weeks, indexed by $s$
$D =$ Days, indexed by $d$
$F =$ Slots, indexed by $f, f1$ and $f2$
$T =$ Types of lab practices, indexed by $t$
$P =$ Lab practices, indexed by $p$
$H =$ Skills, indexed by $h$

**Induced sets**

$PR\{d\} =$ Set of practices $p$ that can be made in day $d$
$SP\{p\} =$ Set of time slots $f$ required for practice $p$
$WM\ \{m\} =$ Set of weeks $s$ that belong to month $m$
$DW\{s\} =$ Set of days $d$ that belong to week $s$
$DWM\{s, m\} =$ Set of days $d$ that belong to week $s$ and month $m$
$PT\{t\} =$ Set of practices $p$ that belong to the type of practice $t$
$TP\{p\} =$ Set of type of practice $t$ which practice $p$ belong to
$PSD\{f, d\} =$ Set of practices that take place at slot $f$ in the day $d$
$PA\{a\} =$ Set of practices that can be made by assistant $a$
$AP\{p\} =$ Set of lab assistants that are able to make practice $p$

**Model parameters**

$ss_f =$ Starting time for slot $f, f \in \mathrm{F}$
$fs_f =$ Finishing time for slot $f$ , $f \in \mathrm{F}$
$ah_{ah} =$ Initial skill level $h$ of the assistant $a, a \in \mathrm{A}$ , $h \in \mathrm{H}$
$mh_h =$ Maximum cumulative skill level $h, h \in \mathrm{H}$
$hr_{ht} =$ Minimum required skill $h$ for practice type $t, h \in \mathrm{H}, t \in \mathrm{T}$
$comp_{f1,f2} =$ Compatibility between the slot $f1$ and slot $f2$ , $f1 \in \mathrm{F}, f2 \in \mathrm{F}$
$ph_{ht} =$ Percentage that increases the skill $h$ of an assistant when performing the type of practice $t, t \in \mathrm{T}, h \in \mathrm{H}$
$hus =$ Maximum hours per week
$hls =$ Minimum hours per week
$M =$ Large value
$hem =$ Maximum overtime per week
$htl =$ Weekly hours for logistics work of the assistants
$hum =$ Maximum idle scheduled hours
$mp =$ Maximum number of practices that an assistant can make per day
$ahm =$ Skill contribution from practice with highest contribution
$tuf =$ End time of the ending later slot

**Decision variables**

$Z_a = 1$ if lab assistant $a$ is scheduled to any practice, 0 otherwise, $a \in \mathrm{A}$
$X_{ap} = 1$ if lab assistant $a$ make the practice $p$, 0 otherwise, $a \in \mathrm{A}, p \in \mathrm{PA\{a\}}$
$Y_{ahp} =$ Cumulative skill level for lab assistant $a$ in skill $h$ during the practice $p$
$BSA_{ahp} =$ Binary that indicates if the assistant $a$ has been over $-$ enabled in skill $h$ when doing the practice $p$
$D_{ad} =$ Total hours that lab assistant $a$ is scheduled on day $d$

$IA_{ad}$ = Entrance time that the lab assistant $a$ has on day $d$
$SA_{ad}$ = Departure time that the lab assistant $a$ has on day $d$
$EH_{ah}$ = Cumulative excess of lab assistant a in skill h with the practice p
$DH_{ah}$ = Cumulative deficiency of lab assistant $a$ in skill $h$ with the practice $p$
$HS_{as}$ = Hours worked by lab assistant $a$ in the week $s$
$ES_{as}$ = Overtime of lab assistant $a$ in the week $s$
$US_{as}$ = Number of hours remaining for the lab assistant $a$ to complete the time slot of the week $s$
$BHES_{as}$ = Binary overtime of lab assistant $a$ in the week $s$
$OS_{as}$ = Scheduled time of the assistant $a$ in the week $s$ without practices
$HMIN$ = Skill level accumulated by the assistant who accumulated lowest skill level

**Objective function**

$$\text{Maximise } HMIN \tag{1}$$

The objective function (1) seeks to maximise the lowest accumulated skill for lab assistants in the last practice. This ensures that assistants' skills are levelled at the end of the horizon planning. Moreover, for further academic terms, the allocation will be easier (assuming the same lab assistants) since all of them will be able to attend the practices generating flexibility for the company.

**Constraints**

$$Y_{ahp} + (1 - Z_a) * ahm * mp * nd \geq HMIN \quad \forall\, a \in A, h \in H, p\ in\ P: p = np \tag{2}$$

$$\sum_{p \in P} X_{ap} \geq Z_a \,\forall\, a \in A \tag{3}$$

$$\sum_{a \in AP} X_{ap} \leq 2 \,\forall\, p \in P \tag{4}$$

$$\sum_{a \in AP} X_{ap} \geq 1 \,\forall\, p \in P \tag{5}$$

$$Y_{ahp} = ah_{ah} * Z_a \quad \forall\, a \in A, h \in H, p\ in\ P: p = 1 \tag{6}$$

$$Y_{ahp} = Y_{ahp-1} + X_{ap-1} * hr_{th} * ph_{ht} \quad \forall\, a \in A, h \in H, p\ in\ P: p > 1, t \in TP\{p-1\} \tag{7}$$

$$X_{ap} = 0 \quad \forall\, a \in A, p \in (P\ diff\ \ PA\{a\}) \tag{8}$$

$$Y_{ahp} + Y_{a2hp} \geq (hr_{th}/2) * (X_{ap} + X_{a2p}) - (2 - (X_{ap} + X_{a2p})) * hr_{th} \,\forall\, a \in A, a2 \in A : a \neq a2, h \in H, p \in P, t \in TP\{p\} \tag{9}$$

$$Y_{ahp} \geq hr_{th} * X_{ap} + hr_{th} * \left(1 - \sum_{a3 \in A} X_{a3p}\right) \quad \forall\, a \in A, \quad h \in H, p \in P, t \in TP\{p\} \tag{10}$$

$$Y_{ahp} \leq mh_h + BSA_{ahp} * ahm * mp * nd \quad \forall a \in A, h \in H, p \in P \tag{11}$$

$$mh_h - Y_{ahp} \leq (1 - BSA_{ahp}) * ahm * mp * nd \quad \forall\, a \in A, h \in H, p \in P \tag{12}$$

$$Y_{ahp} = mh_h * Z_a + EH_{ahp} - DH_{ahp} \quad \forall\, a \in A, h \in H, p \in P \tag{13}$$

$$EH_{ahp} \leq BSA_{ahp} * ahm * mp * nd \qquad \forall\, a \in A, h \in H, p \in P \tag{14}$$

$$DH_{ahp} \leq \left(1 - BSA_{ahp}\right) * mh_h \qquad \forall\, a \in A, h \in H, p \in P \tag{15}$$

$$\sum_{p \in \left((PSD\{f1,d\} \cup PSD\{f2,d\}) \cap PA\{a\}\right)} X_{ap} * (1 - COMP_{f1,f2}) \leq 1 \quad \forall\, a \in A, d \in D, (f1, f2) \in F \tag{16}$$

$$IA_{ad} \leq X_{ap} * ss_f + \left(1 - X_{ap}\right) * tuf \quad \forall\, a \in A, d \in D, p \in PR\{d\}, f \in SP\{p\} \tag{17}$$

$$SA_{ad} \geq X_{ap} * fs_{f} \;\; \forall\, a \in A, d \in D, p \in PR\{d\}, f \in SP\{p\} \tag{18}$$

$$tuf * \sum_{p2\, \in PSD\{d\}:\, p2<p} X_{ap2} + IA_{ad} \geq X_{ap} * ss_{f} \; \forall\, a \in A, d \in D, p \in PR\{d\}, f \in SP\{p\} \tag{19}$$

$$-tuf * \sum_{p2\, \in PSD\{d\}:\, p2>p} X_{ap2} + SA_{ad} \leq X_{ap} * fs_{f} + \left(1 - X_{ap}\right) * tuf \;\;\; \forall\, a \in A, d \in D, p \in PR\{d\}, f \in SP\{p\} \tag{20}$$

$$SA_{ad} \;\leq Z_{a} * tuf \;\;\; \forall\, a \in A, d \in D \tag{21}$$

$$IA_{ad} \;\leq Z_{a} * tuf \;\;\; \forall\, a \in A, d \in D \tag{22}$$

$$SA_{ad} \;\leq \sum_{p \in PR\{d\}} X_{ap} * tuf \;\; \forall\, a \in A, d \in D \tag{23}$$

$$IA_{ad} \;\leq \sum_{p \in PR\{d\}} X_{ap} * M \;\;\; \forall\, a \in A, d \in D \tag{24}$$

$$D_{ad} = SA_{ad} - IA_{ad} \;\; \forall\, a \in A, d \in D \tag{25}$$

$$\sum_{d\, \in DW\{s\}} D_{ad} = HS_{as} \;\;\; \forall\, a \in A, s \in S \tag{26}$$

$$HS_{as} = hus + ES_{as} - US_{as} \;\;\; \forall\, a \in A, s \in S \tag{27}$$

$$HS_{as} \leq hus + BHES_{as} * hem \;\;\; \forall\, a \in A, s \in S \tag{28}$$

$$ES_{as} \leq BHES_{as} * hem \qquad \forall\, a \in A, s \in S \tag{29}$$

$$US_{as} \leq (1 - BHES_{as}) * hus \qquad \forall\, a \in A, s \in S \tag{30}$$

$$hls \leq HS_{as} \leq hus \;\;\; \forall\, a \in A, s \in S \tag{31}$$

$$OS_{as} = HS_{as} \; - \sum_{d\, \in DW\{s\}} \; \sum_{f \in F, p\, \in PSD\{f,d\}} \left(fs_{f} - ss_{f}\right) * X_{ap} \;\;\; \forall\, a \in A, s \in S \tag{32}$$

$$htl \leq OS_{as} \leq hum \;\;\; \forall\, a \in A, s \in S \tag{33}$$

$$Z_{a}, X_{ap}, BSA_{ahp}, BHES_{as} \in \{0, 1\} \tag{34}$$

$$D_{ad}, IA_{ad}, SA_{ad} \in \mathbb{Z}^{+} \tag{35}$$

$$Y_{ahp}, EH_{ah}, DH_{ah}, HS_{as}, ES_{as}, US_{as}, OS_{as}, HMIN \in \mathbb{R}^{+} \tag{36}$$

Constraint (2) linearises the maximin function, while constraint (3) ensures that every scheduled assistant must be assigned to practice. Constraints (4) and (5) set the upper and lower limits of assistants per practice, respectively. Constraints (6) and (7) control the accumulation of skill, while constraint (8) manages the assistants who are unable to perform certain practices. Constraints (9) and (10) guarantee the minimum skill level of the assistants assigned to practices. Constraints (11)–(15) capture the excess of skill acquired by the lab assistants. Constraint (16) prevents overlapping in the assignment of assistants. Constraints (17)–(25) determine the duration of time for which an assistant is scheduled in one day, while constraint (26) consolidates the weekly hours in which an assistant is scheduled. Constraints (27)–(30) define and limit overtime and missing hours per assistant per week, and constraint (31) defines the limits for the weekly working hours of the assistants. Constraints (32) and (33) define and limit the scheduled hours with no assigned practices that the assistants have per week. Finally, constraints (34)–(36) define the domains for the decision variables.

The following constraints (37) (39) have been added to ensure hierarchy in the assignment of practices by days and slots:

$$\sum_{a \in A\{p-1\}} X_{ap-1} \geq X_{a1p} \quad \forall\, p \in P: p > 1, a1 \in AP\{p\} \tag{37}$$

$$\sum_{a \in A\{p-1\}} X_{ap} * na \geq X_{a2p2} \quad \forall\, d \in D, f \in F, p \in PSD\{f,d\}, p2 \in PSD\{f,d+1\}: d < nd, a2 \in AP\{p2\} \tag{38}$$

$$BSA_{ahp} \leq BSA_{ahp+1} \quad \forall\, h \in H, p \in P: p < np, a \in AP\{p\} \tag{39}$$

One of the key aspects of the model is represented in constraints (9) and (10). These constraints allow the model to allocate a lab practice to an assistant while, at the same time, another lab assistant is being trained. Furthermore, constraints (6) and (7) compute the accumulation of skills every time an activity is performed, either for the one executing party (the trainer) or the one receiving the training (trainee). Finally, constraint (8) synthesises two additional contributions of the model. On the one hand, it guarantees flexibility for lab assistants since they can previously define the set of practices they cannot perform due to personal schedules. On the other hand, this constraint also allows to control the skills that are not cumulative, forbidding the allocation of assistants who do not meet the requirement, such as the academic background. Regarding the welfare of the employees, constraint (16) considers that if the employees have been allocated to practices on the night shift the previous day; they cannot be assigned to practices on the morning shift.

## 2.2. Case study

The case study used in this paper was conducted in the laboratories of a university in Colombia, where different types of lab practices are developed for the biology, chemistry and pharmaceutical chemistry programmes. In order to develop these lab practices, it is necessary to schedule lab assistants in different predefined time slots for each day. Laboratory assistants must have specifics academic bachelor's degrees and a certain skill level to handle specialised laboratory equipment, depending on the practice type. To

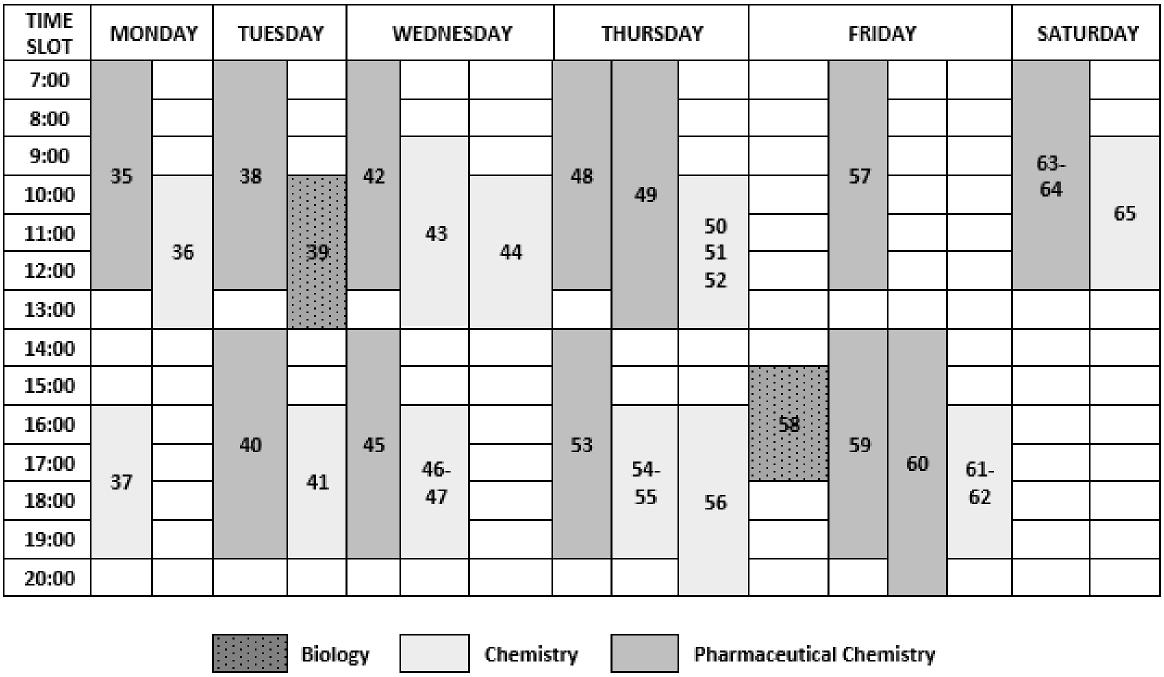


Fig. 1. Example of a weekly schedule for the laboratory practices

be trained in these skills, assistants must be allocated with another assistant to ensure the required skill level.

The scheduling horizon is one academic term (18 weeks, 80 days), during which the university develops 358 lab practices corresponding to 32 types in 18 predefined time slots. For the case study, eight lab assistants with different academic backgrounds were considered: five were chemists, one was a biologist, one was a pharmaceutical chemist, and one was a pharmaceutical chemistry student. Each lab assistant has an initial skill level in handling equipment related to their academic background. Fig. 1 presents an example of a weekly schedule for lab practices. Lab assistants must then be allocated to support the development of each practice. It can be observed, e.g., that for Friday, it is necessary to allocate assistants with three different bachelor's degrees. However, it can also be seen that in the same week, the workload for pharmaceutical chemistry and chemistry practices is higher than for biology, and this situation can change weekly. Moreover, some practices overlap in the same time slot, e.g., practices 59 to 62. Finally, the duration of the time slots is variable, as well as their starting times, generating a total of 18 different time slots.

## 3. EXPERIMENTS

Several experiments have been designed to explore and exploit different uses of the proposed model. Some of these experiments require modifications in the objective functions and constraints. The defined experiments to be analysed are presented below.

### 3.1. Experiment 1. Number of employees vs minimum level of skill

This case explores the relationship between the number of lab assistants and the minimum skill level achieved in the last practice. This experiment represents the initial configuration of the model. Additionally, the following constraint is also introduced to experiment with the maximum number of lab assistants to be programmed. The parameter nap represents the maximum number of lab assistants.

$$\sum_{a \in AP} Z_a = nap \tag{40}$$

Where nap = 6, 7, 8, these values correspond to experiments 1.1, 1.2 and 1.3, respectively. It was found that the problem was infeasible below 6 lab assistants.

### 3.2. Experiment 2. All the lab assistants are able to make all the practices

This case aims to allow all lab assistants to perform any lab practice. In other words, this experiment is interesting since it allows for the exploration of the minimum number of lab assistants required to serve the current instance under the assumption that all of them meet the skill requirements for all the practices.

The modifications for this case are not in the formulation. Instead, the parameters $PA_a$ and $AP_p$ in the data instance are modified to allow all lab assistants to perform all the practices.

### 3.3. Experiment 3. Minimising the number of lab assistants and allocations considering a minimum level of skill

This experiment is designed to study several objective functions while achieving a minimum level of skill. The objective functions, as well as the changes introduced, are presented below. To organise the changes, this case is subdivided into experiments 3.1, 3.2, and 3.3. First, in experiment 3.1, the objective function is modified by minimising the number of lab assistants (same as equation (40)) but ensuring a minimum level of ability for all the assistants. To do this, constraint (2) is modified as follows:

$$\begin{gathered} Y_{ahp} + (1 - Z_a) * ahm * mp * nd \geq 1 \\ \forall\, a \in A, h \in H, p \in P\colon p = np \end{gathered} \tag{41}$$

Second, in 3.2, the same constraint is kept, but the objective function is modified. This allows for finding the minimum number of allocations to ensure the minimum skill level. The objective function is then modified as follows:

$$\text{Minimise} \sum_{a \in A, p \in P} X_{ap} \tag{42}$$

Finally, in 3.3, a weighted objective function is defined that considers both the number of lab assistants and the number of allocations. Some normalisation parameters are used to make the magnitudes similar. The new objective function is presented in equation (43).

$$Minimise \sum_{a \in A, p \in P} X_{ap} + \sum_{a \in A} W * Z_a \quad (43)$$

Where W is a normalisation factor for the number of lab assistants.

# 4. RESEARCH RESULTS AND DISCUSSION

## 4.1. ALLOCATION OF PRACTICES

Lab practices are an important part of education; therefore, the allocation of practices to assistants is an important decision to develop processes correctly. Figs. 2, 3 and 4 show the results of the number of practices assigned to each assistant in each experiment, respectively. In experiments 1 and 2, the objective function aimed to balance the workload of the assistants, while in experiment 3, the main target was to minimise the number of workers and allocations and the minimum of skill that the assistants had to accumulate at the end of the time horizon was set very low, which led to a more unbalanced allocation between the lab assistants.

The number of assigned practices to the assistants depends on the number of available assistants to be

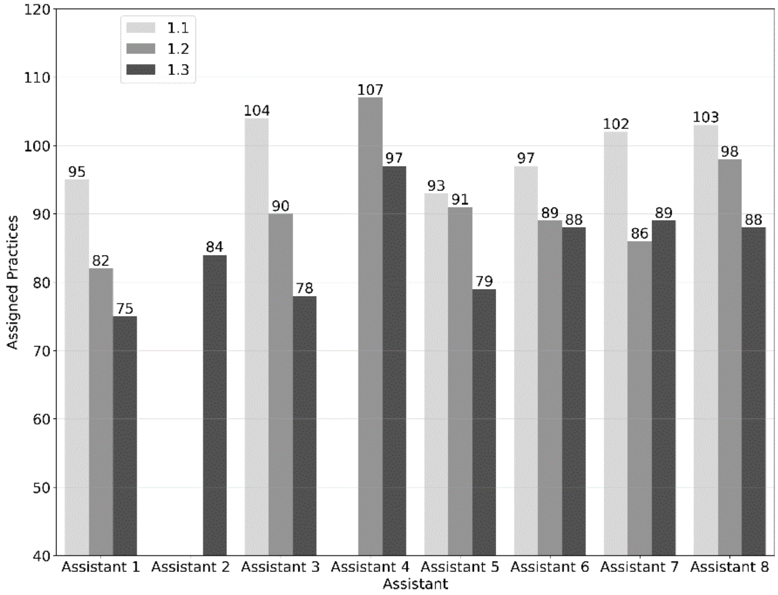


Fig. 2. Assigned practices to the assistants in experiment 1

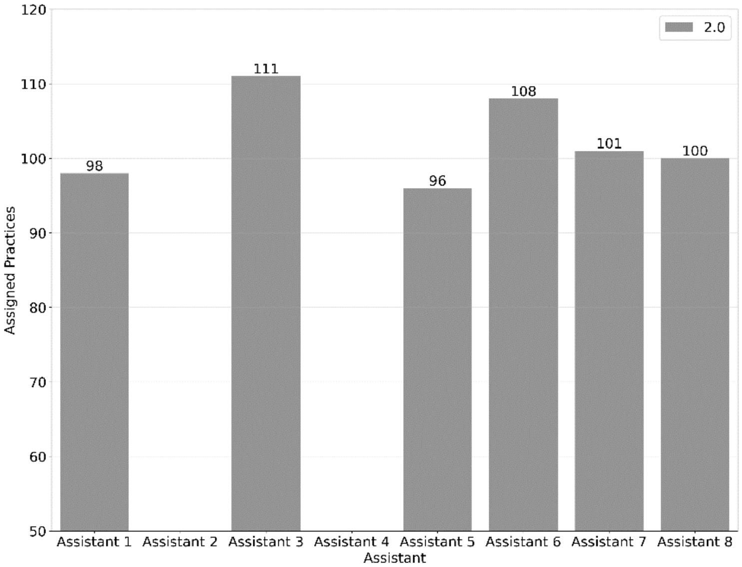


Fig. 3. Assigned practices to the assistants in experiment 2

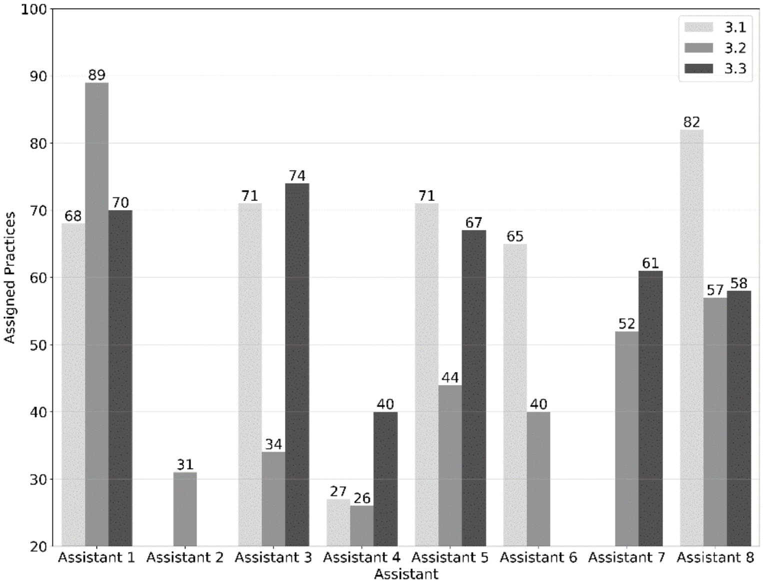


Fig. 4. Assigned practices to the assistants in experiment 3

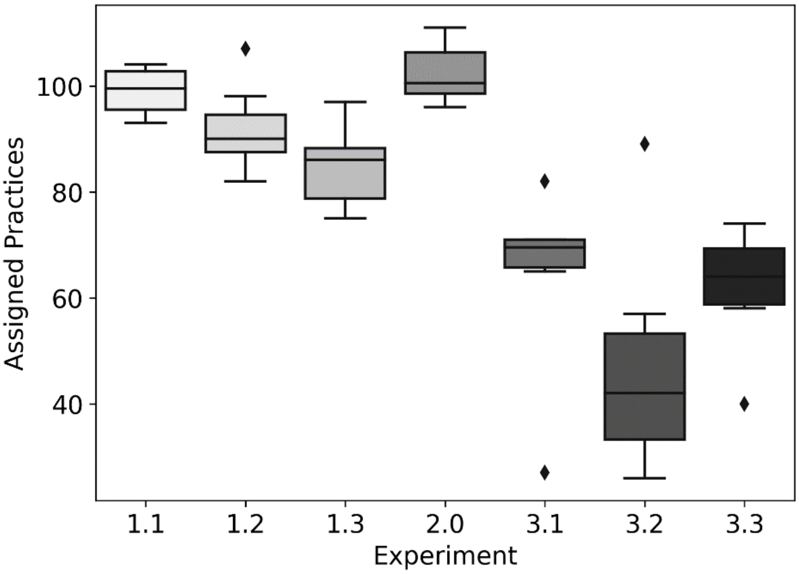


Fig. 5. Balance of the workload

assigned. As mentioned before, for experiments 1.1, 1.2, and 1.3, there were 6, 7, and 8 assistants available, respectively. Fig. 5 shows that the average number of assigned practices to each assistant decreases as the number of available assistants increases. This can also be seen in Figs. 2 and 4.

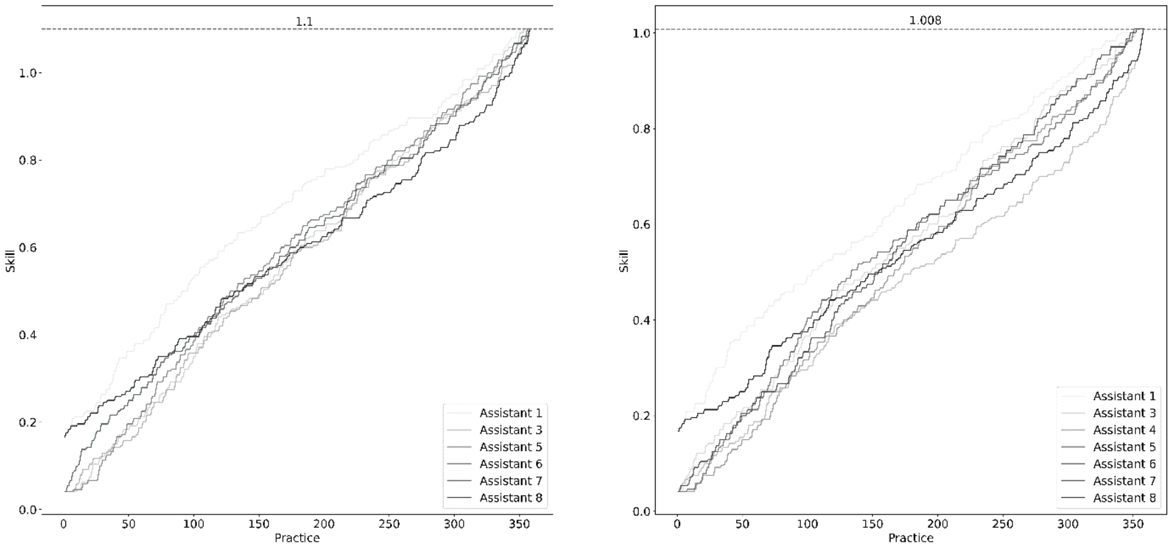
Another factor that affects the number of allocations is the balance of the workload. Fig. 5 indicates that experiments 3.1, 3.2 and 3.3, where no balance restrictions were applied, had either very atypical data of assigned practices, high variance, or both. On the other hand, the use of restrictions for balancing the workload led to no atypical data and low variances in the assignment of practices, as seen in experiments 1.1, 1.3 and 2. The atypical data of experiment 1.2 is small enough to meet the balance restrictions applied to the model.

In experiment 2, all the assistants were allowed to do all the practices. This experiment demonstrates that even if every assistant can do all the practices, the minimum number of assistants needed to comply with the schedule is six. Below this number of assistants, the model did not generate a feasible solution. Moreover, this experiment has the highest number of allocations, as demonstrated in Figs. 3 and 5 because only the minimum number of lab assistants was available. However, each assistant was assigned to a number of practices that ensured the balance of the workload.

Consequently, the assignment of practices becomes more flexible if the lab assistants have higher levels of skill and different skills because that allows for satisfying the personal requirements during the practices while considering the right balance between using as little labour as possible and keeping a high level of service. At the same time, a better workload balance for the assigned assistants is obtained.

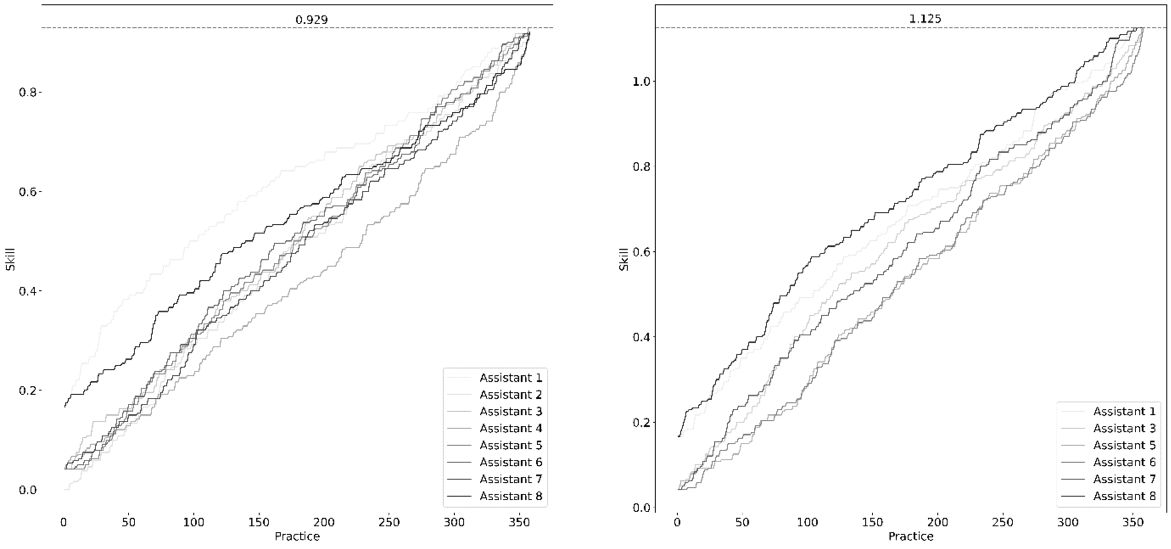
### 4.2. Accumulation of skill

The accumulation of skill depends on the amount and type of practices performed by each lab assistant. The focus of experiments 1 and 2 was to guarantee a balanced assignation of practices and, thus, a balanced accumulation of skills. Figs. 6a, 6b, 6c and 6d show an equal increment of the assistants' skill throughout the practices, which then converge to a close value at the final practice. When comparing the accumulation of skills in experiment 1, it is evi-



(a) Experiment 1.1

(b) Experiment 1.2



(c) Experiment 1.3

(d) Experiment 2

Fig. 6. Accumulation of skill during the practices

dent that the final skill level of the assistants is lower when more assistants are available to be assigned to the practices. This can be explained because the model distributes the total cumulative skill among a higher number of assistants, as demonstrated in Figs. 6a, 6b and 6c.

When comparing experiments 1.1 and 2, as they both assign the minimum number of assistants required to comply with all the practices, it was observed that the final accumulated skill in experiment 2 was higher than in experiment 1.1. This is because, in experiment 2, a higher number of allocations were made, derived from the fact that the lab assistants in this experiment were available for all the practices, which allowed for more training processes. In this pair of experiments, flexibility was contrasted as a benefit for the personnel and flexibility as a benefit for the company. When assistants are given more possibilities to define personal commitments in their working time and a schedule is planned in a way that considers such commitments, the assistants perceive greater flexibility; however, the company has less opportunity to train them and improve their skills, losing flexibility in the sense of not being able to later assign them to a greater number of practices.

### 4.3. Lab assistants training

Training is an important process for companies to carry out tasks and activities correctly. In the presented case study, the level of training for some skills is calculated according to an initial skill and the number of practices developed associated with that skill. For other skills, it is not possible to develop them using training (i.e., a bachelor's degree). In the first type of skill, the more lab practices are assigned, the higher level of knowledge is developed.

Training can be expensive (when assigning more than one person to a task), but the cost depends on the level of required expertise. In experiments 1.1, 1.2 and 1.3, the model was aimed at achieving outstanding levels of knowledge for all the assistants. Hence, for these scenarios, a total of 66%, 80%, and 89% of practices were used for training (more than one person per practice), respectively. This result shows that more assistants will cause more allocations and training to improve the minimum skill level.

In experiment 3, the model is aimed at minimising the number of practices and allocations while meeting a considerably basic level of knowledge. The number of practices allocated to two assistants is considerably low, 7%, 4%, and 3%, respectively. This means that the model is sensitive to the required knowledge level.

Fig. 7 presents the number of practices required to achieve a minimum skill level in the final practice for different numbers of lab assistants. In other words, for a fixed number of practices, different skill levels are achieved depending on the number of lab assistants. The more lab assistants are available, the lower the skill level achieved for a defined number of practices. Furthermore, to achieve higher skill levels,

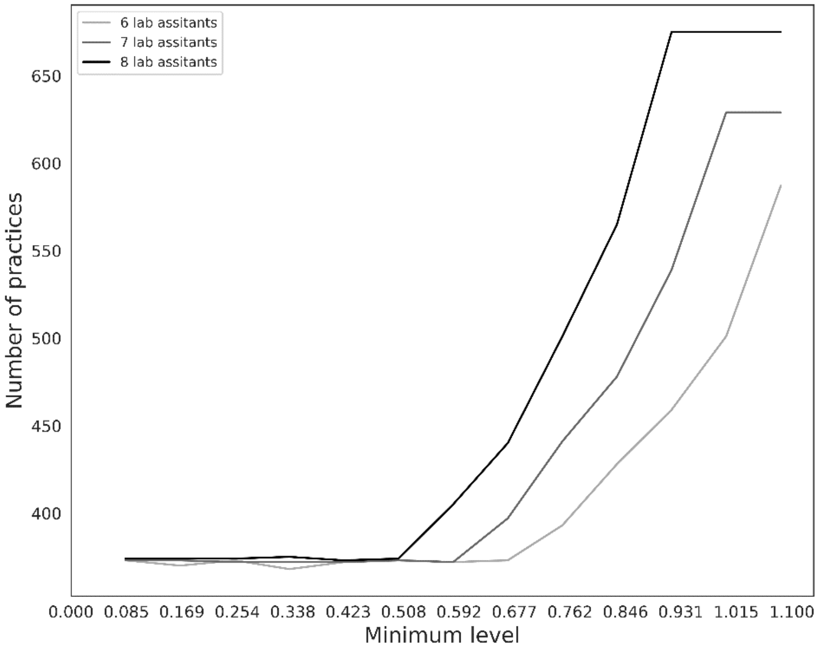


Fig. 7. Minimum level of skill vs number of practices

more practice allocations (training) are required. Hence, achieving high levels of skills is expensive.

Fig. 7 demonstrates that the number of practices required is relatively low for levels below 50 %; however, for levels between 50 % and about 90 %, intensive training is required since the number of required practices grows exponentially. Furthermore, when the number of lab assistants is eight, the maximum skill level that can be achieved is 90 %; for higher levels, the model becomes infeasible.

## CONCLUSIONS

The labour scheduling problem is complex; however, when advanced decision-making methodologies are used, it is possible to optimise different objectives, including improving skills and meeting welfare constraints. Good scheduling allows for considering availabilities and exploiting them to generate welfare conditions. This can be seen as flexibility for workers to define available time slots.

Flexibility is an essential condition to be considered in labour scheduling models. It should be implemented in both ways, allowing employees to gain more skills and conduct more tasks and allowing organisations to offer flexible shifts to their employees. A good labour schedule should consider both aspects while keeping the number of required staff.

Multiskilled and well-trained workers can reduce the impact of adverse events, such as sickness or strikes. Employees who can perform multiple tasks are a valuable resource for organisations since they can reduce the impact of absenteeism. Therefore, organisations should include training in their labour scheduling.

A practice can be exploited for training unskilled staff and accumulating and reinforcing skills for skilled staff. Developing a practice with a partner helps to train unskilled people and acquire expertise for skilled people. Expertise is an important feature since lab practices are made for different users each term, and their requirements can depend on various dynamic aspects, such as disposition, previous knowledge, and cultural aspects. Hence, permanent training is vital for these kinds of tasks.

The schedule of practices should be made carefully. Bad planning can cause additional staff to attend practices. The day and time of practices depend on the class; however, this should be made carefully since overlapping lab practices that require similar knowledge could require more people to support them.

Further research on this topic can consider more objectives, such as environmental issues. While welfare aspects have been considered, sustainability is an important topic. This model could be extended to consider sustainability aspects, such as reducing the number of trips to the workplace.

Labour scheduling is very sensitive to situations that affect the population, such as pandemics. Hence, more studies could be conducted to analyse and develop strategies to mitigate these situations.

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